UWEX
University of Wisconsin-Extension
GEOLOGICAL AND NATURAL HISTORY SURVEY

INFORMATION CIRCULAR
NUMBER 16
(Rev. 1978)

# GEOLOGY OF THE UPPER MISSISSIPPI VALLEY BASE-METAL DISTRICT

Prepared in cooperation with the U.S. Geological Survey
for the Annual Meeting of
THE GEOLOGICAL SOCIETY OF AMERICA
and
ASSOCIATED SOCIETIES
Milwaukee, Wisconsin, 1970
(Revised 1978)

Printing history:

First Edition (1970) prepared as Information Circular 16 in cooperation with the U.S. Geological Survey for the Annual Meeting of the Geological Society of America and Associated Societies, Milwaukee, Wisconsin; 45 p. of text, 4 p. of road log.

Second Edition (1973) prepared as a reprint with slight modification of Information Circular 16 in cooperation with the U.S. Geological Survey for the 19th Annual Institute on Lake Superior Geology, Madison, Wisconsin; 45 p. of text as First Edition, 5 p. of newly prepared road log.

Third Edition (1978) prepared as Information Circular 16 in cooperation with the U.S. Geological Survey. Changes: retitled Geology of the Upper Mississippi Valley Base-Metal District; Table 1 (p. 6-7) amended and updated; 45 p. of text as First Edition; no road log. Companion road log is in Geological and Natural History Survey Field Trip Guide Book series.

Cover illustration:

Headframe of a southwestern Wisconsin zinc-lead mine *circa* 1930, courtesy of the Platteville Mining Museum, 365 East Main Street, Platteville, Wisconsin 53818.

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UNIVERSITY OF WISCONSIN-EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY
Meredith E. Ostrom, State Geologist and Director

# GEOLOGY OF THE UPPER MISSISSIPPI VALLEY BASE-METAL DISTRICT

By

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Madison, Wisconsin
1970
(Revised 1978)

Publication authorized by the Director, U.S. Geological Survey

Available from the Wisconsin Geological and Natural History Survey,
University of Wisconsin-Extension, 1815 University Avenue, Madison,
Wisconsin 53706

CONTENTS

## ILLUSTRATIONS

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TABLE

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# GEOLOGY OF THE UPPER MISSISSIPPI VALLEY BASE-METAL DISTRICT

By A. V. Heyl, W. A. Broughton, and W. S. West

## INTRODUCTION

The Upper Mississippi Valley district (fig. 1) is a major zinc and lead source and minor copper and barite source (for details of district, see Heyl and others, 1955, pl. 25). Ores are chiefly in the Galena Dolomite and in limestones and dolomites of the Decorah and Platteville Formations, all of Middle Ordovician age. Locally, lead, zinc, and copper deposits have been mined from Lower Ordovician dolomites and Upper Cambrian sandstones. Small deposits of lead, zinc, and iron sulfides have been found in the Upper Ordovician Maquoketa Shale, in the Lower Silurian Edgewood and Kankakee Formations, and the Middle Silurian Hopkinton Formation. No post-Precambrian igneous rocks are known in the region, and the granitic and metasedimentary Precambrian basement rocks unconformably underlie the district at depths of 1,500 to 2,000 feet.

Parts of this paper have been abstracted with permission from a much longer paper by Heyl (1968b) published in "Ore Deposits of the United States, 1933-1967," volume 1 of the Graton-Sales volume. Publisher's permission to use this information is gratefully acknowledged. The history and production section was contributed by W. A. Broughton, with a few small additions by Heyl. A section on the stratigraphy of the dolomitized section of the eastern part of the district was contributed by W. S. West. All three authors have made additions and corrections elsewhere in the manuscript.

## GLACIAL GEOLOGY

Most of the district lies within the Driftless Area (Grant and Burchard, 1907, p. 2-3; Shaw and Trowbridge, 1916, p. 1-2; Van Hise and Bain, 1902), but glaciers of pre-Wisconsin age have crossed the eastern and western boundaries and part of the southern boundary. To the east, the nearest glacial deposits of Wisconsin age are in the immediate vicinity of Madison, Wis. Glacial drift of Illinoian age extends southward from the Wisconsin moraine west of Madison through central Wisconsin to Monroe, and thence southwestward to Stockton and Mt. Carroll, Ill. (fig. 1). West of the Wisconsin and Illinoian drift fronts are some scattered patches of outwash for a few miles, but the main part of the mineralized district is free of known glacial drift of any sort, except for the deposits mentioned below.

West and southwest of the district glacial deposits of Nebraskan age thin gradually toward the boundary of the Driftless Area and are represented only by small remnants of drift, which are restricted to

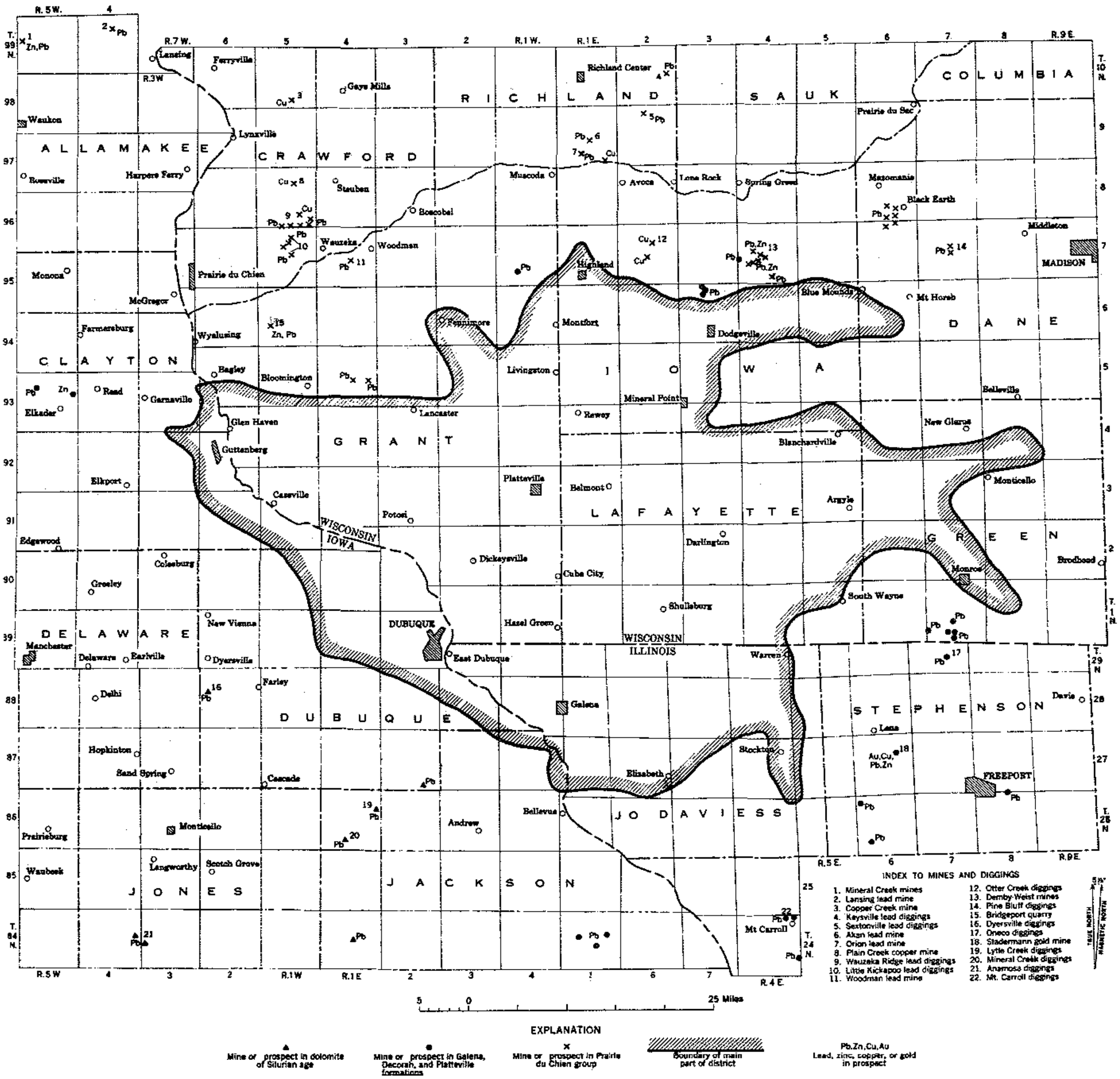



*Figure 1.--Map of the main part of the Upper Mississippi Valley district and mineral deposits in outlying parts of the district. (From Heyl and others, 1959, fig. 101.)*

Iowa, the southwesternmost corner of Wisconsin near Dubuque, Iowa, and the northwesternmost corner of Illinois along the Mississippi River near Galena (fig. 1, this rept.; Heyl and others, 1959, p. 20). 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 (Brown and Whitlow, 1960, p. 8-9). 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. Quite probably, the Mississippi River was channeled along the glacial margin during the Nebraskan Glaciation (Willman and Frye, 1969; Trowbridge, 1966).

## HISTORY AND PRODUCTION

By W. A. Broughton

Mining in the Driftless Area has been more or less continuous for the last 285 years; thus the Upper Mississippi Valley zinc-lead district is the oldest continuously producing zinc-lead district in the United States. Indians are frequently given credit for being the first miners in the area, but such statements are somewhat misleading. Undoubtedly, prehistoric Indians picked up "float" galena and possibly used the mineral for decorative and ceremonial purposes, because galena cubes have occasionally been found at old village sites and in burials. However, no evidence is known that Indians actually practiced mining and smelting of the lead sulfide before contact with white men.

Nicholas Perrot, early French explorer, was probably the first exploiter of the Driftless Area ores. He supposedly built a fort in 1685 in the vicinity of East Dubuque, Ill., and, for a short period, mined "lead" on the west side of the Mississippi near Catfish Creek just south of Dubuque, Iowa. The mining was probably done with Indian labor, and there is evidence that Indians continued to operate the mines after Perrot's departure for over 140 years, until well into the 19th century. The product of these mines was apparently bartered to white trappers and traders.

Pierre Charles LeSueur, on his ascent of the Mississippi in 1700, reported visiting Indian lead mines on Fever River (Illinois), and Tetes de Morts River and Catfish Creek (Iowa). LeSueur supplied himself from a lead mine with many rattlesnakes, very probably Snake Cave at Potosi, Wis.

Julien Dubuque was undoubtedly the first real miner in the Driftless Area. Dubuque, from about 1788 until 1810, not only mined but smelted lead ore in the vicinity of the Iowa city that now bears his name. His miners were largely Indians, probably working as semi-slaves. After Dubuque's death (1810) the area reverted to wilderness and was regarded as Indian Territory, the only mining being done by Indians. During this period the Indians smelted the ore in crude brush or log furnaces and sold the metallic lead to white traders. The remains of such furnaces are occasionally found today.

A treaty with the Sac and Fox in 1815 gave the United States title to the "lead region." As a result, in 1819 Jesse W. Shull and Dr. Samuel Muir established a lead trading post on Fever River at the present site of Galena, Ill., which was settled and grew rapidly in the 1820's. The first permanent American mining camps, in what is now Wisconsin, were made in 1824 at New Diggings and Hardscrabble (Hazel Green) in areas of known Indian "digs." Within the next few years thousands of white miners entered the district.

The early lead mining was extremely crude. Production was largely from "float" deposits formed by weathering of sulfide veins that left concentrations of residual galena on hillside bedrock overlain by varying thicknesses of residual soil. The miners would dig a pit to bedrock and then reach out in all directions, dragging the galena to the center. The mining limit of each pit was soon reached, and then the miners simply moved a short distance away and dug another pit. This system of "suckering" produced the pock-marked hillsides so common in the district.

The pick and shovel were soon supplemented by other mining tools and explosives that made it possible to work the deeper "crevices." Depth of lead mining was limited to a short distance below water table, owing to inadequate pumping equipment and to change from supergene to hypogene ore below the water table.

This was the heyday of lead mining in the Driftless Area. Also during this period about a million pounds of matte copper was smelted in lead furnaces from ore mined near Mineral Point, Gratiot, and north of the Wisconsin River in Richland and Crawford Counties.

Interest in mining the zinc ores began about 1859, and initial production was "drybone" (smithsonite--zinc carbonate) which occurred above the water table overlying "black jack" (sphalerite--zinc sulfide) deposits. The mining of zinc sulfide began at about the end of the Civil War and still continues.

The Jones brothers, in 1886, built their Mineral Point Zinc Company smelter in which, initially, smithsonite was converted to white zinc oxide. This smelter became, for a short period, "the largest zinc plant in the world." Eventually the Mineral Point smelter treated zinc sulfide ore; in 1896 it was purchased by the New Jersey Zinc Company. The plant was permanently closed in 1928. The only other successful attempt to treat zinc ore in the district, for purposes other than making concentrates, was the manufacturing of sulfuric acid at Cuba City, Wis., from 1920 to 1947 by the Vinegar Hill Zinc Company of Platteville, Wis.

Compared to ores of some other districts the zinc ores now produced from the district are relatively low grade. The zinc-lead ratio is about 10:1. Early zinc mining was very selective and average grades of 9 or 10 percent zinc were common. Today the mining has been considerably mechanized and is relatively nonselective; as a result, the average mined ore contains about 4 percent zinc. The average grade is, however, quite variable from mine to mine and from stope to stope. Maintaining a lower grade mill feed prolongs the life of the mine and results in an overall higher metal production. Individual ore bodies are rather small, few containing more than a million tons.

The Upper Mississippi Valley zinc-lead district in the past has been largely a "boom or bust" district. The "booms" were primarily the result of periods of emergency and high metal prices. Just prior to World War II there was little mining activity, except that stimulated by the Vinegar Hill Zinc Company acid plant at Cuba City. At the beginning of the war, outside interest in the district was revived by activities of the U.S. Geological Survey-Wisconsin Geological Survey-Illinois State Geological Survey cooperative program, by the U.S. Bureau of Mines, and by a rising zinc market. Large companies such as Tri-State Zinc, Calumet and Hecla Copper, Eagle-Picher Zinc, New Jersey Zinc, and American Zinc, Lead, and Smelting entered the district. This change was responsible for the modernization and mechanization of mining methods in the district.

The years 1917 and 1952 were peak production times for the district. The 1917 production was 64,000 tons of metallic zinc. In 1952 the mines produced 34,716 tons of metallic zinc and 3,532 tons of metallic lead with an aggregate gross value of more than $12,663,016. During World War II about 50 small operators were producing roughly 4,500 tons of zinc ore per day. In the 1960's, the principal producing companies were Eagle-Picher Industries, Inc., American Zinc, Lead, and Smelting Company (Vinegar Hill Division), New Jersey Zinc Company, Tri-State Zinc Company, Ivey Construction Company, Piquette Mining Company, Mifflin Mining Company, and Grimes Mining Company. Nearly 30 mines were operated in that decade, which produced ore from about 65 ore bodies. At present, three large and one small company, mining several ore bodies and operating four concentrating plants, are producing about 3,300 tons of zinc ore daily.

Some annual production figures for the Upper Mississippi Valley district and for the Wisconsin part of the district are given in table 1.

## GEOLOGIC HISTORY AND STRATIGRAPHY

The rocks exposed in the district are Cambrian, Ordovician, and Silurian in age. Rocks of the Precambrian basement have been found only in wells at depths of 1,500 to 2,000 feet. The oldest rocks exposed—the Franconia Sandstone and Trempealeau Formation of Late Cambrian age—crop out 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). The rocks that form outcrops in the district are shown in figure 2. Of these, the Galena Dolomite of Middle Ordovician age (fig. 2) is the most widely exposed, but the older Middle Ordovician Decorah, Platteville, and St. Peter Formations are common, particularly

**Table 1. Upper Mississippi Valley mining district zinc-lead production 1940-1977 as compiled by W. A. Broughton, M. G. Mudrey, Jr., and J. Funck from U.S. Bureau of Mines Minerals Yearbooks.**

[Subsequent to 1962 the U.S. Bureau of Mines discontinued publication of separate records of Illinois production of zinc and lead from the Upper Mississippi Valley district and from the Rosiclare district in the southern part of the state. All production from the Rosiclare district contains fluorspar; all production from the Upper Mississippi Valley district is free from fluorspar. Illinois statistics after 1962 are estimated from tonnages of the non-fluorspar zinc-lead ore mined, and an assumed average ore grade of 3 to 3.5 percent zinc in a ratio of zinc to lead of about 10:1. These figures are a gross estimate for Illinois production. After 1974 Wisconsin production is estimated, and values calculated from average metal prices. After 1962 the district ranking is for the Wisconsin part of production only. Very small quantities of lead were produced in Iowa intermittently during 1940-1950. This lead production is included with Wisconsin production where the ores were processed. Perhaps 1.5 short tons of lead concentrates were mined and shipped from Iowa in 1953 that yielded 1 ton of metallic lead. A very small tonnage of high-grade copper ore was mined in Wisconsin in 1947, 1948, 1950, and byproduct copper concentrates were produced in small quantities in the late 1960's and early 1970's. Sulfuric acid, a byproduct of iron sulfide roasting, was produced in large quantities by the Vinegar Hill Zinc Co. from 1940 through 1948 (Heyl and others, 1959) ]

| | ZINC | | | | | | LEAD | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | TONS OF METAL | | % OF U.S. PRODUCTION | | VALUE (thousand dollars) | | TONS OF METAL | | % OF U.S. PRODUCTION | | VALUE (thousand dollars) | | TOTAL ZINC-LEAD VALUE (thousand dollars) | U.S. DISTRICT RANK FOR ZINC | NUMBER OF MINES | |
| | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | | | Wis. | Ill. |
| 1940 | 5,770 | 6 | 0.98 | 0.01 | 727 | 1 | 445 | 8 | 0.10 | 0.01 | 44 | 1 | 763 | 16 | 141 | 1 |
| 1941 | 6,238 | 1,718 | 0.96 | 0.26 | 936 | 258 | 1,225 | 120 | 0.26 | 0.03 | 139 | 14 | 1,345 | 15 | 123 | 2 |
| 1942 | 9,426 | 1,700 | 1.50 | 0.27 | 1,753 | 316 | 775 | 133 | 0.17 | 0.03 | 104 | 18 | 1,451 | 14 | 94 | 2 |
| 1943 | 14,387 | 1,152 | 2.42 | 0.19 | 3,108 | 249 | 920 | 84 | 0.23 | 0.02 | 138 | 13 | 2,691 | 11 | 69 | 3 |
| 1944 | 15,549 | 1,693 | 2.84 | 0.30 | 3,545 | 386 | 1,415 | 93 | 0.36 | 0.02 | 226 | 15 | 3,036 | 11 | 61 | 2 |
| 1945 | 15,561 | 3,757 | 3.33 | 0.80 | 3,579 | 864 | 1,776 | 485 | 0.50 | 0.14 | 305 | 83 | 3,475 | 7 | 48 | 3 |
| 1946 | 14,276 | 4,068 | 3.11 | 0.89 | 3,483 | 993 | 1,588 | 273 | 0.54 | 0.09 | 346 | 60 | 3,499 | 8 | 53 | 5 |
| 1947 | 12,224 | 4,853 | 1.92 | 0.95 | 2,958 | 1,174 | 1,166 | 650 | 0.30 | 0.17 | 336 | 187 | 4,123 | 11 | 52 | 8 |
| 1948 | 7,864 | 6,197 | 1.25 | 1.15 | 2,092 | 1,648 | 861 | 946 | 0.22 | 0.28 | 308 | 339 | 4,462 | 13 | 41 | 7 |
| 1949 | 5,295 | 12,551 | 0.89 | 2.11 | 1,313 | 3,113 | 857 | 1,189 | 0.21 | 0.29 | 271 | 376 | 4,954 | 11 | 46 | 5 |

| Year | ZINC | | | | | | LEAD | | | | | | TOTAL ZINC-LEAD VALUE (thousand dollars) | U.S. DISTRICT RANK FOR ZINC | NUMBER OF MINES | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TONS OF METAL | | % OF U.S. PRODUCTION | | VALUE (thousand dollars) | | TONS OF METAL | | % OF U.S. PRODUCTION | | VALUE (thousand dollars) | | | | | |
| | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | Wis. | Ill. | | | Wis. | Ill. |
| 1950 | 5,722 | 21,071 | 0.92 | 3.38 | 1,625 | 5,984 | 532 | 1,269 | 0.12 | 0.30 | 144 | 343 | 7,910 | 7 | 11 | 5 |
| 1951 | 15,754 | 15,649 | 2.31 | 2.29 | 5,734 | 5,696 | 1,391 | 532 | 0.36 | 0.14 | 481 | 260 | 12,094 | 7 | 22 | 5 |
| 1952 | 20,588 | 14,128 | 3.09 | 2.12 | 6,835 | 4,690 | 2,000 | 1,532 | 0.51 | 0.39 | 644 | 493 | 12,663 | 7 | 24 | 7 |
| 1953 | 16,830 | 9,456 | 3.07 | 1.82 | 3,871 | 2,175 | 2,094 | 1,594 | 0.61 | 0.46 | 549 | 418 | 7,012 | 7 | 29 | 7 |
| 1954 | 15,534 | 9,907 | 3.28 | 2.09 | 3,355 | 2,140 | 1,261 | 1,968 | 0.39 | 0.60 | 346 | 586 | 6,380 | 7 | 7 | 6 |
| 1955 | 18,326 | 13,085 | 3.56 | 2.54 | 4,508 | 3,219 | 1,948 | 1,861 | 0.58 | 0.55 | 581 | 555 | 8,862 | 6 | 10 | 4 |
| 1956 | 23,890 | 14,608 | 4.40 | 2.69 | 6,546 | 4,003 | 2,582 | 1,724 | 0.73 | 0.49 | 811 | 541 | 11,901 | 6 | 14 | 4 |
| 1957 | 21,575 | 22,185 | 4.06 | 4.17 | 5,006 | 5,147 | 1,900 | 2,970 | 0.56 | 0.88 | 543 | 849 | 9,615 | 5 | 16 | 5 |
| 1958 | 12,140 | 18,540 | 2.95 | 4.50 | 2,477 | 3,782 | 800 | 970 | 0.30 | 0.36 | 187 | 227 | 6,748 | 4 | 2 | 5 |
| 1959 | 11,635 | 19,615 | 2.74 | 4.61 | 2,676 | 4,511 | 745 | 1,370 | 0.29 | 0.54 | 171 | 315 | 6,758 | 5 | 6 | 5 |
| 1960 | 18,410 | 20,325 | 4.22 | 4.67 | 4,750 | 5,244 | 1,165 | 1,245 | 0.47 | 0.50 | 273 | 291 | 10,558 | 13 | 8 | 6 |
| 1961 | 13,865 | 18,425 | 2.99 | 3.97 | 3,189 | 4,238 | 680 | 1,205 | 0.26 | 0.46 | 140 | 248 | 7,815 | 12 | 9 | 4 |
| 1962 | 13,292 | 17,066 | 2.63 | 3.38 | 3,057 | 3,925 | 1,394 | 837 | 0.59 | 0.35 | 256 | 154 | 7,393 | 14 | 9 | 4 |
| 1963 | 15,114 | 10,520 | 2.86 | 1.99 | 3,476 | 2,420 | 1,116 | 1,000 | 0.44 | 0.39 | 241 | 216 | 6,353 | 13 | 9 | 4 |
| 1964 | 26,278 | 5,400 | 4.57 | 0.94 | 7,148 | 1,470 | 1,742 | 840 | 0.61 | 0.29 | 456 | 221 | 9,295 | 10 | 8 | 2 |
| 1965 | 26,993 | 5,560 | 4.42 | 0.91 | 7,882 | 1,620 | 1,645 | 560 | 0.55 | 0.19 | 513 | 175 | 10,190 | 10 | 13 | 2 |
| 1966 | 24,775 | 3,840 | 4.33 | 0.67 | 7,185 | 1,110 | 1,694 | 390 | 0.52 | 0.12 | 512 | 120 | 8,927 | 10 | 16 | 2 |
| 1967 | 28,953 | 5,900 | 5.27 | 1.07 | 8,106 | 1,630 | 1,596 | 590 | 0.50 | 0.18 | 447 | 165 | 10,348 | 7 | 16 | 2 |
| 1968 | 25,711 | 6,100 | 4.86 | 1.15 | 6,942 | 1,650 | 1,126 | 600 | 0.31 | 0.17 | 298 | 159 | 9,049 | 7 | 13 | 2 |
| 1969 | 22,901 | 8,000 | 4.14 | 1.45 | 6,687 | 2,340 | 1,102 | 800 | 0.22 | 0.16 | 328 | 238 | 9,593 | 10 | 11 | 3 |
| 1970 | 20,634 | 11,000 | 3.86 | 2.06 | 6,322 | 3,370 | 761 | 1,000 | 0.13 | 0.17 | 238 | 306 | 10,236 | 9 | 9 | 3 |
| 1971 | 10,645 | 7,000 | 2.17 | 1.43 | 3,428 | 2,250 | 752 | 850 | 0.13 | 0.15 | 207 | 235 | 6,120 | 12 | 8 | 3 |
| 1972 | 6,873 | 7,300 | 1.44 | 1.53 | 2,440 | 2,582 | 757 | 840 | 0.12 | 0.13 | 228 | 253 | 5,503 | 13 | 3 | 3 |
| 1973 | 8,672 | 1,150 | 1.81 | 0.24 | 3,583 | 474 | 844 | 48 | 0.14 | 0.01 | 275 | 6 | 4,338 | 12 | 1 | 2 |
| 1974 | 8,737 | 0 | 1.75 | -- | 6,273 | 0 | 1,285 | 0 | 0.19 | -- | 578 | 0 | 6,851 | 13 | 2 | 0 |
| 1975 | 9,000 | 0 | -- | -- | 7,000 | 0 | 900 | 0 | -- | -- | 387 | 0 | 7,387 | -- | 2 | 0 |
| 1976 | 9,000 | 0 | -- | -- | 6,660 | 0 | 900 | 0 | -- | -- | 416 | 0 | 7,076 | -- | 2 | 0 |
| 1977 | 9,000 | 0 | -- | -- | 6,120 | 0 | 900 | 0 | -- | -- | 551 | 0 | 6,671 | -- | 2 | 0 |

| Formation | Member and subdivision | | Local terminology | Description | Unaltered thickness, in feet | | |
|---|---|---|---|---|---|---|---|
| Maquoketa | | | Shale | Shale, blue or brown, dolomitic; with dolomite lenses; phosphatic depauperate fauna in lower few feet | 108–240 | | |
| Galena | Dubuque | Noncherty unit | Buff or sandy | Dolomite, yellowish-buff, thin- to medium-bedded; with interbedded dolomitic shale | 35–45 | 120 | 225 |
| Galena | Stewartville | Noncherty unit | Buff or sandy | Dolomite, yellowish-buff, thick-bedded, vuggy; *Receptaculites* in lower part | 37–47 | | |
| Galena | Prosser: P | Noncherty unit | Buff or sandy | Dolomite as above; bentonite rarely at midpoint | 38 | | |
| Galena | Prosser: A | Cherty unit | Buff or sandy / ? / Drab | Dolomite, drab to buff, thick- to thin-bedded; cherty; bentonite at base | 32 | 105 | |
| Galena | Prosser: A | Cherty unit | Drab | Dolomite as above; *Receptaculites* at top | 6 | | |
| Galena | Prosser: A | Cherty unit | Drab | Dolomite as above; cherty | 6 | | |
| Galena | Prosser: A | Cherty unit | Drab | Dolomite as above; some chert; *Receptaculites* at midpoint | 26 | | |
| Galena | Prosser: B | Cherty unit | Drab | Dolomite as above; little chert; *Receptaculites* abundant | 15 | | |
| Galena | Prosser: B | Cherty unit | Drab | Dolomite as above; much chert | 10 | | |
| Galena | Prosser: C | Cherty unit | Drab | Dolomite as above; | 10 | | |
| Galena | Prosser: D | Cherty unit | Drab | Dolomite and limestone, light-gray, argillaceous; grayish-green dolomitic shale | 11–15 | 20 | 32–44 |
| Decorah | Ion | | Gray beds / Blue beds | Dolomite, limestone, and shale as above, but darker | 5–9 | | |
| Decorah | Guttenberg | | Oil rock | Limestone, brown, fine-grained, thin-bedded, nodular, conchoidal; dark-brown shale | 12–16 | | |
| Decorah | Spechts Ferry | | Clay bed | Shale, green, fossiliferous; greenish-buff fine-grained limestone; phosphatic nodules near top; bentonite near base | 0–8 | | |
| Platteville | Quimbys Mill | | Glass rock | Dolomite and limestone, dark-brown, fine-grained, sugary, medium-bedded, conchoidal; dark-brown shale especially at base | 0–18 | | 55–75 |
| Platteville | McGregor | | Trenton | Limestone and dolomite, light-gray, fine-grained | 13–18 | 30 | |
| Platteville | McGregor | | Trenton | Limestone, light-gray, fine-grained, thin-bedded, nodular, conchoidal | 12–17 | | |
| Platteville | Pecatonica | | Quarry beds | Dolomite, brown, medium-grained, sugary, thick-bedded; blue-gray where unweathered | 20–24 | | |
| Platteville | Glenwood | | Shale | Shale, green, sandy | 0–3 | | |
| St. Peter | | | Sand rock | Sandstone, quartz, medium- to coarse-grained, poorly cemented, crossbedded | 40+ | | |

*Figure 2.--Detailed stratigraphic column of Platteville, Decorah, and Galena Formations in zinc-lead district. From Heyl and others (1959, fig. 3).*

in the valleys. Maquoketa Shale of Late Ordovician age (Mullens, 1964, pl. 25; Shaw and Trowbridge, 1916) covers some of the high hills and underlies the land 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 cap a few isolated erosional outliers within the district.

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 the Galena Dolomite. Small lead, zinc, and copper deposits are found locally in the northern part of the district (fig. 1) in the Prairie du Chien Group (Agnew and others, 1956, p. 292-295) and the Trempealeau and Franconia Formations. In places, the St. Peter Sandstone is pyritized, most heavily where it directly underlies zinc deposits.

Some of the details of the stratigraphy, as described by the U.S. Geological Survey (Agnew and others, 1956; Heyl and others, 1959; Mullens, 1964), are illustrated by the detailed and generalized stratigraphic section (figs. 2 and 8). 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 and shale and a few beds of sandstone. Between these carbonate rocks are the predominantly clastic St. Peter Sandstone and Maquoketa Shale. The Franconia, Trempealeau, and St. Peter Formations are permeable sandstones that are widespread aquifers.

Recently Templeton and Willman (1963) redefined much of the rock stratigraphic section on the basis of their work in Illinois and in eastern Missouri and northwestward along the Mississippi River. Many of their units are useful for the entire area, but some units are most useful in the subsurface. Some others are too thin or too indistinct lithologically within the greater Upper Mississippi Valley district to be mappable on the 1:24,000 scale of the present quadrangle mapping. So thicker and simpler units are retained for practical mapping, although equivalents of many of their units such as the Buckhorn (blue), St. James (gray), and Beecher (lower buff) Members of their Dunleith Formation of the Galena Group are mapped throughout the district. Other units such as their Eagle Point Member of the Dunleith have only local usefulness in the district.

Ostrom (1969) further reclassified the Middle Ordovician stratigraphic units (fig. 3) in Wisconsin, simplifying Templeton and Willman's units and retaining and combining them with those of the U.S. Geological Survey. This is a very useful contribution, and all the units are mappable on the quadrangle map scale, except the Hennepin and Harmony Hill Members of the Glenwood Formation, which are, however, distinctive thin units within the district.

The Platteville, Decorah, and Galena Formations (fig. 2) represent an unusually widespread and uniform marine environment of a relatively

| Time-Stratigraphic | | Rock-Stratigraphic | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Series | Stage | Group | Formation | Member | Bed | Max. thck. in ft. | | | Dominant Lithology |
| Cincinnatian | | | Maquoketa Shale | | | 490 | | | Shale |
| Champlainian | Trentonian | Sinnipee* | Galena Dolomite | Dubuque | | 330 | 230 | 40 | Dolomite |
| | | | | Wise Lake | | | | 70 | |
| | | | | Dunleith | | | | 120 | Dolomite and limestone |
| | | | Decorah | Guttenberg | | | 20 | 17 | Limestone and shale |
| | | | | Spechts Ferry | | | | 8 | Shale and ls. |
| | Black-riveran | | Platteville | Quimbys Mill | | | 80 | 18 | Dolomite and limestone |
| | | | | McGregor | | | | +30 | |
| | | | | Pecatonica | | | | 22 | |
| | | | | | Chana | | | 2 | Dolomite, sandy |
| | | Ancell | Glenwood | Hennepin | | +395 | 13.5 | 2 | Shale and silt-stone, very calcareous |
| | | | | Harmony Hill | | | | 3.5 | Shale |
| | | | | Nokomis | | | | 8 | Sandstone, argillaceous |
| | | | St. Peter + | Tonti | | | +385 | | Sandstone |
| Canadian | | Prairie du Chien | | | | 240 | | | Dolomite |

*Subdivisions modified from Agnew et al. (1956) and Templeton and Willman (1963).

+Basal conglomerate of St. Peter Sandstone referred to as Kress Member by Illinois Geological Survey (Buschbach, 1964).

*Figure 3.--Proposed classification of the Sinnipee Group (middle and upper Champlainian) in Wisconsin by Ostrom (1969, fig. 2).*

shallow water platform that had remarkable stability during deposition (Agnew and others, 1956, p. 251). Throughout the 4,000 square miles of the district, the lateral and vertical variations of the mappable units within the formations are remarkably small. Even where dolomitized locally or regionally, the same units can be distinguished within the dolomite with very small variations in thicknesses and other lithologic features. Reefs, bioherms, bars, channels, and other unconformities are notably absent, although the Lower Ordovician beneath and the Upper Ordovician and Silurian above have most of these stratigraphic variations.

The Platteville Formation (except the Glenwood Member) decreases a total of about 20 feet in thickness toward the west, whereas all members of the Decorah Formation increase a total of about 5 feet toward the west. The Galena Dolomite is remarkably uniform in thickness throughout the district, but changes from a coarsely crystalline massive vuggy dolomite in the east to a somewhat argillaceous fossiliferous limestone westward and northwestward. Agnew (1955a) described these changes throughout Iowa.

Brown and Whitlow (1960, p. 22-43) have worked out in detail the stratigraphy of the well-exposed Upper Ordovician Maquoketa Shale and the Silurian System in the Iowa part of the district. They have well-established the apparently conformable relationship of the top of the Galena Dolomite to the overlying Maquoketa Shale within the district (fig. 2). This Galena-Maquoketa contact is an unconformity in the Illinois basin. Within the district the detailed mapping and abundant drilling have shown that a hiatus may exist, but no evidence was found for the unconformity which Callahan (1967) and Ostrom (1967) showed. Templeton and Willman (1963) also considered this contact to be conformable within the district.

Limestones in the Middle Ordovician formations are progressively dolomitized from the central part of the district eastward toward the Wisconsin Arch. The facies change to dolomite is not uniform in each stratigraphic unit, but, in general, all the units east of Mineral Point and Darlington, Wis. (fig. 1), are mainly dolomite, but those to the west contain more limestone than dolomite. Allingham (1963, p. 182-183) described this change in the Platteville Formation, and Taylor (1964, fig. 44, p. 292-295) illustrated it well in the Quimbys Mill Member of the Platteville. These regional dolomite facies closely resemble physically the much more local dolomite alteration aureoles that surround ore bodies, but they are probably not related.

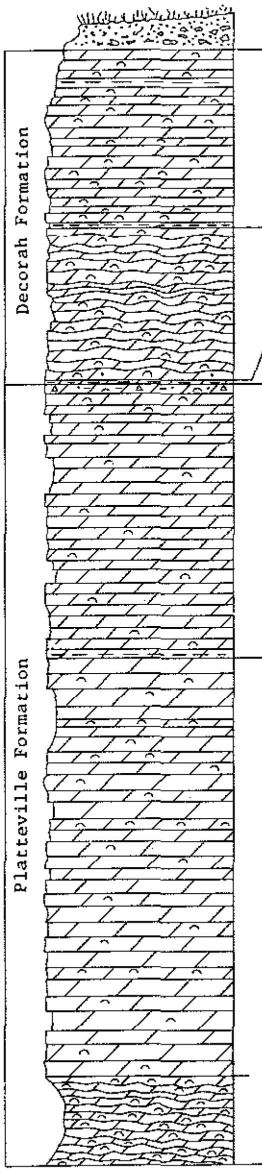
In the central and western parts of the district, the upper members of the Platteville and all the members of the Decorah Formation are partly limestone (fig. 2). These limestone members are the first limestones of any consequence above the Precambrian, and thus provided a favorable host for later leaching and ore deposition. Two limestone units--the Quimbys Mill and Guttenberg Members--contain interbedded carbonaceous shales, a further probably favorable factor in ore deposition.

Superimposed on this mixed dolomite-limestone-shale lithology of the Middle Ordovician strata is the notable sparsity of caves and sinkholes within the district, even though a typical karst topography is widespread in these same units, where they are mainly limestone in southeastern Minnesota and northeastern Iowa. The Prairie du Chien below and Silurian dolomites above have many sinkholes and caves.

## CHARACTERISTICS OF DOLOMITIZED PLATTEVILLE AND DECORAH FORMATIONS IN THE EASTERN PART OF THE DISTRICT IN WISCONSIN

By W. S. West

In contrast with the limestone facies of the Platteville, Decorah, and Galena Formations in the western half of the mining district, the dolomitic rocks near Darlington, Wis., and to the east generally become coarser grained, more sugary in appearance, paler in color, and less shaly, and they contain fewer and less well-preserved fossils, possibly because of obliteration or partial obliteration during diagenesis or dolomitization. The dolomitic section is well exposed north of Darlington (fig. 4); the units are described both in the columnar section,




| | Thickness (feet) |
|---|---|
| Ion Dolomite Member: | |
| Dolomite, light-grayish-blue to yellowish-gray, coarsely crystalline, sugary, thin-bedded, fossiliferous; bluish-green shale partings------ | 9+ |
| Shale, white to light-brown; weathers yellowish orange like bentonite but is hard and gritty because of dolomite grains------------------ | .2 |
| Guttenberg Limestone Member: | |
| Dolomite, light-brownish-buff to dark-yellowish-brown, fine- to medium-grained, wavy thin to medium beds, fossiliferous; some light-brown shale partings; sparse phosphatic nodules in basal bed--------------- | 8.0 |
| Spechts Ferry Shale Member: | |
| Dolomite, like underlying member, but with blebs of greenish-gray shale and sparse phosphatic nodules; dolomitic shale partings at base------ | .2 |
| Quimbys Mill Member: | |
| Dolomite, buff, fine-grained with very sparse small chert nodules; fucoidal openings containing phosphatic pebbles and greenish-gray shale fragments in uppermost 0.2 ft--------------------------------- | .5 |
| Dolomite, light-grayish-buff to light-brownish-gray, dense, fine-grained to very fine grained, medium thick bedded; conchoidal fracture; fossiliferous; brown shale at base-------------------------------------- | 13.5 |
| McGregor Limestone Member: | |
| Dolomite, light-bluish-gray to light-yellowish-brown, fine- to medium-grained, thin- to medium-bedded; fossiliferous; uppermost 2 ft is very fine grained or aphanitic, breaking with a conchoidal fracture, and is difficult to distinguish from Quimbys Mill Member above; correlates with Magnolia Member of Bays and Raasch (1935)------------ | 21.0 |
| Dolomite, light-gray, fine-grained, thin nodular or wavy bedded; grayish-blue to brownish shale partings; very fossiliferous; correlates with Mifflin Member of Bays (1938)---------------------------------------- | 4+ |

*Figure 4.--Dolomitized strata of the Decorah and Platteville Formations exposed in the quarry 1 mile north of Darlington, Wis., in SW 1/4 SE 1/4 sec. 27, T. 3 N., R. 3 E., Lafayette County.*

figure 4, in the quarry near Darlington and briefly below.

In the Platteville the Glenwood Shale Member thins and the Quimbys Mill Member thickens eastward, whereas the Spechts Ferry Shale and Guttenberg Limestone Members of the Decorah become thinner in this direction. There are a few small isolated areas or islands of limestone or dolomitic limestone within the dolomite facies, especially in the McGregor Limestone Member of the Platteville.

The Pecatonica Dolomite Member near Darlington is much like that found throughout the rest of the district, being a fine- to medium-grained buff to pale-gray dolomite that weathers to light yellowish brown and contains casts of marine fossils. It is about 20 feet thick. Medium to coarse grains of well-rounded and frosted quartz and phosphatic nodules are abundant in the lower 2 feet.

The dolomite in the McGregor becomes coarser grained in general, loses its lithographic aspect, and is lighter colored; its lower part resembles the Guttenberg, and the uppermost strata are similar to the Quimbys Mill. The McGregor is approximately 30 feet thick here. The Quimbys Mill Member dolomite has lost its typical dark-purplish-brown color and its lithographic limestone look; it appears to be more sugary and lighter colored. The basal shale layer is generally thinner than in the limestone area and is light to medium brown rather than dark brownish black. The Spechts Ferry is a thin seam of dolomite with sparse blebs of greenish shale and phosphatic nodules in the west and diminishes east to just a few remaining phosphatic nodules. The Guttenberg becomes sugary--the dolomite itself and shale partings are paler colored--and it more closely resembles the Quimbys Mill and McGregor. The Ion corresponds in appearance to the overlying Prosser Member of the Galena Dolomite, but still retains some green shale. The Ion in this area is about 21 feet thick.

The Glenwood Shale Member of the Platteville Formation (fig. 2) consists (5 miles northwest of Darlington at Calamine) mainly of sand and phosphatic nodules with very little bluish-green shale and has thinned to less than a foot in thickness. The uppermost beds of the Pecatonica are generally thin in the dolomite area and are more difficult to distinguish from the overlying McGregor Limestone Member, although the contact is still discernible.

The dolomitized Platteville and Decorah Formations extend across the Wisconsin Arch into eastern Wisconsin where they are reported (Chamberlin, 1882) to change back to limestone. The members of the dolomitized formations continue almost unchanged across the arch, the lithologies almost unchanged from those described at Darlington and Calamine. The contacts are still distinguishable and the units are mappable by experienced field geologists as far east, at least, as Columbus, Belleville, and Beloit. Studies are in progress by West and Heyl to trace the dolomitized formations back into limestone in eastern Wisconsin.

## STRUCTURE

The mining district lies within about 100 miles of the northern edge of Paleozoic sedimentary rocks that overlap the North American Precambrian shield. The Wisconsin Arch (fig. 5), a broad northward-trending anticlinal arch, lies east of the area. The Illinois basin is south of the district, and the Forest City basin lies west and southwest of the district, in Iowa.

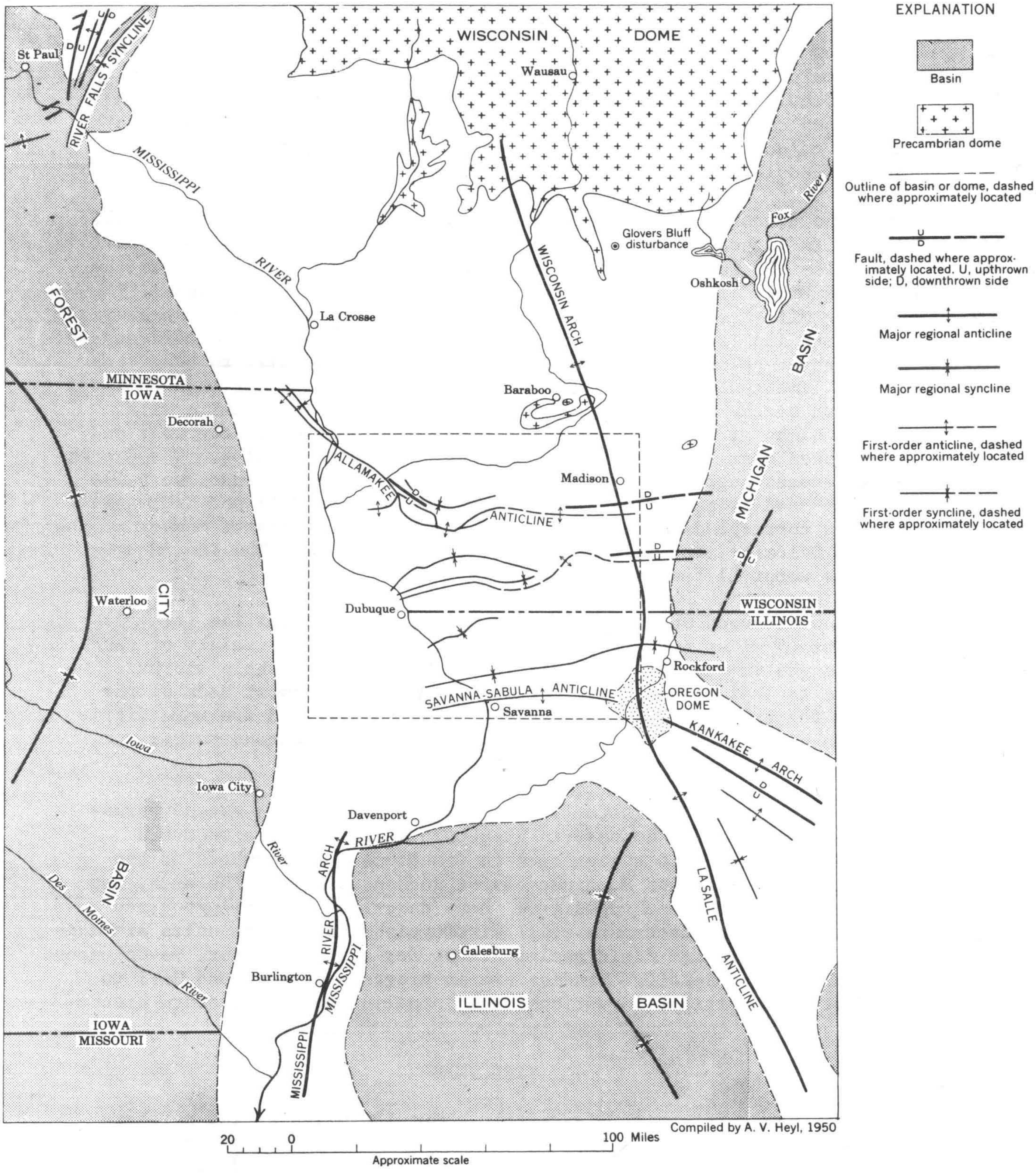



*Figure 5.--Generalized diagram showing the major structural features of the region bordering the Upper Mississippi Valley district (shown by the central square area), and their relations to the principal structures within the district itself. From Heyl and others (1959, fig. 12).*

The regional strike of the sedimentary formations is N. 85° W. throughout most of the district, but it progressively changes to N. 45° W. in the western part. The regional dip is about 17 feet per mile toward the south-southwest. The rocks of the district are folded into low broad undulations that trend northeastward, eastward, northwestward, and a few northward.

The larger broad folds generally trend eastward and range from 20 to 30 miles in length, from 3 to 6 miles in width, and from 100 to 200 feet in amplitude (fig. 5). Rarely do the folds have dips greater than 15° on their limbs, and commonly the dips are much less. Generally the north limbs dip more steeply than the south limbs. The smaller folds trend either eastward to northeastward or northwestward. Folds with these two general trends occur throughout the area and form an unusual rhombic pattern (fig. 6).

Most faults in the district are small reverse, bedding-plane, normal, and shear faults. Displacements commonly range from 1 foot to 10 feet, but small thrusts on the north limbs of folds have displacements of 25 to 50 feet, and some strike-slip shear faults have displacements of from 25 to possibly 1,000 feet (Heyl and others, 1959, p. 37-38; fig. 7, this rept.).

Many of the ore deposits in the district are localized along small faults--chiefly strike-slip, vertical, bedding-plane, and reverse faults on the limbs of folds. Bedding-plane faults are present in the incompetent shaly uppermost part of the Platteville and lower part of the Decorah (fig. 2). Reverse faults curve upward from these bedding-plane faults, at first at low angles, but steepening to about 45° in the overlying competent beds. In general, these two types of faults are confined to the flanks of the folds and tend to follow the outline of the folds to form arcuate or linear patterns. Most commonly the reverse faults dip toward the bordering anticlinal areas (fig. 7, section). Many differences of opinion exist as to the development of the small bedding-plane and reverse faults in ore bodies; for example, see Willman and Reynolds (1947), Reynolds (1958), Mullens (1964), Chamberlin (1882), Allingham (1963), and Klemic and West (1964).

All the formations in the district contain well-developed vertical and inclined joints. The vertical joints are traceable for as much as 2 miles horizontally and for as much as 300 feet vertically. Quite a few of the long joints are actually strike-slip faults that have virtually no vertical component of displacement. Joints are especially well developed in the Galena Dolomite. Most of the vertical joints may be grouped into three average trends--N. 77° W., N. 13° W., and N. 25° E. (Heyl and others, 1959, p. 43-46). 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 fractures of local extent, and many of them are probably incipient reverse faults.

Most of the larger folds, faults, and joints observed in the district are probably a result of a general period of deformation by lateral

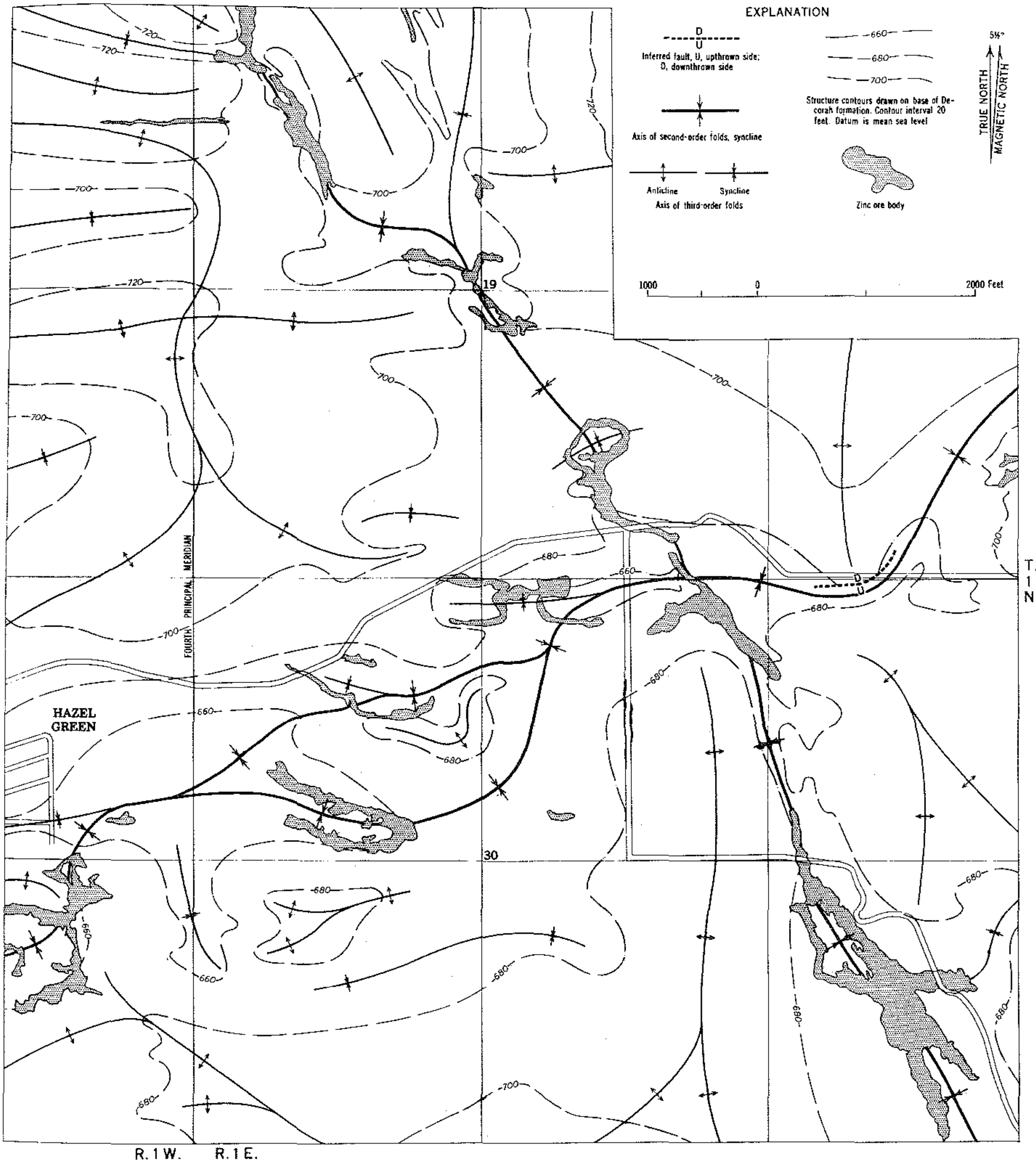



*Figure 6.--Structure map of area east of Hazel Green, Wis., illustrating intricate crossfold patterns and interrelationships of zinc ore bodies and folds. From Heyl and others (1959, fig. 18).*

compression and differential vertical uplift, accompanied by some rotational forces transmitted through the basement by adjustment of basement blocks. This deformation was preceded by earlier minor regional deformations. After the main period of deformation, some uplift and tilting of the rocks took place.

Many of the smaller folds, faults, and joints may be of similar tectonic origin, as described in detail by Heyl and others (1959, p. 31-66), and reiterated by Agnew (1963, p. 258-260), but many of the mineralized structures probably have been markedly accentuated by later solution and slump of the limestone beds just before and during mineralization. Some geologists, such as Carlson (1961, p. 117-118), Mullens (1964, p. 474, 489, 494, 513-518), and Paul Herbert (oral commun. to Heyl, 1945-60), consider that some or all of the smaller structures have formed by solution and slump without tectonic control other than joints. Other geologists, including Reynolds (1958) and Klemic and West (1964, p. 393, 405-407), suggest that the smaller structures may be controlled by initial tectonic fracture systems, but that the structures were developed in their present form by solution and slump.

Linear dislocations in the magnetic patterns of the basement (Heyl and King, 1966) suggest that northwest and northeast fault trends are present beneath the Paleozoic rocks in the Precambrian basement. The coincidence of some of these lines with known major folds (for example, the main northeast-trending fold shown on fig. 6) and faults, such as the Mifflin fault (Heyl and King, 1966, pl. 1), that deform the exposed Paleozoic strata shows that tectonic movement was renewed along some of these linear dislocations in post-Precambrian time. Gentle upward, downward, and lateral adjustments took place in the basement crustal blocks between the linear dislocations. These movements probably provided the necessary basement control of most of the larger faults, gentle folds, and flexures in the overlying Paleozoic strata.

A regional tectonic deformation apparently began sometime before the deposition of the ores; it continued with diminishing intensity during the deposition of the ores and ceased at the end of the ore deposition, or probably shortly thereafter. This sequence of deformation produced the joints, the major folds and some of the minor folds, bedding-plane and reverse faults, shear faults, and some of the brecciation of the ores which occurred several times during their deposition, most probably in the order just given.

## AGE OF MINERALIZATION

The age of the deposits cannot be definitely determined from any of the known relations in the Mississippi Valley. The rocks of the district were all gently warped during the main regional tectonic deformation, which was at least as young as post-Middle Silurian, and, judged from nearby regional relations, was probably Pennsylvanian or later.

The known intrusions elsewhere in the Mississippi Valley are rather remote from the district, and most of their age relations are not

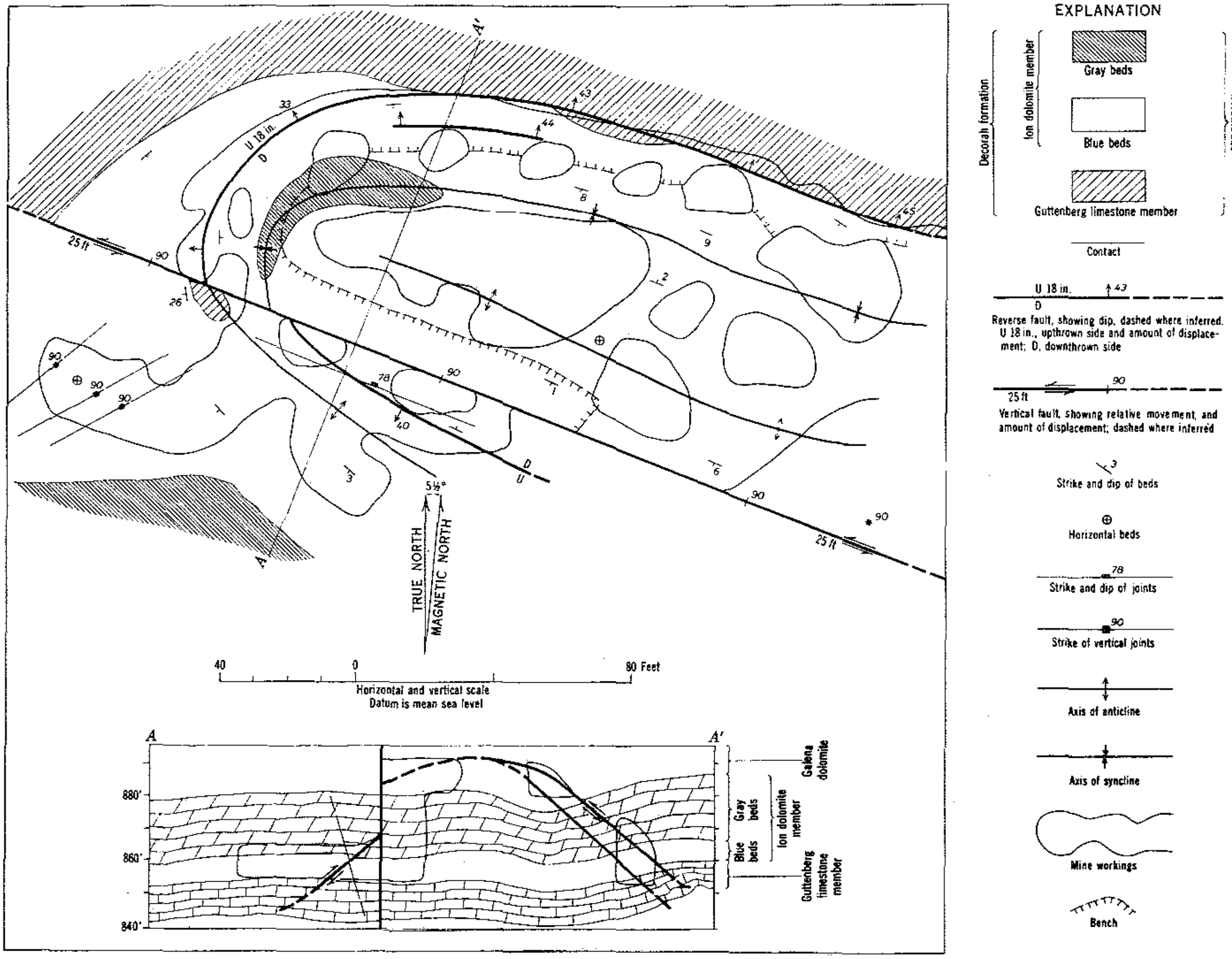



*Figure 7.--Geologic map and section showing the strike-slip fault in the west end of the Liberty mine. From Heyl and others (1959, fig. 23).*

especially clear. In the Illinois-Kentucky fluorspar district, mafic intrusions cut the Pennsylvanian rocks, but not those of Late Cretaceous age (Bastin, 1939, p. 131); they have been isotopically dated as Early Permian by Zartman and others (1967). An igneous intrusion, in part breccia, is reported in Paleozoic rocks near Adair, Iowa (H. G. Hershey, written commun., 1965). The petrology and age of this intrusion are not known.

As the deformation that produced the La Salle anticline extension of the Wisconsin Arch continued at least to the close of the Pennsylvanian, the best probable inference is that the ore deposition occurred sometime between late Paleozoic and the end of the Mesozoic. Lead ore has been found in older glacial gravels of Clinton County, Iowa; so, the deposits were in existence before the Pleistocene Epoch. McGinnis (1968), however, has recently proposed that the deposits were formed during the Pleistocene.

## ORE DEPOSITS

### Stratigraphic relations of the ore bodies

Deposits of lead, zinc, copper, and iron sulfides have been found in most of the Cambrian, Ordovician, and Silurian strata that are exposed in the district (fig. 8). However, all the deposits of lead, zinc, and copper of commercial size occur in the Ordovician--the Prairie du Chien Group and the Platteville, Decorah, and Galena Formations. Considerable limonite and hematite, formed by the oxidation of iron sulfides, and a little lead have been produced from deposits in Cambrian sandstones (Strong, 1882, p. 49-56; Chamberlin, 1882, p. 518-520).

Most of the known deposits in Cambrian and Lower Ordovician rocks are in the main outcrop areas of these rocks in the northern fringe of the district. Similarly, most of the deposits in Silurian rocks are southwest of the district. Exploratory drilling by the U.S. Geological Survey within the main district has located lean deposits of zinc, lead, and iron sulfides in these rocks (Heyl and others, 1951; Agnew and others, 1953). Almost no company prospect drilling has penetrated the St. Peter Sandstone into the underlying dolomites of the Prairie du Chien Group, although the dolomites both in the Prairie du Chien and in the Upper Cambrian Trempealeau Formation are potential host rocks for sulfide minerals.

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 known commercial mineral deposits in the main part of the district are in the Middle Ordovician Galena, Decorah, and Platteville Formations (fig. 8). 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, sphalerite, and barite were found at the Glanville prospect (Heyl and others, 1959, p. 137-138) 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 and Illinois, southwest of the main part of the district. Only a few tons of ore were produced from any of these deposits. Sphalerite is disseminated in basal Silurian rocks at Belmont Mound, Belmont, Wis.

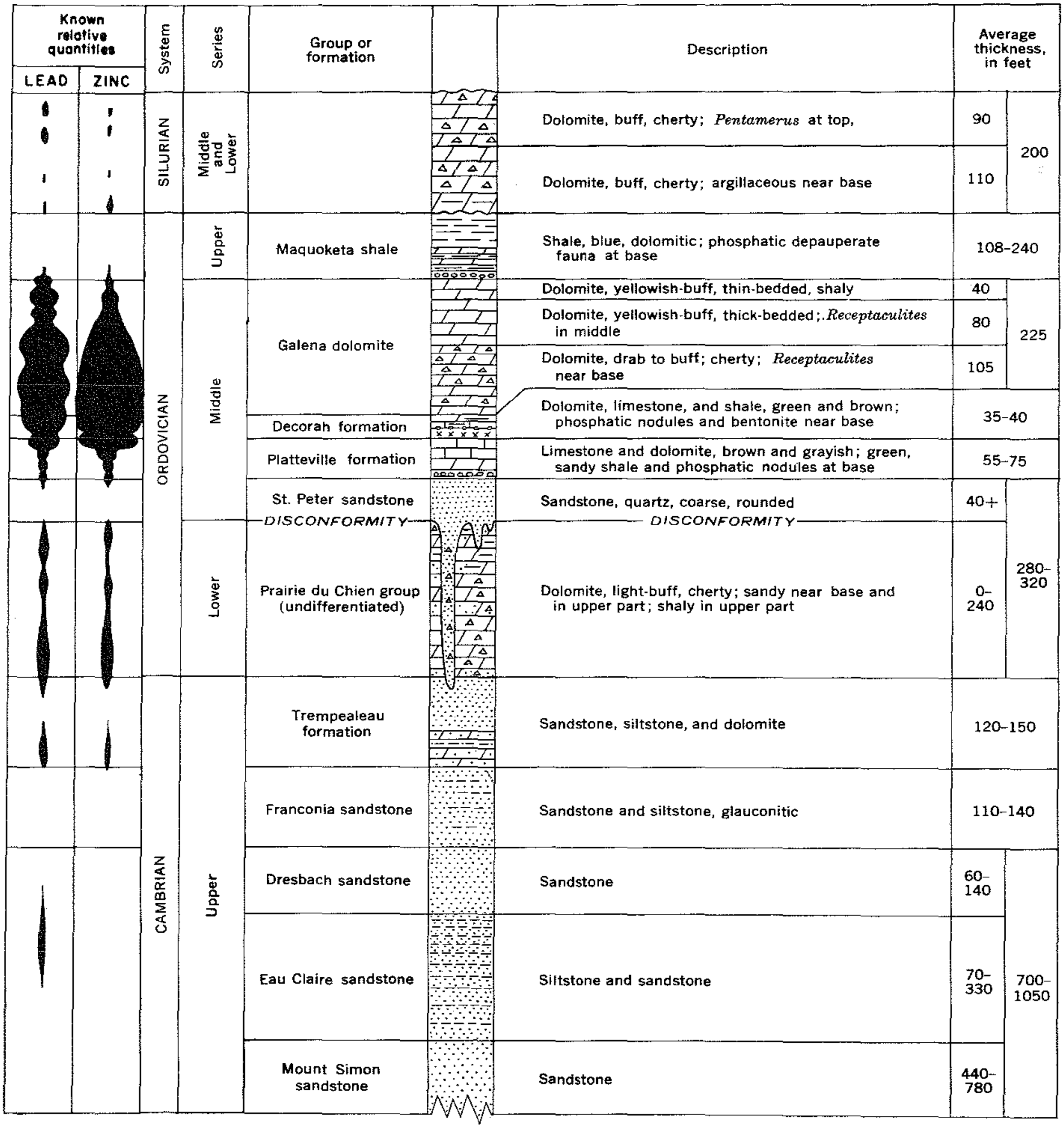



*Figure 8.--Simplified stratigraphic section showing relative quantitative stratigraphic distribution of lead and zinc in the Upper Mississippi Valley district. From Heyl and others (1959, fig. 2), with addition of relative quantities of lead and zinc for this report.*

Forms and controls of the ore bodies

The mineral deposits can be classified into several types: (a) pitch-and-flat deposits (figs. 7, 9), which are veins and replacements in and near reverse and bedding-plane fault zones (pitches and flats, respectively) of small displacement controlled by gentle folds and accompanied by some sagging from solution thinning; (b) gash-vein deposits, which are discontinuous veins controlled by selective solution of beds along joints; and, less commonly, (c) stockworklike deposits; (d) bedded replacements; (e) solution-collapse breccias; (f) fissure veins and lodes; and (g) rare ore-lined giant vugs or small sulfide-encrusted caves.

The zinc and lead deposits of the pitch-and-flat type are found in systems of reverse and bedding-plane faults that show more advanced development in size and displacement in the southern part of the district (Heyl and others, 1959, p. 109). The ore bodies of linear, arcuate (figs. 6, 7, 9), and elliptical form in plan are on the flanks and around the ends of folds. The bodies are more commonly around the ends of synclines than around the ends of anticlines. Many bodies are 1/4-1 mile long and contain 50,000-1,000,000 tons of ore. A few are larger and contain as much as 4,000,000 tons of ore. In places, the pitch-and-flat ore bodies are underlain by broad blankets of breccia and bedded replacement and bedded vein ores, in part controlled by bedding-plane faults and by the basal parts of the reverse fault systems. These blanket ore bodies are in many respects similar to the "sheet ground" deposits beneath fracture-controlled "runs" of the Tri-State district (Fowler and Lyden, 1932). The ore in the pitches and flats and in the underlying bedded blankets is deposited mainly as (a) veins along the fractures and bedding planes; (b) cavity fillings in tectonic and solution breccias; (c) disseminations by replacement and impregnation in favorable beds, particularly shaly strata.

The origin of structures in the pitch-and-flat ore bodies has long been a subject of major controversy. Opinions include the following methods of origin: (a) compressional or rotational tectonics (Behre and others, 1937, p. 788-802); (b) a combination of tectonics followed by subsiding solution and slump (Heyl and others, 1959); (c) initial inclined compressional (Reynolds, 1958; Carlson, 1961) or tensional (Chamberlin, 1882) tectonic fractures controlled by vertical joints followed by major solution and slump; (d) formation by simple slump with only initial joint control as seen in many a brick wall (Grant, 1906; Klemic and West, 1964); and (e) "formation by subsidence around areas of dissolved or weakened rock * * * related to vertical joints, but the position of inclined fractures being definitely related to the altered ground by pressure arch and plate mechanics" (T. E. Mullens, written commun., 1969; see also Mullens, 1964). Further study, especially very detailed geologic drill hole and mine mapping, may resolve some of these matters. Simple collapse pitchlike postmineralization fractures formed by weathering along joints are common on a small scale in some joint-controlled deposits above the water table. They were formed in Recent geologic time above the water table. A few collapse pitches and tumbled

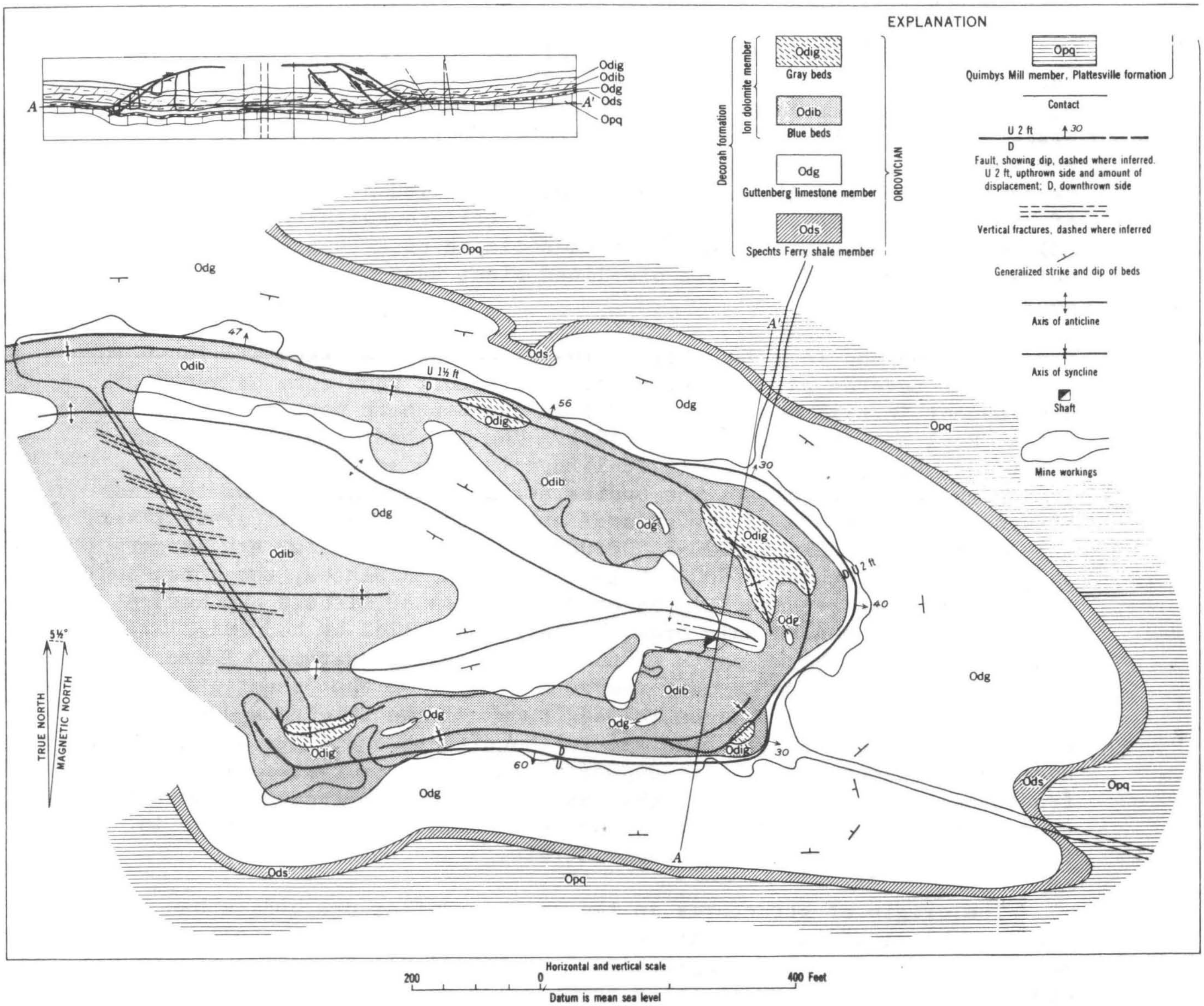



*Figure 9.--Map and section of the Hoskins mine, New Diggings, Wis., showing a large arcuate pitch-and-flat ore body. From Heyl and others (1959, fig. 41).*

breccias formed by simple solution sag by the ore solutions along vertical joints were observed by Heyl.

The gash-vein lead deposits are in joints or strike-slip faults (fig. 10), which for the most part are in beds of the Galena Dolomite stratigraphically above (but not necessarily directly above) the beds containing pitch-and-flat deposits or in the Platteville Formation, some separate and some below such deposits. The ore is in veins of limited extent filling vertical joints and in podlike deposits in

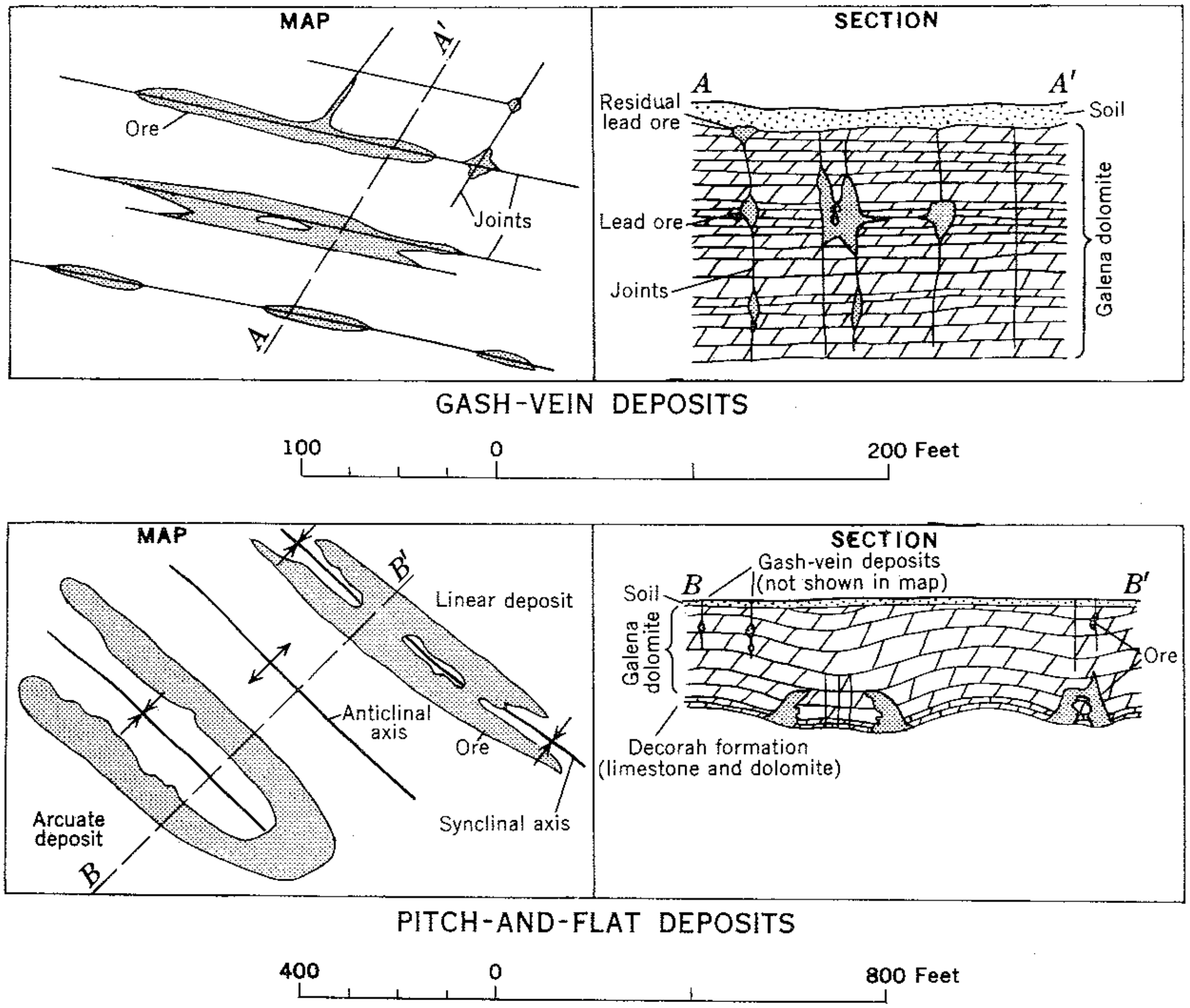



*Figure 10.--Diagrammatic plans and sections illustrating typical patterns of gash-vein lead deposits and underlying pitch-and-flat zinc deposits of the arcuate and linear types and their stratigraphic position to one another. From Heyl and others (1959, fig. 50).*

breccias, replacements, and solution breccias of sanded dolomite in favorable beds along these joints. The podlike deposits, locally known as openings, may lie one above the other in different beds along the same joint. The pods are connected by thin gash veins of galena in the joints. Single mineralized joints are traceable for more than a mile; they commonly have nearly constant strikes. Gash-vein deposits commonly contain 100 to 10,000 tons of lead ore (less commonly zinc, copper, or barite). Structurally they are very similar to deposits described by Eckel (1949, p. 78, fig. 6) in the southern San Juan Mountains of Colorado. Mullens (1964) has described in detail joint-controlled deposits in the Platteville Formation that in recent years have produced abundant ore near Shullsburg, Wis. (see also Heyl and others, 1959, p. 123, 130).

Of the other types of mineral deposits, most of the known fissure veins and lodes are in the north fringes of the district where they occur in faults cutting dolomites and sandstones of Early Ordovician and Late Cambrian age.

Zonation of ore deposits

The ore deposits show both areal and vertical zoning. The areal zoning is illustrated in the east-central part of the district where copper, barium, nickel, and arsenic are relatively abundant in the ores; this unusual metal zone extends northwesterly through the east-central part of the district, irrespective of structure. The vertical zoning is shown by the greater concentrations of lead near the surface, whereas zinc, iron sulfides, nickel, silica, and dolomite are relatively abundant in the deeper deposits. Some of the vertical zoning may reflect the completely different composition of carbonaceous limestone versus dolomite or sandstones in different stratigraphic units and the manner in which the ore-bearing solutions reacted with these chemically different lithologies.

Recent trace-element studies of galena (Hall and Heyl, 1968) indicate that both silver and antimony show an irregular spotty pattern throughout the district, but they do increase in quantity eastward across the district. Unlike the somewhat similar northeastward changes in the lead isotopes, silver and antimony are most abundant in the eastern and southeastern parts of the district.

Wallrock alterations

The ore-bearing solutions have formed alteration halos in the host limestones and shales and, to a lesser extent, the dolomites in the immediate vicinity of the deposits (fig. 11). Alteration is of six types: (1) solution of carbonate rocks, particularly the limestones; (2) silicification; (3) dolomitization; (4) clay mineral alteration; (5) pyritization; and (6) formation of sanded dolomites. Solution or leaching of carbonate rocks has considerably thinned some of the favorable beds to residue shales in many ore bodies. It was first recognized by H. B. Willman in 1943. This thinning has caused fractures in the rock to open, 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 breccia tumbled into the underlying softened, plastic residue shales. Crystals of sphalerite or galena, which nucleated in these soft residue shales, are euhedral. They forced the softened shales upward and aside as the crystals grew. In harder rock the crystals replace the rock or fill small fractures or vugs.

Dolomitic rocks within and near the ore bodies have locally been "sanded" (Lovering, 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. The jasperoids of the silicified

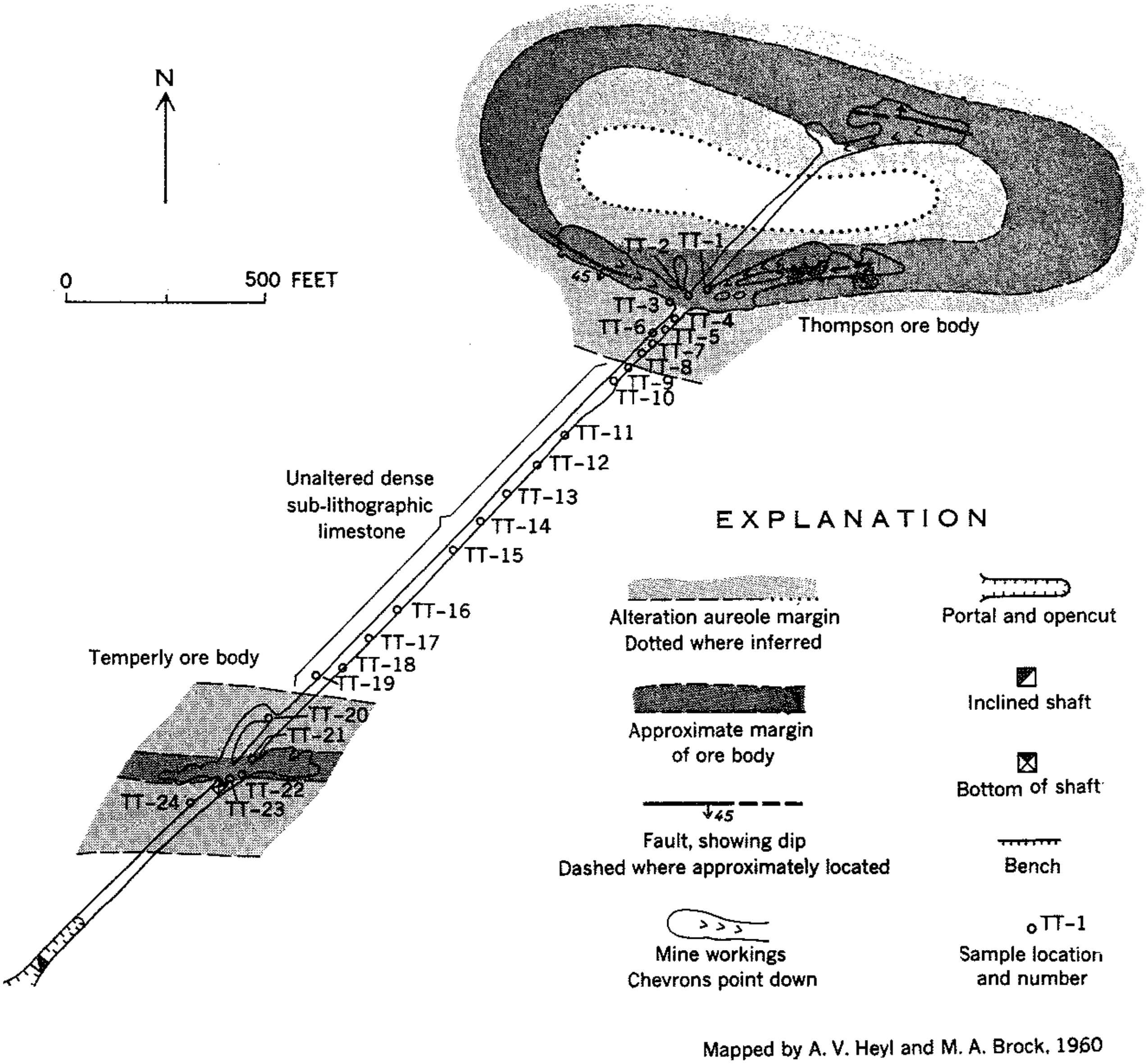



*Figure 11.--Map of the Thompson-Temperly mine showing aureoles of wallrock alterations and location of shale samples (Quimbys Mill Member). From Hall and Heyl (1968, fig. 5).*

zones, the fine-grained dolomite halos, and the sanded dolomites all closely resemble the same kinds of alterations in the Tintic district, Utah, except that in Wisconsin they are not nearly as widespread or abundant.

The limestone, dolomite, and shale walls of the pitch-and-flat and gash-vein types of deposits frequently show rather intense pyritization. Replacement aureoles extend for as much as several feet into the wallrocks. They contain euhedral crystals of pyrite and marcasite and irregular masses or zones of disseminated iron sulfides. Such pyritized walls frequently are somewhat leached and sanded, and when pyritized rock occurs above the flat-type veins it may produce unstable back conditions in the mines.

Nodular bedded pink or buff cherts near the sulfide deposits commonly become changed to a dark gray or almost black, because of abundant microscopic iron sulfide crystals. "Black chert" is considered by some prospectors as indicating proximity to possibly commercial lead and zinc deposits. Locally, desilicated chert nodules have been noted; deep-green celadonite and thin quartz veins are present in deposits of the Prairie du Chien Group, and in one place crystallized flakes of sericite are in small wallrock vugs (Heyl and others, 1964b).

X-ray diffraction of a series of samples from a thin carbonaceous basal shale bed of the Quimbys Mill Member of the Platteville Formation shows well-defined alteration aureoles around the two ore bodies of the Thompson-Temperly mine (fig. 11) (Heyl and others, 1964a). Clay minerals change progressively from the Md polymorph of illite in the unaltered rock to 1M and 2M illite in the aureoles, and the 2M polymorph increases markedly within the ore deposits themselves (fig. 12). In the same samples, calcite decreases, and dolomite and microcline increase toward the ore zone.

The Md polymorph of illite in the unaltered rock between the Thompson and Temperly ore bodies is present in the unaltered strata everywhere throughout the district. The abundance of this low-order illite, which is formed at low temperatures (probably at less than 125°C) during either syngenesis or diagenesis, is strong evidence against a high "fossil" geothermal gradient throughout the district in some past geologic time, which White (1968, p. 311) had proposed.

Stable isotope studies show little fractionation of $O^{18}/O^{16}$ and $C^{13}/C^{12}$ of coexisting limestone and dolomite samples from the Thompson-Temperly mine and nearby mines, as compared with the ratios from barren outcrops. However, systematic decreases in $\delta O^{18}$ and $\delta C^{13}$ values found in limestone and dolomite host rock toward ore are interpreted by Hall and Friedman (1969) as resulting from diminishing fractionation with the increase in temperature toward ore. The decrease toward ore is accompanied by a change in mineralogy of the host rock at the Thompson-Temperly mine from illite of 1Md polymorph in the altered rock to 2M mica and microcline in the ore zone, and also by changes in the major-(fig. 13) and minor-element content of the host rock (Hall and Heyl, 1968; Hosterman and others, 1964).

The wide range of $O^{18}$ and $C^{13}$ in the late-stage ore minerals, as determined by order of deposition, is consistent with an origin for the ore fluid suggested by Hall and Friedman (1963), who proposed that heated oil-field brines mixed with meteoric water during the later stages of mineralization composed the ore fluid. They (1969, p. C146) concluded that the calculated $\delta O^{18}$ of the ore fluid during the late

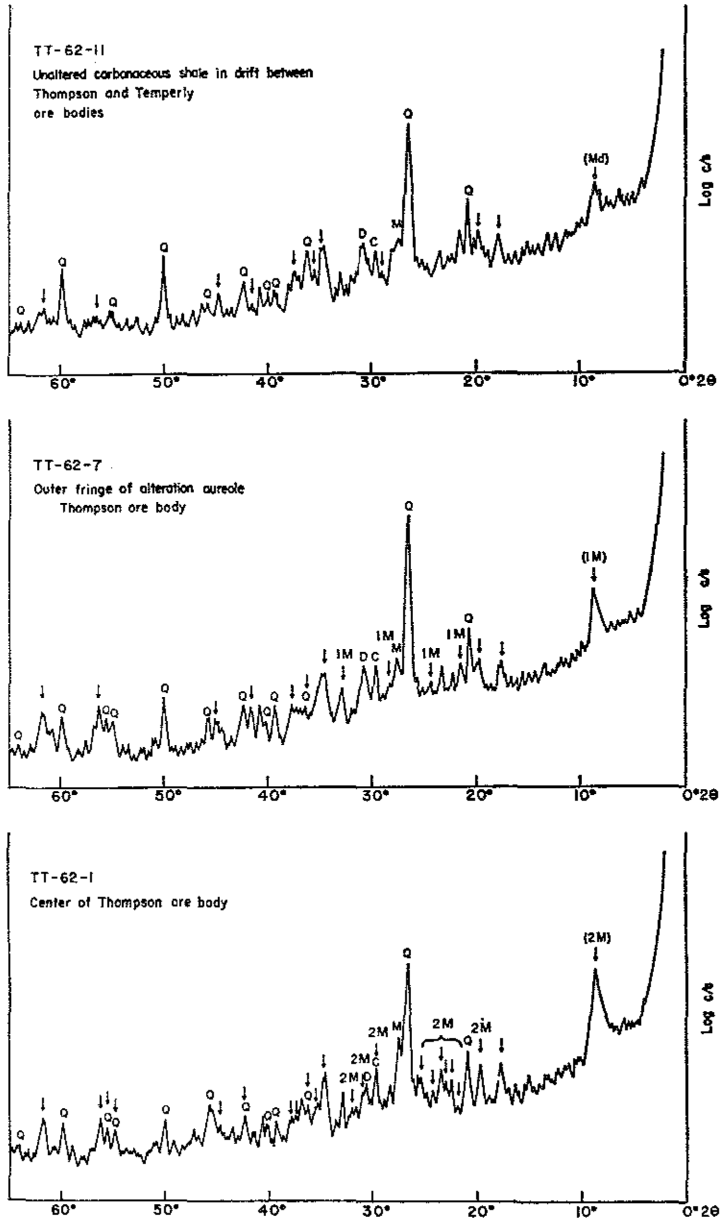



*Figure 12.--X-ray diffraction traces (CuKα radiation) of the clay fraction from three acid-treated carbonaceous shale samples, Thompson-Temperly mine. C, calcite; D, dolomite; Q, quartz; ↓, illite; M, K-feldspar (microcline?). From Heyl, Hosterman, and Brock (1964, fig. 5).*

stages of mineralization of +0.4 to -1.6 is reasonable for the suggested type of ore fluid.

Qualitative X-ray fluorescence and semiquantitative spectrographic analyses of the Thompson-Temperly mine samples (fig. 13) show slight decreases in potassium, aluminum, magnesium, silica, titanium, iron, and manganese in the outer part of the alteration aureoles and marked increases of these major elements in the ore zone (Hosterman and others, 1964). For example, aluminum decreases markedly at the outer edge of the altered zone compared to the amount in the unaltered wallrock. At the inner edge, it increases slightly, and in the ore zone, markedly. Calcium, in contrast, increases slightly in the altered zone and decreases markedly in the ore zone. These facts indicate leaching in the outer fringe of the aureole and migration of the elements toward the ore zone. However, the proportionate volumes and relative contents of the leached zone as compared with those of the inner-alteration aureole and ore zone suggest that much of the aluminum, magnesium, iron, silica, titanium, and manganese was added by the ore-bearing solutions from sources other than the narrow leached outer part.

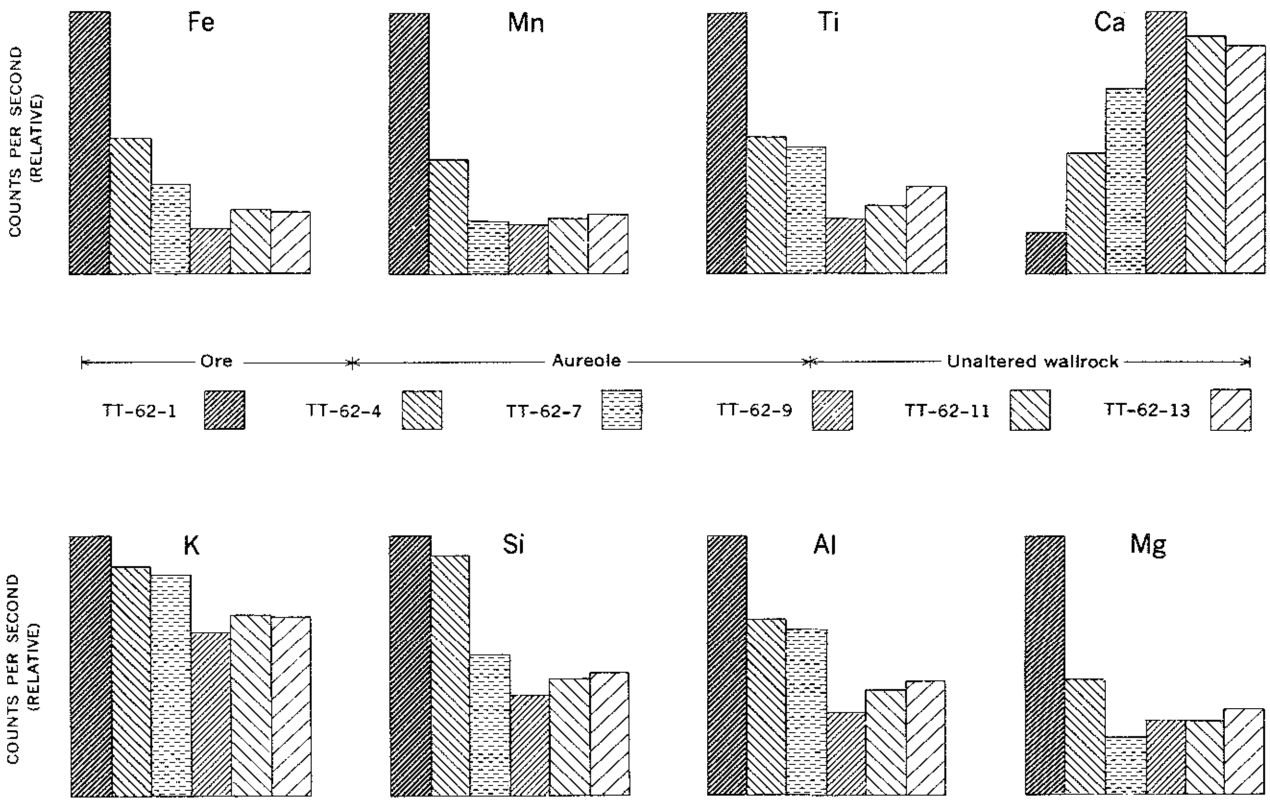



*Figure 13.--Graphs showing relative amounts of eight major elements in six samples of basal shale (Quimbys Mill Member) from the Thompson-Temperly mine, as determined by X-ray emission analysis. From Hosterman, Heyl, and Jolly (1964, fig. 4).*

## Ore textures

Several varieties of ore textures that vary with type of deposit, structural controls, and wallrock alterations are: (a) veins with comb structures with symmetrical or asymmetrical "colloform" banding; (b) solid veins of only one mineral; (c) individual well-formed crystals impregnating softened altered host rock without notable replacement of the rock grains; (d) individual euhedral crystals that replaced the host rock; (e) coarse crystals lining open cavities; (f) reniform, "colloform," nodular, and stalactite-shaped masses; (g) replacement of fossils; and (h) pseudomorphic replacement of earlier formed minerals.

## Mineral paragenesis

The primary minerals of the deposits, in general paragenetic order, are quartz (including chert, jasperoid, and other forms of cryptocrystalline silica), illite, dolomite, pyrite, marcasite, wurtzite(?), sphalerite, galena, barite, chalcopyrite, millerite, enargite, and calcite (fig. 14). A cobalt-nickel-arsenic mineral, not yet identified but possibly having the composition and atomic structure of nickeliferous cobaltite, is known as fine intergrowths with marcasite. Recent mineralogic studies by Whitlow and West (1966a) found that a late primary blue metallic copper sulfide associated with chalcopyrite and enargite was digenite rather than chalcocite. E. R. Roseboom (U.S. Geological Survey, oral commun., 1963) examined the X-ray diffraction traces of this mineral and confirmed this identification. A similar blue chalcocitelike late mineral collected by Roseboom in 1962 has been identified by him (oral commun., 1965) as djurleite. It is closely associated with chalcocite. Fluorite has been found in scattered vugs in the fringe area of the district (Brown, 1967) in Iowa, and also in very small quantities at Mineral Point, Wis. (Philip Blacet, oral commun. to Heyl, 1966), in lead-zinc-copper ore.

Silver occurs in the galena and chalcopyrite in quantities as much as 2 ounces per ton, and is more abundant in some sphalerite. A very little gold has also been noted in pyrite and chalcopyrite. Elements in small quantities in the ores are cadmium, mercury, antimony, manganese, germanium, gallium, niobium, molybdenum, and zirconium.

In the Upper Mississippi Valley district, the paragenetic sequence was investigated as follows: (a) the study was started in those veins and vugs where the original walls were armored by pyrite. It was found that the first sulfide to be deposited was pyrite, and later the other minerals were crystallized in a simple succession of crystals and crusts from the walls to the vein center; (b) it was recognized that sphalerite had a very long period of deposition relative to other minerals, and, though multibanded, the early-deposited sphalerite is generally darker than the later-deposited sphalerite; (c) three successive crystal habits of galena were noted: early-deposited galena is in cubes, later-deposited galena is in cubo-octahedrons, and the last galena is in octahedrons; (d) districtwide calcite stages were identified: calcite is deposited in four successive stages marked by distinctive crystal

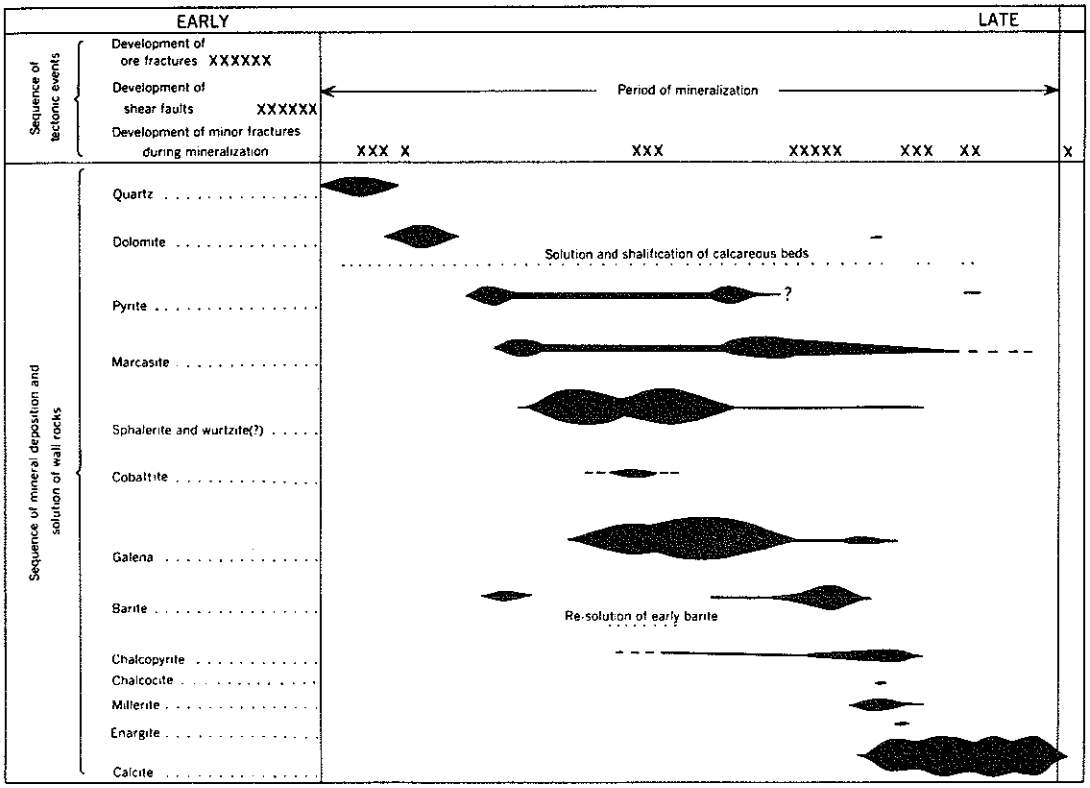



*Figure 14.--Sequence of tectonic events and deposition of primary minerals and leaching of wallrocks in the Upper Mississippi Valley district. From Heyl (1968b, fig. 14).*

habits and it forms overgrown and zoned crystals in the later periods of ore deposition. The earlier calcite stages overlap with the sulfides, and all four stages are separated from each other by periods of leaching and etching which become progressively weaker. The crystal habits of the four successive stages are distinguished by a change from rhombohedrons or stubby scalenohedrons truncated by basal pinacoids, through two scalenohedral habits, to a final rhombohedral habit. Within each stage, many microcolor bands are detectable; some of the early stages can be further divided into at least two substages.

A study of the trace elements through the full paragenetic sequence of the main minerals in the Thompson-Temperly mine by Hall and Heyl (1968) shows a general tendency for all the later minerals to be relatively free of trace elements, except for cadmium, iron, and copper in sphalerite which increase in the youngest sphalerite. The late-deposited calcites in stage 3 and stage 4 were notably lean in trace elements.

It should be emphasized that the paragenetic sequence just presented is generalized. Deposition throughout the general sulfide period took place under conditions of rhythmic oscillations in both composition and temperature during deposition; such oscillations formed the hundreds of minute color bands characteristic of all the main minerals. There is abundant evidence, too, that deposition occurred under conditions which pulsated without equilibrium (P. M. Bethke, oral commun., 1965) between precipitation and leaching during deposition of any one mineral. The banding is particularly well preserved in the translucent minerals such as sphalerite, barite, and calcite, but it can be seen upon etching in colloform pyrite and even in galena. Certain bands and stages were deposited in one vug, one vein, or one deposit and not in others; hence, many minor variations can be found by comparing the minerals of one locality with those of another, but the overall sequence remains the same and in the same superposition wherever studied. Detailed work started by P. M. Bethke and P. B. Barton (oral commun., 1963) on the banded sphalerites in the district has suggested that many of the minute bands can be traced and correlated in the sphalerites within one deposit and that a reasonable possibility exists that many of the bands can be correlated over large areas of the district.

Roedder (1968) pointed out that such "colloform"-banded sphalerites reveal crystal growth features that cannot have been formed by crystallization from gels. Most features indicate that they grew directly as minute druses of continuously euhedral crystals projecting into the ore fluids. He interpreted some of the more regular bands as annual varves that result from annual changes in the ore fluid upon dilution with surface meteoric waters. Haranczyk (1969) agreed with Roedder that most "colloform"-banded sphalerites are not deposited from gels, but he suggested that the banding is the result of rhythmic pulsating hydrothermal (hot-water) solutions derived from mafic alkalic magmas.

Geochemistry of ore fluids

In the Upper Mississippi Valley district, Hall and Friedman (1963, p. 900-907) found that the inclusion fluid in the early ore minerals is a very concentrated Na-Ca chloride brine approximately of the same composition as that in the sulfide minerals in the Cave-In-Rock mineral district in southern Illinois. Inclusions could not be recovered from some of the early minerals such as dolomite, pyrite, and early barite in the Upper Mississippi Valley district, and, hence, only the inclusions of the later part of the paragenesis were analyzed. Sphalerite and galena contain inclusions that are similar in most respects to Illinois basin oil-field brines, such as total concentration D/H, Mg/Na, and Cl/Na ratios, but differ in respect to relatively high Ca/Na and K/Na ratios, and by high-calcium concentrations which are several times those found in most oil-field brines.

Hall and Friedman (1963) found that the inclusion fluids in the later calcite gangue minerals are less concentrated and contain a relative deuterium concentration about that of meteoric water. They concluded that the early ore minerals were deposited from a predominantly Na-Ca-Cl type of solution of approximately the same composition as an oil-field brine and that this solution was gradually flushed by meteoric water during the final stages of mineralization. They concluded that "the addition of magmatic water in the system in the [district] can neither be postulated nor refuted from the chemical evidence."

Sawkins (1968) compared the same data with nearby basin brines and magmatic and hot-spring brines. He concluded that the distinctive Na/K and $Cl/SO_4$ ratios are consistent with a genetic model involving the mixing of relatively high potassium saline brines containing sulfate with average saline basin brines. He suggested that alkalic intrusive rocks are the source of the K and sulfate-enriched fraction. According to White (1968), the data suggest strongly that saline basin brines were dominant in ore fluids during sulfide stages, and that sedimentary rocks probably were the sources for most critical constituents. West and Heyl have recently collected siliceous and lead-bearing probable hot-spring sinters in two places in the eastern part of the district.

An independent extraction of fluid inclusions and analysis by Roedder, Ingram, and Hall (1963, p. 364-365) from the core and rim of a galena crystal from Platteville, Wis., provided main ratios of the principal constituents very similar to those obtained by Hall and Friedman.

Bailey and Cameron (1951) measured the temperature of filling of fluid inclusions in the Upper Mississippi Valley district and found temperatures (uncorrected for pressure) of 121°C to 75°C for several stages of sphalerite and 78°C to 50°C for stage 2 and stage 3 calcite. They pointed out that the temperature decline from sphalerite to calcite is consistent with standard assumptions that temperature decreases during mineralization, and, thus, their study is consistent with the evidence of dilution by meteoric water noted during the calcite stage by Hall and Friedman (1963).

Erickson (1965) has made a detailed study of fluid-inclusion temperatures in specimens of calcite from four mines in the Upper Mississippi Valley district using the four districtwide stages of calcite deposition worked out by Heyl and others (1959, p. 97-102). Erickson's results strongly support and confirm those of Bailey and Cameron (1951), for the general range of calcite temperatures is almost identical with theirs (74°C to 46.2°C uncorrected for pressure), and he was able to include measurements from the final stage 4 calcite. Erickson (1965, p. 506) stated:

> "Results indicate a decline in the temperature of calcite deposition. The temperature ranges of deposition (uncorrected for pressure) are: calcite II, 74° to 51°C; calcite III, 62.5° to 46.5°C; and calcite IV, 56° to 46.2°C."

Correction for pressure would raise the above ranges from 5°C to 10°C.

Erickson's data (1965) support the hypothesis that during later sulfide and perhaps postsulfide calcite stages of deposition, the fluids were being diluted and cooled by mixing with meteoric waters.

Lead-isotope and sulfur-isotope studies

Regional variations in the abundance of lead isotopes from galena in mineral deposits throughout the district are being investigated by A. V. Heyl, Maryse Delevaux, R. M. Zartman, and M. R. Brock. Preliminary lead-isotope analyses (Heyl and others, 1966) of galenas collected across the district indicate a very large range for the isotopes of lead, all of which are radiogenic J-type leads. There is a systematic pattern of wide variation throughout the district. The results suggest a regular progression in isotopic composition from the lowest $Pb^{206}/Pb^{204}$, $Pb^{208}/Pb^{204}$, and $Pb^{206}/Pb^{208}$ ratios in the west near the Forest City basin, and in the south near the Illinois basin, toward notably more radiogenic lead in the northeast near the crest of the Wisconsin Arch (fig. 15). It appears from the pronounced regional isotopic variations that local variations would be of only secondary magnitude. No vertical variations in isotopic composition were observed which are comparable to those occurring laterally, despite a rather complete sampling of various mineralized horizons. The lead-isotope pattern crosses the district's copper-centered zonation without any distinctive local variations that would mark a focus of deep-seated magmatism. The lead-isotope studies are now being extended into the basins and across the Wisconsin Arch on galenas that definitely have the crystal habits typical of the district.

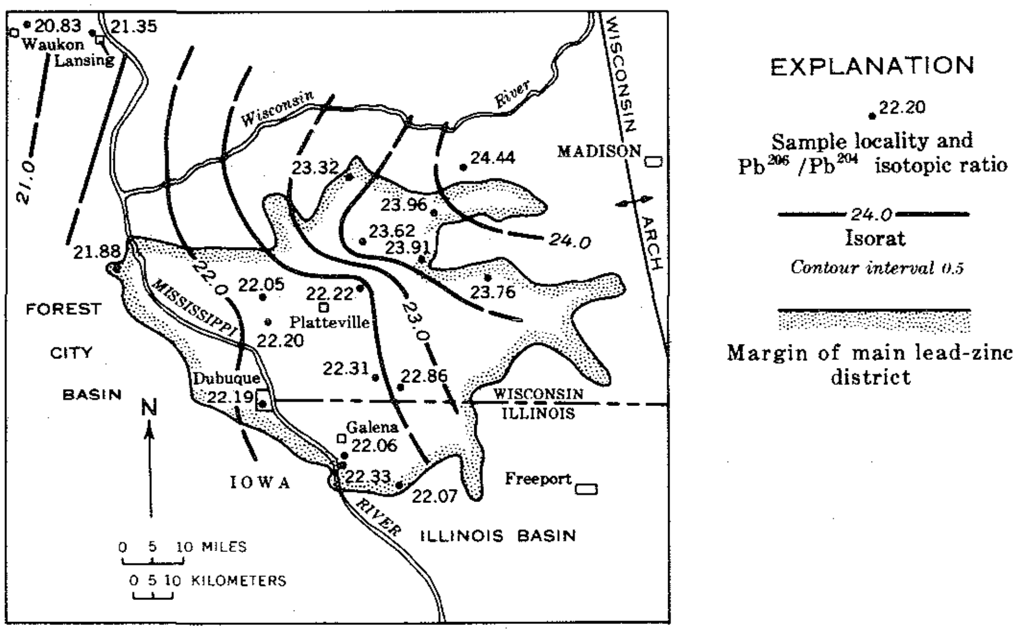



*Figure 15.--Map showing location of samples and distribution of $Pb^{206}/Pb^{204}$ isotopic ratios (contour interval 0.5) in the Upper Mississippi Valley district. From Heyl (1969, fig. 6).*

Cannon and Pierce (1969) analyzed lead isotopes of galenas from the Bautsch mine in northern Illinois and found a relatively small range in isotopic ratios. They analyzed the center and exterior of a large cubic crystal of galena and found only slight variations, with the center slightly more radiogenic than the exterior, the opposite of evidence from the Tri-State and Southeast Missouri districts.

Sulfur-isotope studies (Kulp and others, 1956; Jensen, 1957; Ault and Kulp, 1960; Jensen and Dessau, 1967) indicate that each of the Mississippi Valley districts has markedly distinctive sulfur-isotope compositions in the ore minerals (that is, $\delta S^{34}$ in the Southeast Missouri district ranges from +35 to -10 per mil; in the Tri-State district from 0 to -10 per mil; and in the Upper Mississippi Valley district from +16 to 0 per mil). The Southeast Missouri district has a relatively wide spread compared to magmatic sulfurs. Jensen and Dessau (1967) stated that $\delta S^{34}$ values exceeding +20 per mil are characteristic of sulfate in evaporite beds and sulfate in the ocean. Biogenic sulfurs, however, tend to be in the negative range from -10 to -40 per mil. Sulfur isotopes from some magmatic deposits tend to have a narrow spread from +10 to -10 per mil. Thus, Southeast Missouri sulfur isotopes have their large spread centered in the range of evaporite-derived sulfates. Tri-State district sulfur isotopes have a very small spread, centered on the minus side within the range of magmatic sulfurs. Upper Mississippi Valley district ores also have a much smaller sulfur isotope spread than Southeast Missouri ores, but the spread is a little larger than for most magmatic districts. The range of these sulfur-isotope ratios extends from the center of the magmatic field somewhat toward evaporite sulfur-isotope ratios (from 0 to +16 per mil). The sulfur isotopes in the Upper Mississippi Valley ore minerals, it should be pointed out, overlap half of the magmatic sulfur range, and they have no greater spread than the sulfurs in the magmatic ore minerals in the Tintic district of Utah--each has a $\delta S^{34}$ range of about 15 mils. Thus, the Upper Mississippi Valley ores have sulfur-isotope ratios that suggest a mixture of magmatic and evaporite (or saline basin) brines. This conclusion does not agree with conclusions of the papers cited, which favor simple evaporite or biogenic sulfur origins.

## NEW PROSPECTING GUIDES

Cannon and Pierce (1969) have recently made useful suggestions on the application of lead isotopes in prospecting in the district. They propose that the largest deposits of the district lie in the west-central part where the $Pb^{206}/Pb^{207}$ ratios range between 1.38 and 1.42, and that a promising area extends eastward from near Galena, Ill., toward Freeport, an area of promise for other geologic reasons.

Keith (1969) has recently pointed out some relationships of lead and zinc contents of trees and soils in the district, following up the excellent pioneer geochemical prospecting studies of Huff (1952) and Kennedy (1956).

The spring-sampling methods of Huff and Kennedy for zinc were notably successful in locating nearby areas worthy of prospecting. These rapid methods aided in the discovery of the Piquette No. 2 ore body at Tennyson and some ore near Potosi. However, they were little applied or improved until De Geoffroy and his associates (De Geoffroy and others, 1967, 1968; De Geoffroy, 1969) started using the spring and seep sampling methods, and rapidly surveyed most of the northern part of the district from Beetown east to the Green County line near Blanchardville, and south to near Dickeyville and Argyle, an area of 900 square miles. Following the field tests, statistical methods selected 81 promising exploration targets. Five targets were drilled in part, and ore or lean zinc-mineralized rock was located in several holes in each target. Unquestionably the results of this geochemical study to date warrant some very serious consideration by companies prospecting in the district. The later phases of this study were done by the Wisconsin Geological and Natural History Survey.

By far the most successful prospecting effort in the district was that of Ewoldt and Reynolds (1951) and associates during the late 1940's. Nevertheless, some of their methods have not been applied by other mining companies in the district.

In 1949-52 the U.S. Geological Survey drilled many holes for geological information in the Wisconsin and Iowa parts of the district. These holes were located for geological and structural data points, but some intersected ore or very encouraging mineralized rock. In addition to many holes in the Galena, Decorah, and Platteville strata, 32 holes were drilled through the Prairie du Chien and some into Cambrian strata. None of the deep holes penetrated commercial ore, but most of them, though widely spaced throughout the district, intersected mineralized rock (Heyl and others, 1951; Agnew and others, 1953). The results of the program showed that the Prairie du Chien and Trempealeau carbonate strata merit further exploration for breccia and disseminated lead and zinc deposits of large size. Surprisingly, not a single one of these many encouraging indications in the upper and lower strata was apparently followed up by prospectors later.

## ORE GENESIS

The origin of the ores of the Upper Mississippi Valley zinc-lead district has been controversial for over a hundred years. Theories for the deposition of the ores by meteoric and artesian water were developed, which later were adapted to the Tri-State and other similar districts. Thus, the district is the type area in the study of ore deposits of the Mississippi Valley type in the United States. Many variations in genetic theories of cold-water deposition have been advanced, and the suggested sources of metal are numerous. Similarly, numerous variations of these cold-water deposition theories have recently been developed and applied to the equally controversial bedded uranium deposits of the Colorado Plateau, Wyoming, and the Black Hills.

The senior author is among those whose studies in recent years have led them to return to support a hypothesis of origin by rising warm aqueous solutions accompanied by widespread lateral distribution through the available sandstone aquifers under the ore bodies. Unequivocally, all the lead, zinc, and copper deposits within the main boundaries of the district (fig. 1) and most deposits of the iron sulfides, except perhaps the widespread pyrite disseminations in the Glenwood Shale Member of the Platteville Formation and basal Maquoketa Shale, are epigenetic and not syngenetic. Although the author's studies were undertaken with the meteoric and artesian hypotheses in mind, nearly all the evidence obtained concerning the origin of the ores favored their genesis by deposition from thermal waters rising from the underlying rocks. Deposits of epigenetic sulfides extend down into the sandstones of Cambrian age. The ultimate source of the solutions, therefore, may be in these underlying beds, or derived from widespread solutions of connate origin in these Cambrian sandstone aquifers that moved into the district by artesian circulation, as hypothesized by Van Hise and Bain (1902), or from rising thermal waters that moved through these beds. The ultimate heat source was possibly magmatic bodies. The absence of any major deformation or metamorphism of the rocks of Paleozoic age excludes an origin by reheating of the rocks and associated ground waters to redissolve the metals from the Middle Ordovician wallrocks and deposit the ore minerals in their present form.

Probably the ore solutions were mixtures of connate and meteoric waters blended, heated, and mobilized by heated solutions from some deeper source that provided most of the base metals of the deposits. The ultimate source of the heated solutions, not known, could have been a magmatic body that intruded the Precambrian rocks but did not extend up into the Cambrian sandstones. The juvenile fraction of the solutions, which perhaps was small, may have risen from faults and lineaments in the Precambrian basement (either underlying the district as suggested by Heyl and King (1966) or underlying the basement of the nearby basins as suggested by Pb-isotope studies). After entering the thick sandstone aquifers of early Paleozoic age, the hot solutions may have heated and mobilized the connate brines, causing them to spread laterally widely beneath the district. Then the mingled and heated solutions may have risen above the aquifers through the many available joints, faults, and permeable zones into the carbonate rocks of Middle Ordovician age. The solutions deposited their metal content in the first limestones and dolomites above the Precambrian basement that contained shale partings rich in hydrocarbons and that lay beneath a thick impermeable shale cap. The fracture systems in which the ores were deposited had previously been formed by widespread gentle tectonic disturbances of the craton possibly in late or post-Paleozoic time. During the later stages, the meteoric waters within the Middle Ordovician carbonate rocks may have diluted and cooled the solutions, and eventually meteoric waters flushed the concentrated brines out of the district.

## CONCLUSIONS

Localization of the ore deposits in crosscutting structures, which postdate deposition of the Middle Ordovician and probably the Silurian sedimentary rocks, makes it unequivocal that the deposits were emplaced, in their present form, after sedimentation of the host rocks and are, therefore, epigenetic. Many questions remain unresolved, however, concerning the ultimate source of the metal and the nature of the mineralizing fluid.

The authors believe that the evidence favors the hypothesis which postulates the deposition of the ores by hydrothermal (hot-water) solutions, probably from a mixture of heated connate and magmatic waters, the latter being probably the smaller fraction. Later in the ore-forming process, meteoric waters were drawn into the system and the other two fractions were diluted progressively. The notable similarity between ore bodies of this epigenetic district and those of proven hydrothermal districts is apparent; however, the question cannot be considered closed, and the authors are well aware of the limitations of the evidence presented to support this hypothesis. Much more must be known about the mineralogy, temperatures, and other physical and chemical factors controlling ore deposition, about the geology of the hitherto unexplored rocks beneath the known part of the geologic formations, and about the basement before the origin of these deposits can be proven beyond any doubt.

The district is very large and has many small- to moderate-sized deposits of good grade. For 20 years it has been the fourth to twelfth largest producer of lead and zinc in the country, a very large and stable source. A very large part of it is unexplored by modern physical and chemical exploration methods. Without question, the potential resources of both zinc and lead are large, and the district should be an important source of these metals for many years to come. Copper, barite, and pyrite should be future byproducts in places.

Future prospecting will very probably include searches for major extensions of the district, particularly to the south and east in Illinois and toward the southwest in Iowa (fig. 1, this rept.; see also Heyl, 1968a, p. 586, 591-592). Many old areas, scarcely prospected in recent years, such as many parts of the central and northern parts of the district, will again become productive, as will little-known outlying zinc areas near Potosi and Beetown, Wis., to the west, and near Yellowstone and Wiota, Wis., to the east. (See Heyl and others, 1955, pl. 25, for locations.)

The Prairie du Chien Group and the more calcareous Upper Cambrian units underlying the central and southern parts of the district at considerable depth must be considered as potential producing horizons. The Prairie du Chien Group has produced both zinc and lead along the shallow northern fringe of the district. There has been practically no prospect drilling deeper than the top of the St. Peter Sandstone, but interest in the deeper rocks is developing. The numerous relatively small, but intense magnetic anomalies within the district are generating some interest in the basement Precambrian as a possible mineral source. The possibility of copper deposits disseminated in the upper part of the St. Peter Sandstone in the Mineral Point and Gratiot areas has never been tested.

If new smelting methods now being developed make possible the mining of oxidized or mixed oxidized-sulfide zinc-lead ores, then large resources of such ores still exist in many parts of the district, mostly at shallow depths.

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I.C. 16 GEOLOGY OF THE UPPER MISSISSIPPI VALLEY BASE–METAL DISTRICT 1970 (Rev. 1978)