Contributions to Economic Geology 1966

GEOLOGICAL SURVEY BULLETIN 1242

This volume was published as separate chapters A–F

UNITE STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

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[Letters designate the separately published chapters]

Aeromagnetic and Tectonic Analysis of the Upper Mississippi Valley Zinc-Lead District

By ALLEN V. HEYL *and* ELIZABETH R. KING

CONTRIBUTIONS TO ECONOMIC GEOLOGY

GEOLOGICAL SURVEY BULLETIN 1242-A

Prepared in cooperation with the Wisconsin Geological and Natural History Survey

A magnetic study indicating major geologic structures in the basement rock which controlled in part the locations of overlying ore deposits

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

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For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 70 cents (paper cover)

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ILLUSTRATIONS

AEROMAGNETIC AND TECTONIC ANALYSIS OF THE UPPER MISSISSIPPI VALLEY ZINC-LEAD DISTRICT

By ALLEN V. HEYL and ELIZABETH R. KING

ABSTRACT

Aeromagnetic surveys of the central part of the Upper Mississippi Valley zinc-lead district in 1948–50 suggest a Precambrian basement complex that consists largely of granitic rocks, however, small plutons of more mafic rocks are suggested for the northern part of the district, and folded metasedimentary rocks for the southern part. Linear dislocations of magnetic patterns suggest major basement faults of several trends. These faults coincide with and control, in part, folds and faults in the overlying Paleozoic strata, which are 1,200–2,400 feet thick. Leakages of rising and probably heated solutions along the basement faultlines possibly provided some of the ore-bearing solutions, which heated and blended with brines in the sedimentary rocks. Solutions may have moved upward through aquifers into entrapment areas in the overlying fractured carbonate rocks and also laterally into similar traps on the flanks of buried monadnocks of Precambrian rocks.

Ore deposits apparently are associated with areas of magnetic highs, and future prospecting might be concentrated in such areas and along the linear trends, especially where prospecting has been insufficient in the past. In addition, deep prospecting into Lower Ordovician and Cambrian rocks might be worthwhile on the flanks of small buried monadnocks of Precambrian rocks.

INTRODUCTION

The results of an aeromagnetic survey of the commercially most important central part of the Upper Mississippi Valley zinc-lead district in southwestern Wisconsin, northwestern Illinois, and northeastern Iowa (figs. 1, 2) are presented in contoured form on a map (pl. 1) showing the principal geologic structure and the location of the zinc-lead deposits.

The geologic structural data and the locations of zinc-lead deposits were compiled and modified from Heyl, Agnew, Lyons, and Behre (1959, pls. 1, 3, 5, 8) and from geologic mapping done at scales of 1 : 24,000 or larger by the U.S. Geological Survey (Allingham, 1963; Agnew, 1963; Carlson, 1961; Taylor, 1964; Klemic and West, 1964;

Agnew and others, 1954; Allingham and others, 1955) and by the Illinois Geological Survey (Willman and Reynolds, 1947; Bradbury and others, 1956).

The aeromagnetic survey was flown partly in 1950–1951 and partly in 1960 after preliminary aeromagnetic surveys in 1948–49. The magnetic data were recorded as continuous profiles by a flux-gate AN/ASQ–3A magnetometer towed by the U.S. Geological Survey's DC–3 aircraft along a series of north-south traverses spaced a quarter of a mile apart. The aircraft flew at a barometric altitude of approximately 1,800 feet above sea level. The surface of the surveyed area lies between 600 and 1,200 feet above sea level, except for a few hills that reach 1,700 feet above sea level.

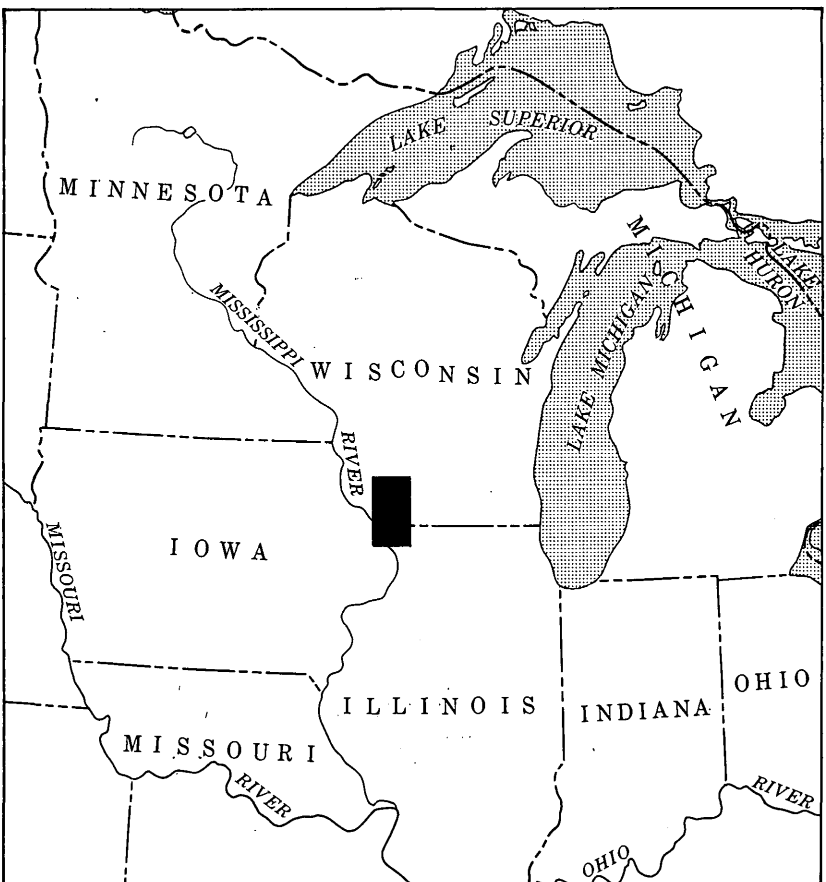
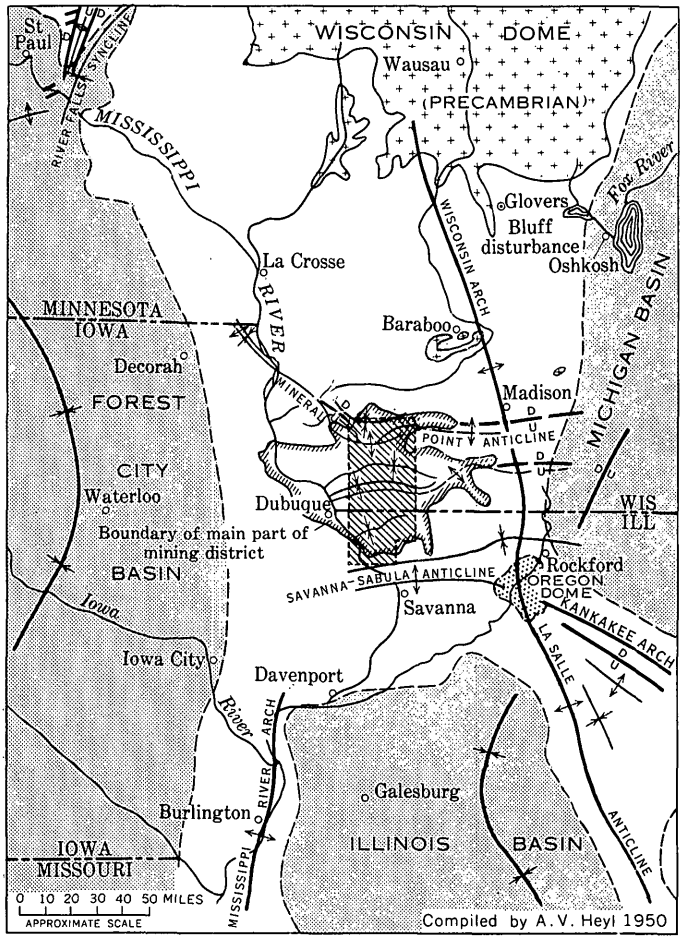


FIGURE 1.—Area of this report (in black).



EXPLANATION

Outline of basin or dome
Dashed where approximately located

U
D
Fault
Dashed where approximately located. U, upthrown side; D, downthrown side

Major regional anticline

First-order anticline
Dashed where approximately located

Major regional syncline

First-order syncline

Outline of area shown on aeromagnetic and tectonic map

FIGURE 2.—Upper Mississippi Valley zinc-lead district, area of aeromagnetic map, and major structural features of district and surrounding region.

Location of the flight path was recorded by a gyrostabilized continuous strip camera. The data, in the form of magnetic contours having an arbitrary datum, were compiled on U.S. Geological Survey 7½-minute topographic quadrangle maps. Location of some of the magnetic data may be in error by as much as a quarter of a mile; the resulting slight variations in datum produce the artificial wavy pattern of some of the contours as they cross the north-south flight pattern, especially in areas of low magnetic gradient. The maximum discrepancy between adjacent flight lines is of the order of 20 gammas and does not interfere with the interpretation of the data. The instrumentation, surveying method, and compilation procedures used are described by Balsley (1952).

The data accumulated by the 1950–51 surveys were released as four aeromagnetic maps by Dempsey and Kirby (1958 a–d). The north half of the Highland map (1958a) and the south part of the Galena map (1958d) have not been included in this report owing to the lack of geologic data for comparison.

GENERAL GEOLOGIC SETTING

The Upper Mississippi Valley mining district is about 3,000 square miles in extent and lies in an area of gently southward- and southwestward-dipping limestone, dolomite, sandstone, and shale. These strata form a 2,000-foot thick Paleozoic section that lies unconformably upon a Precambrian shield surface of moderate relief. The rocks exposed in the district are Cambrian, Ordovician, and Silurian in age; but nearby, in the Illinois and Forest City basins, thick sections of Devonian and Carboniferous rocks also are present. The district is gently uplifted and is bounded by the Wisconsin dome on the north (fig. 2), the Wisconsin arch on the east, and the Savanna-Sabula anticline and Illinois basin on the south. On the west, the district is bounded by the Forest City basin and by faults and folds in the Paleozoic rocks overlying the Keweenawan volcanic rocks that give rise to the midcontinent gravity anomaly (Sims and Zietz, 1966) near Minneapolis, Minn.

The district is about 100 miles south of the main area of outcrop of rocks of the Precambrian shield in Wisconsin. The mineralized district is in the northern fringe of the huge covered shield that forms the craton of the Midwest.

The Precambrian basement rocks in southwestern Wisconsin, northeastern Iowa, and northwestern Illinois, are known from drill holes and are mainly granitic; however gneiss, schist, basalt, gabbro, and quartzite have been found locally. An area of mafic basement rocks is near Decorah, Iowa, and quartzites have been penetrated in wells south of Dubuque, and near Cedar Rapids and Tipton, Iowa (Muehlberger and others, 1964. The quartzites suggest that buried synclines similar to the Baraboo and Waterloo synclines of quartzites and metasedimentary rocks (Thwaites, 1931), are present in central and eastern Wisconsin. Eastward-trending mafic dikes are widely distributed in northern Wisconsin and upper Michigan, particularly near Marquette (H. L. James, oral commun., 1964). Many of these dikes have a strong remanent magnetization and give rise to sharp linear negative anomalies (Balsley and others, 1949; Case and Gair, 1965). In and near Madison, Wis., wells 700–850 feet deep on the crest of the Wisconsin arch penetrated mostly basaltic and rhyolitic rocks (Thwaites, 1923). In the Baraboo area (fig. 2), about 30 miles northeast of the district, is a closed syncline of late Precambrian quartzite, hematitic iron-formation, and small stocks of granite porphyries that form a partly buried ridge and valley land surface having a relief of about 500 feet.

In the district, rocks of the Precambrian basement have been described as "granite" in wells at depths of 1,200–2,400 feet below the surface. In the northern part of the district, the top of the Precambrian is inferred to be about 1,200 feet beneath the surface on the basis of deep wells into the Cambrian along the Wisconsin River and city water wells into the Cambrian at Montfort, Cobb, and Dodgeville, Wis. In Platteville, Wis., basement is at 1,714 feet beneath the surface (Heyl and others, 1959, p. 6; Agnew, 1963, p. 250). Three deep wells have been drilled into or nearly into the Precambrian along the Mississippi River in Dubuque, Iowa (Whitlow and Brown, 1963, p. 144). All were drilled from an altitude of about 600 feet along the Mississippi River; two of these wells are next to the city waterplant, and the third is about 2 miles south. The Dubuque city wells penetrated the basement rocks at depths of 1,765 and 1,789 feet below surface; the well 2 miles south was still in Cambrian sandstone at a depth of 1,950 feet below surface. The difference in depth indicates that a Precambrian surface, having a relief of about 200 to 300 feet is buried beneath the Paleozoic cover. Measured from the tops of the hills of the rolling land surface bordering the Mississippi Valley in the Iowa part of the district, the depth to the Precambrian is probably between 2,200 and 2,400 feet.

The only well in the mapped area to penetrate Precambrian rocks is the old city well in Platteville, which penetrated "granite" (Agnew, 1963, p. 250). West of the mapped area, but still in the district, the Dubuque city well penetrated biotite granite or granite gneiss.

About 1,000–1,200 feet of Cambrian sandstone interbedded with thin dolomite and shale units overlies the Precambrian. The Prairie du

Chien Group, mostly dolomite of Early Ordovician age, is exposed in some of the deeper valleys and along the north and east margins of the district (Agnew and others, 1956, p. 272). About 150 feet of limestone, dolomite, and shale of the Decorah and Platteville Formations and sandstone of the St. Peter crops out in many of the valleys. Most of the outcrops in the district are of Galena Dolomite, which is about 225 feet thick. The Maquoketa Shale of Late Ordovician age caps some of the high hills and underlies long slopes that rise toward the southwest to high isolated hills and escarpments that are capped by the dolomitic Edgewood, Kankakee, and Hopkinton Formations, all of Silurian age (Brown and Whitlow, 1960, p. 31–44).

Post-Precambrian intrusive igneous rocks are not known within the district. The nearest large area in which these rocks are found is in southern Illinois, western Kentucky, and southeastern Missouri (Brock and Heyl, 1961, fig. 306.1), where dike and diatreme swarms of mafic alkalic rocks occur.

GEOLOGIC STRUCTURE

The regional strike of the sedimentary formations within the mining district is N. 85° W., but in the western part the strike changes to N. 45° W. The regional dip is about 17 feet to the mile toward the south and southwest.

The rocks of the district have been flexed into low, broad folds that differ greatly in magnitude. The limbs of the folds rarely have dips greater than 15°, and dips of only a few degrees are more common. The largest folds range from 20 to 60 miles in length, 3 to 6 miles in width, and 100 to 200 feet in amplitude. The axial trends of the largest folds that have been mapped are shown on figure 2, and parts of them are also shown on plate 1. From east to west across the district, the folds trend southwestward, westward, and northwestward; however, the trends change sharply from place to place, and many folds are continuous structures for miles. The largest anticlines are commonly asymmetric, the north limbs dipping more steeply. The folds of intermediate and small magnitude (pl. 1) trend either eastward to northeastward or northwestward. Local oval domes, basins, and cross folds are not uncommon. These folds occur throughout the district and form a rhombic pattern (Heyl and others, 1959, figs. 18, 56, 57).

Reverse, strike-slip, normal, and bedding-plane faults are fairly common throughout the district; most of them have small displacements. Most measurable displacements range from 1 to 10 feet, but thrusts on the north limbs of folds have displacements of 25–50 feet, and a few strike-slip faults have displacements of 25 to possibly 1,000 feet. Field investigations in recent years by Brown and Whitlow

(1960) and by Heyl since 1960 have located several strike-slip faults, not previously described, in the district; and their presence suggests that strike-slip faults may be common.

Most of the folds and faults observed in the district are probably the result of an extended period of regional deformation that can only be dated as post-Silurian and pre-Pleistocene. This deformation was preceded by earlier minor regional deformations, particularly near the crest of the Wisconsin arch. After the main period of deformation some epeirogenic uplift and tilting of the rocks took place, especially during the Pleistocene.

ORE DEPOSITS

The Upper Mississippi Valley zinc-lead district contains thousands of small lead mines, about 400 zinc mines, and a few small copper and barite mines. The mined areas of zinc, lead, and copper are shown in green on the aeromagnetic map (pl. 1). Most of the lead-zinc mines are in closely spaced clusters of shallow shafts and pits known locally as "diggings"; thus they are grouped on plate 1 as green areas. Since 1940 the district has been one the principal domestic sources of zinc, and lead has been an important byproduct.

Most of the ore deposits are restricted to the dolomite, limestone, and shale of Middle Ordovician age, but deposits are known in all the Paleozoic formations. Locally, fissure veins and mineralized breccias have been mined in the Prairie du Chien Group of Early Ordovician age, and small deposits of lead, zinc, and iron sulfides have been found in the formations of Cambrian and Silurian age.

The ore deposits mined at present are restricted to the Galena Dolomite, the Decorah Formation, and the underlying Platteville Formation. The total thickness of the main ore-bearing strata of Middle Ordovician age is about 330 feet.

The main zinc-lead ore deposits are mantolike and are commonly linear or arcuate in plan. The ore is in veins, replacements, and impregnations and is deposited along small reverse and bedding-plane faults and in breccias that have been further opened by solution sag and slump of the carbonate wallrocks. Most of the deposits are fairly large and contain as much as a few million tons of ore. Gash-vein lead deposits in the Galena Dolomite occur as veins and replacements along vertical joints and strike-slip faults of small to moderate displacement. Both the mantolike zinc-lead deposits and the gash-vein lead deposits are most commonly associated with folds of intermediate and small size, such as those whose axes are shown on the aeromagnetic map in the area bounded by Cuba City, Shullsburg, and Hazel Green, Wis. Some deposits, such as those north of Mifflin and near Livingston, Wis., are clustered near the larger faults that probably extend into the Precambrian basement in such a way that the ore-bearing solutions could have used these faults as main channels. Other deposits are alined in well-defined, notably straight lines, such as: the line of deposits that extend for miles from State Highway 80 in northern Illinois northeastward through New Diggings and Shullsburg, Wis.; the nearly parallel line of ore bodies that are north of the New Diggings line and that extend across the south edge of Hazel Green, Wis.; the northwestward-trending line of deposits that lies south of Galena, Ill. These alined deposits, which contain some of the largest ore bodies in the district, follow intermediate-sized folds. Their markedly straight pattern suggests that they may overlie deep-seated basement faults that do not extend to the surface, but that acted as major channels for the ore-bearing solutions.

The main primary minerals of the deposits, listed in their overall order of deposition, are quartz (in the form of jasperoid), dolomite, pyrite, marcasite, sphalerite, galena, chalcopyrite, barite, and calcite. The source of the solutions is not known, but studies of the geochemistry of the deposits and of the fluid inclusions in the ore minerals have provided evidence that the solutions during the main period of ore deposition were heated, concentrated sodium and calcium chloride brines that had a high relative deuterium concentration (Hall and Friedman, 1963; Bailey and Cameron, 1951; Heyl and others, 1964). Such solutions are quite similar in composition to the brines now in the deeper parts of the Illinois basin to the south; heat, at least, must have been added from some source deep in the basement to raise the temperatures of the solutions to the 90°–120°C that were recorded by the fluid-inclusion temperature studies of Bailey and Cameron (1951).

INTERPRETATION OF THE MAGNETIC ANOMALIES

The absence of known post-Precambrian igneous rocks in the district and the uniform nonmagnetic lithology and very gentle dips of the overlying Paleozoic rocks suggest that nearly all the magnetic anomalies correlate with features in the covered Precambrian basement.

Several attempts have been made to discover ore bodies in the district by geophysical surveys without very favorable results (Heyl and others, 1959, p. 174). Magnetic, self-potential, electromagnetic, and induced potential methods have been tried at various times and in various parts of the district. Ordinary Gurley dip needle and Hotchkiss superdip surveys were made in the district by the U.S. Bureau of Mines in the 1940's. Some of these magnetic surveys were made with great care and detail over known, but unmined, ore bodies at shallow depths, and practically no favorable results were achieved

(Lincoln, 1948). Hence, it is fairly certain that the zinc-lead ore bodies themselves do not cause the anomalies recorded in the aeromagnetic surveys.

The mapped area is one of moderate-sized magnetic anomalies, with few amplitudes greater than 700 gammas and overall relief less than 1,000 gammas. The earth's main magnetic field decreases approximately 5 gammas per mile to the south in this area, and this amounts to a decrease of more than 250 gammas from the north to the south edge of the mapped area. If this gradient were removed, the highest magnetic values would be found at the extreme south end of the survey, where a pronounced linear east-west gradient of 150 gammas cuts off the north-south magnetic trends that dominate the southern half of the area.

NORTHERN AREA

The magnetic character of the northern half of the area (north of Wisconsin Highway 81) is strikingly different from that of the southern half. In the northern part there are a number of relatively sharp local anomalies, some of which tend to form clusters in a gently undulating magnetic field of 1,300–1,400 gammas relative to the arbitrary datum assigned to the contoured map. Two prominent and relatively isolated highs occur near Montfort and Dodgeville, Wis. The other anomalies tend to form groups or strings having northeastward or less pronounced northwestward trends. The magnetic highs partially encircle a magnetically flat area north of Platteville, Wis., which is sharply outlined by a steep gradient of 100 gammas or more. Among the significant east-west trends observed in the northern part are both the linear high south of Rewey and Arthur, Wis., that forms a prong west of the main anomaly cluster and the steplike gradient of about 50 gammas that crosses the mapped area at Linden, Wis.

Some of the sharp positive anomalies in the northern part of the map (pl. 1) may represent small stocks or dikes of a moderately magnetic rock, such as a diorite or gabbro of Precambrian age, that intrudes a much larger area of granitic basement. A few of the sharpest anomalies could be caused by intrusions into the Cambrian sandstones but as no known contact metamorphism is near the highs, they are probably caused by magnetic contrasts in the basement rock. Alinement of the structural and magnetic trends can be observed at many points, and this alinement suggests that the basement complex is involved in at least some of the observed faults, flexures, and domes. It is improbable that the magnetic features could be produced solely by basement relief, because an abnormally high magnetic susceptibility would be required, and the observed gradients are too sharp. Some of the more magnetic rocks may form monadnocks in the Precambrian erosion surface. Gentle domes in the Ordovician strata overlying the two very marked highs near Montfort and Dodgeville, Wis., support this interpretation.

In the northern half of the mapped area, several sharp oval magnetic highs of 200–300 gammas form a large arcuate cluster around the large steep-sided magnetic low north of Platteville. This magnetic low has few marked magnetic irregularities in its broad central part and probably consists of granite or granitic gneiss of low magnetic susceptibility. City well 2 at Platteville, at the south edge of the magnetic low, penetrated basement rocks of this lithology (Agnew, 1963, p. 250). The low coincides very closely with a large structural high that contains very few known lead-zinc deposits and that forms the western part of the Mineral Point anticline in the area shown on the aeromagnetic map. Southeast of Rewey the crest of the structural high plunges sharply eastward (Heyl and others, 1959, pl. 8; Taylor, 1964, pl. 1). The curved east side of the big magnetic low very closely matches the area of steepest eastward plunge of this part of the Mineral Point anticline. The narrow linear prong of the magnetic highs that bounds the low area on the north side follows very closely the steep north limb of the Mineral Point anticline, where it probably is draped over an inferred eastward-trending fault in the basement that may extend into the overlying cover of sedimentary rocks nearly to the surface. The prong may represent a dike of Precambrian age intruded into this fault, along which renewed movement took place in Paleozoic time.

Several other linear trends evident in the anomaly pattern appear to be related to known or inferred faults. The cluster of magnetic highs near Mifflin, Wis., is cut off sharply by magnetic lows along the northeast side. This side is the location of the Mifflin fault (Heyl and others, 1959, pls. 2, and 8), which is a southeastward-trending strike-slip fault that cuts Paleozoic rocks and possibly the fault has considerable displacement. The anomaly trends suggest that the Mifflin fault may extend much farther southeast, through the saddle separating the prong-shaped Mineral Point anomaly from the central cluster along the northeast side of the large oval anomaly to the south. The deflection of the trends of the surface flexures as they cross the northeast side of these positive magnetic features is strongly suggestive of basement control, perhaps basement relief associated with the more mafic rocks on the southwest side of the Mifflin fault and its inferred southeastward continuation. The magnetic patterns show strong evidence for a very linear northeastward-trending fault intersecting the Mifflin magnetic trend near the Iowa-Lafayette County line. A straight line from Mineral Point to just south of Platteville follows northeastward-trending gradients along the northwest sides of a series of positive magnetic anomalies, which are thus cutoff from the anomaly cluster near Mifflin. Near the southwest end of the possible fault line at Platteville (just west of the mapped area), a surface fault several miles long and of east-northeastward trend has been mapped (Heyl and others, 1959, pl. 3). The southeastern extension of the Mifflin fault is possible offset in a right lateral direction by this fault.

SOUTHERN AREA

The area south of Wisconsin Highway 81 is characterized by a much more linear pattern of broad, elongated highs and lows that have predominant north-south and nearly east-west trends and more local features that have northwestward trends. Unlike the northern area, there are no broad, flat magnetic areas to establish a reference level for the positive and negative features; however, some of the linear closed lows are so persistent and sharply defined that they may be caused by a nonmagnetic basement rock unit, possibly one that has a strong remanent magnetization opposing the present field, rather than being the usual induction lows that appear on the north flanks of larger magnetic highs. The large rectangular magnetic high that occupies part of the area south of Shullsburg and Benton, Wis., and east of Cuba City, Wis., and Galena, Ill., is bounded on the north and west by conspicuous linear magnetic lows. A dominantly northward-trending 400-gamma low occurs within the high, near Council Hill Station, Ill. Along Wisconsin Highway 81, in the middle of the mapped area, is a series of lows that make a 90° bend to the north through Truman, Wis.

The overall anomaly pattern in the southern half of the district suggests the presence in the basement rocks of an open basin or fold closed toward the northwest, with nonmagnetic rocks, such as quartzites, forming the rim. Geologically similar are the quartzites that form the rim of the Baraboo Range and that surround a core of more iron-rich shales, slates, or graywackes in the central part of that structural feature. The rim of magnetic lows closed toward the northwest is broken only north of Galena, Ill., where its extension may have been displaced eastward along the postulated northeastward-trending fault to form the band of rocks marked by the strong negative anomaly near Council Hill Station, Ill. An alternate interpretation would be that the basement fold has a gentle west limb and that the block on the southeast of the postulated fault has been displaced vertically relative to that on the northwest.

The big rectangular magnetic high in the southern part of the district is bounded on two sides by a long linear magnetic low that extends westward across the entire mapped area from northeast of Shullsburg to Cuba City, Wis., where it hooks sharply southward, curves southeastward to the Illinois-Wisconsin State line south of Hazel Green, Wis., and ends abruptly. The westward-trending part of this broad-hooked low is followed in a remarkable way by the broad crest of the Meekers Grove anticline, including rather small details. For example, both the anomaly and the large structural high bend southward and have a saddle northeast of Shullsburg, Wis., and the anomaly and the anticline both bend northward at Cuba City, Wis. Also, the monoclinal south slope of the large structural high that is the central highest part of the Meekers Grove anticline closely follows the very steep linear gradient between the magnetic low and the large magnetic high to the south. This steep linear magnetic gradient also marks a change in the grain of the smaller structural features from the more complex pattern in the south to a simpler eastward pattern in the north.

ORE-BODY RELATIONSHIPS

Most of the large and important ore deposits of the district are located over and clustered about the major magnetic highs. This relationship is particularly noticeable near Montfort, Mifflin, and Platteville, Wis., (pl. 1), and over the big rectangular magnetic high of about 400 gammas that extends from Scales Mound, Ill., and Shullsburg, Wis., on the east, westward to Cuba City and Hazel Green, Wis., and then southward beyond Galena, Ill. These same areas have notably more complex folds and fault systems than many of the adjacent parts of the district.

In the northern part of the district, the two prominent, isolated magnetic highs marked by gentle domes in the overlying strata, near Montfort and Dodgeville (pl. 1), are overlain or bordered by ore deposits. The Montfort high has few known deposits on its magnetic and domal crest, however, a major mining area in the town of Montfort is on the north flank of the high, and smaller deposits occur on the west, southwest, and northeast flanks of the anomaly and the associated structure. Similarly, a line of deposits curves gently around the north, east, south, and southwest flanks of the Dodgeville magnetic high and structural dome, but no deposits are known toward the northwest, possibly because the beds most favorable for ore deposition in that part of the district are covered by thick caps of uneroded barren strata. The clustering of ore deposits around these two anomalies may represent updip movement of the ore-bearing solutions toward the crest of the gentle domes above the possible buried monadnocks of more magnetic rocks. Where these solutions were trapped, the ores were deposited in fractures on the flanks of these structures.

The area of the big hooked magnetic low and the large Meekers

Grove anticlinal structural high in the southern half of the mineral district is also marked by the absence or sparsity of large ore deposits along its entire length, except in the structural and magnetic saddle north of Shullsburg. This absence of ore deposits is particularly noticeable where the magnetic low hooks south at Cuba City, Wis., and along the southward prong west of Hazel Green, Wis. The southeast end of this long prong, however, is crossed by two very marked northeastward-trending lines of lead and zinc deposits and structural synclines. These lines extend northeastward to Shullsburg where they merge into a single line that continues northeastward for about 4 more miles across the structural and magnetic saddle north of Shullsburg. The two converging lines of synclines and ore deposits are the most marked in the entire district and may be surface expressions of basement faults of Precambrian age through which some of the solutions that deposited the ores may have leaked and thereby concentrated deposits above them. In post-Silurian times, minor structural adjustments probably formed the synclines in the Cambrian and Ordovician strata above these faults, and perhaps formed the initial fractures that control the lead and zinc deposits.

Further evidence of the northeastward lines of wrench faults in the basement is provided by the marked negative linear anomaly near Council Hill Station, Ill., as pointed out by Isidore Zietz (oral commun., 1964); this anomaly points northwestward south of New Diggings, Wis., and extends southward for about 12 miles toward Elizabeth, Ill. This negative anomaly is also notably free of known lead and zinc deposits and may represent the same band of magnetically negative rocks as those at Hazel Green, Wis., but dislocated, dragged, and offset left laterally along a northeastward trending basement fault for about 3 miles relative to those at Hazel Green in Precambrian times. A similar but smaller offset in the same direction is possible where the buried fault line cuts across the magnetic and structural saddle north of Shullsburg, Wis.

CONCLUSIONS

The magnetic and geologic data suggest a basement of complex geology, consisting largely of granitic rocks interrupted by a broad open fold of possibly metasedimentary rocks in the south half of the district and by more local pre-Paleozoic plutons of more mafic rocks in the north half. Linear dislocations in the magnetic patterns suggest that major faults of eastward, northwestward, and northeastward trends are present in the Precambrian basement. The coincidence of some of these dislocations with known major folds and faults deforming the exposed Paleozoic strata shows that tectonic movement was renewed along some of the faults and folds in post-Precambrian time by gentle adjustments of the intervening crustal blocks upward and downward relative to one another. These movements provided the necessary basement control of a large part of the larger gentle folds and flexures found in the overlying capping strata of Paleozoic sedimentary rocks. Leakage of rising and probably heated solutions along the basement faultlines and along the margins of the more magnetic basement rock bodies possibly have provided at least some of the solutions that deposited the ores in the district. The ore-bearing solutions may have entered the overlying Cambrian sandstone aquifer system and spread out laterally as well as upward into the overlying carbonate rocks. Thus, they could have moved away from the feeding fissures into the entrapment areas around the buried monadnocks, where the ores were deposited. This hypothesis is supported by the marked concentration of the known lead and zinc deposits near or above the magnetic highs and along probable faults.

A second hypothesis is that the ore-bearing heated connate solutions could have entered the district laterally through the Cambrian sandstone aquifer system. Once in the district, local lines of fractures in the sandstones above the basement lineaments could have acted as channelways into the overlying Ordovician carbonate rocks where the ore bodies were deposited in lines above the basement faults. Elsewhere, the laterally flowing solutions could have been concentrated and deposited in clusters in the beds that wedge out and dip gently upward around the flanks of the buried monadnocks.

Ore deposits appear to be associated with the areas of magnetic highs. In spite of good exposures and considerable prospecting, very few ore deposits, either of lead or zinc, have been found in the prominent lows or magnetically flat areas. This dearth of ore deposits is notable in the following lows: (1) the northward-trending low west of Hazel Green and Cuba City, Wis., that flanks the large rectangular high in the southern part of the district, (2) the northward-trending low east of Council Hill Station, Ill., (3) the series of lows along Wisconsin Highway 81 in the center of the map, which make a bend north near Truman, Wis., (4) the magnetically flat area north of Platteville, Wis., (5) the flat area in the vicinity of Cobb, Wis. The two areas where most of the known lead and zinc deposits are concentrated are the northwestern part of the large rectangular magnetic high shown in the southern part of the map and the general area of magnetic highs shown in the northern part of the map.

Some consideration might be given to prospecting in areas of magnetic highs and linear trends where insufficient prospecting has been done in the past. Examples of such favorable areas are (1) the area southward from Galena, Ill., to the south boundary of the map, (2) the magnetic high trending southward through Scales Mound, Ill., toward the old lead mining area at Elizabeth, Ill., (3) the east-southeastward extension of the large rectangular high in the southern part of the district, which follows the upper part of the Apple River valley towards Nora, Ill. (Heyl and others, 1959, pl. 1), (4) the area of little dissected topography near Platte Mounds and Belmont marked by a large northeastward-trending magnetic high, (5) the flanks of the two large magnetic highs near Montfort and Dodgeville, Wis. These flanks are mineralized, but very little prospecting has been done on them since 1915. Both anomalies might be worthy of a carefully planned prospect drilling program. Some deep prospecting into the reef-bearing Prairie du Chien and dolomitic Trempealeau Formations might be worthwhile on the flanks of the highs to search for deeply buried ore bodies that are possibly structurally similar to those in the southeast Missouri lead district.

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U.S. GOVERNMENT PRINTING OFFICE: 1966