Geology of the Cuba City, New Diggings, and Shullsburg Quadrangles, Wisconsin and Illinois

GEOLOGICAL SURVEY BULLETIN 1123-H

Prepared in cooperation with the Wisconsin Geological and Natural History Survey

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By THOMAS E. MULLENS

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By Thomas E. Mullens

ABSTRACT

The Cuba City, New Diggings, and Shullsburg quadrangles cover 155 square miles in the Upper Mississippi Valley zinc-lead district and are in the Driftless Area of southwestern Wisconsin and northwestern Illinois. Rocks exposed in the quadrangles have an aggregate thickness of about 600 feet and are mainly of Middle and Late Ordovician, Early Silurian, and Quaternary age. Quartz sandstone dikes of unknown age cut Middle Ordovician rocks, and sparse patches of gravel of probable Quaternary age occur locally.

The St. Peter Sandstone of Middle Ordovician age is the oldest formation exposed. About 35 feet of fine- to coarse-grained quartz sandstone in cross-laminated beds assigned to the St. Peter crop out along the Galena River in the northern part of the area. The Platteville Formation of Middle Ordovician age is 55 to 75 feet thick and conformably overlies the St. Peter Sandstone. The Platteville is divided, in ascending order, into the Glenwood, Pecatonica, McGregor, and Quimbys Mill Members. The Glenwood Shale Member is 2 to 7 feet thick and consists of shale, shaly sandstone, and dolomitic siltstone. The Pecatonica Dolomite Member is 20 feet thick and consists mainly of dolomite. The McGregor Limestone Member is about 30 feet thick and consists of limestone and dolomite. The Quimbys Mill Member is about 2 feet thick and is limestone in the western part of the mapped area, but it thickens to about 20 feet and grades to dolomite in the southeastern part.

The Decorah Formation of Middle Ordovician age is 25 to 40 feet thick and conformably overlies the Platteville Formation. It is divided, in ascending order, into the Spechts Ferry, Guttenberg, and Ion Members. The Spechts Ferry Shale Member is 5 feet thick and is interbedded limestone and shale at the west boundary of the mapped area, but it thins to a film of greenish-gray shale in the Shullsburg quadrangle. The Guttenberg Limestone Member is 12 to 14 feet thick in the Cuba City and New Diggings quadrangles and thins to about 6 feet in the southeastern part of the Shullsburg quadrangle. The decrease in thickness is accompanied by a change from wavy-bedded limestone to very fine grained dolomite. The Ion Dolomite Member is about 20 feet thick; it contains limestone, dolomite, and shale in the basal 6 to 7 feet and dolomite in the upper 13 to 14 feet.

The Galena Dolomite of Middle Ordovician age is about 220 feet thick and conformably overlies the Decorah Formation. It is divided into two parts of

about equal thickness: a lower cherty unit and an upper noncherty unit. The cherty unit is thick-bedded dolomite that contains chert masses and nodules oriented parallel to bedding planes. The basal 75 to 80 feet of the noncherty unit is dolomite similar to that in the cherty unit; the upper 35 to 40 feet is argillaceous thin-bedded dolomite.

The Maquoketa Shale of Late Ordovician age is 185 to 200 feet thick and conformably overlies the Galena Dolomite. The basal 30 to 40 feet of the Maquoketa is dolomitic siltstone; the upper 160 to 170 feet is clayey siltstone and thin interbedded silty dolomite. The Maquoketa Shale is unconformably overlain by small remnants of Edgewood Dolomite of Early Silurian age on four hills in the Shullsburg quadrangle. The sparse exposures of Edgewood are thin-bedded dolomite.

Geologic structures in the mapped area are those caused by regional stress and those caused by subsidence in localized zones of leached rock. Structures caused by regional stress include a southward regional dip of about 20 feet per mile, an eastward-trending asymmetric anticline about 15 miles long, smaller folds that trend mainly northeastward, a few faults, and well-formed vertical joints. The steep limb of the asymmetric anticline is 1 to 2 miles wide and dips about 150 feet per mile. The gentle limb is 1 to 3 miles wide and dips southward about 35 feet per mile. The vertical joints form conjugate systems, but the type of stress which caused the systems is not known. In the southern part of the quadrangles one set of joints in the conjugate system strikes eastward, the other northward. In the northern part of the quadrangles one set strikes northeastward, and the other strikes northwestward.

About 285,000 tons of lead and 820,000 tons of zinc have been produced from ore mined in the mapped area through 1958. Much of the lead ore was mined in the 19th century when the district was a major lead-producing district in the United States. During the 20th century, zinc ore that contains small amounts of lead has been the chief ore from the area. Typical ore mined in the 1950's averaged 3.33 percent contained-zinc and 0.33 percent contained-lead.

Lode deposits commonly contain the same principal primary minerals—sphalerite, galena, marcasite, pyrite, barite, and calcite. Most of these minerals were deposited in space formed directly or indirectly by solution of carbonate rock, although minerals locally replace country rock. Space formed by solution of carbonate rock depended upon several factors. Mineralizing fluids dissolved limestone and thin-bedded rock more readily than dolomite and thick-bedded rock. However, the readily soluble rocks commonly were leached in relatively large areas, and overlying beds were thus allowed to compact the altered rock. Actual open space is therefore not as common in altered limestone as in altered dolomite.

Mineral deposits are (1) those associated with vertical joints, (2) those associated with inclined and bedding fractures, and (3) those not associated with obvious fracture control. Deposits associated with vertical joints are mainly in the upper two-thirds of the Galena Dolomite and in the McGregor and Quimbys Mill Members of the Platteville Formation. The deposits in the Galena have been mined mainly for the contained-galena, which occurs in openings along joints. Joint-controlled deposits in the Platteville Formation are mined mainly for the contained-sphalerite.

The largest mineral deposits contain mainly zinc ore as veins along inclined fractures and opened bedding, as fillings in breccia, as disseminated crystals or aggregates of crystals, and as replacements of country rock. These deposits are associated with extensive altered zones in the Guttenberg and Quimbys Mills Members and most of them occur in shallow synclines or basins as expressed at the top of the Guttenberg Member and younger units.

The origin of the fractures, synclines, and breccia is a matter of controversy. In this report, the structures are interpreted as having been caused by subsidence in areas where ore-bearing fluids dissolved considerable quantities of carbonate rock from the Guttenberg and Quimbys Mill Members. The synclines and basins as expressed at the top of the Guttenberg Member and much of the breccia in the deposits are interpreted as having formed when overlying rocks subsided and compacted the altered rocks. The inclined fractures and opened bedding are interpreted as having formed where certain rock units served as structural plates and allowed overlying rocks to sag, instead of collapsing randomly, into the altered zone.

The deposits associated with inclined fractures are not localized at particular types of folds as expressed at the top of the McGregor Member of the Platteville Formation. Many deposits, however, are elongate in a direction that parallels a set of joints in the local dominant conjugate-joint system, and some deposits associated with inclined fractures are overlain by mineral deposits controlled by joints. The deposits associated with inclined fractures are interpreted as having formed where altered zones along vertical joints in the Quimbys Mill and Guttenberg Members overlapped and formed weakened areas so large that overlying rocks were not supported.

INTRODUCTION

LOCATION, ACCESS, AND INDUSTRY

The Cuba City, New Diggings, and Shullsburg quadrangles make up about 155 square miles in Lafayette and Grant Counties in southwestern Wisconsin and in Jo Daviess County in northwestern Illinois (fig. 51). The quadrangles lie wholly within the Driftless Area, and they contain many of the zinc- and lead-ore deposits in the Upper Mississippi Valley zinc-lead district.

Good State and county roads and two railroads provide access to most parts of the quadrangles. The Chicago and North Western Railway, which offered only freight service in 1959, serves Cuba City and Benton in the Cuba City quadrangle. The Illinois Central Railroad, which crosses the southeastern part of the Shullsburg quadrangle, offers both freight and passenger service at Galena, Scales Mound, and Apple River, Ill. These towns are within 7 miles of the south border of the quadrangles.

Agriculture, mining, and processing agricultural products, in about that order of importance, are the chief industries in the three quadrangles Corn, hay, and oats are the chief crops, and they are used mainly as feed for dairy cattle, beef cattle, and hogs. Cheese manufacturing is the most important of the agricultural processing activities, although some corn and peas are canned in a plant just east of Cuba City. The importance of mining varies directly with the price of zinc. In 1956, when zinc sold for 13½ cents a pound, about 210 men were employed at six mines and three mills and ore was mined from 13 deposits. In early 1959, when zinc sold for 11 cents a pound, about 105 men were employed at two mines and one mill and ore was mined from seven deposits.

Shullsburg, population about 1,325, and Cuba City, population about 1,525, are the largest towns and local trade centers. Dubuque, Iowa, population about 57,000, is 10 miles west of the mapped area; Madison, Wis., population about 127,000, is 45 miles northeast.

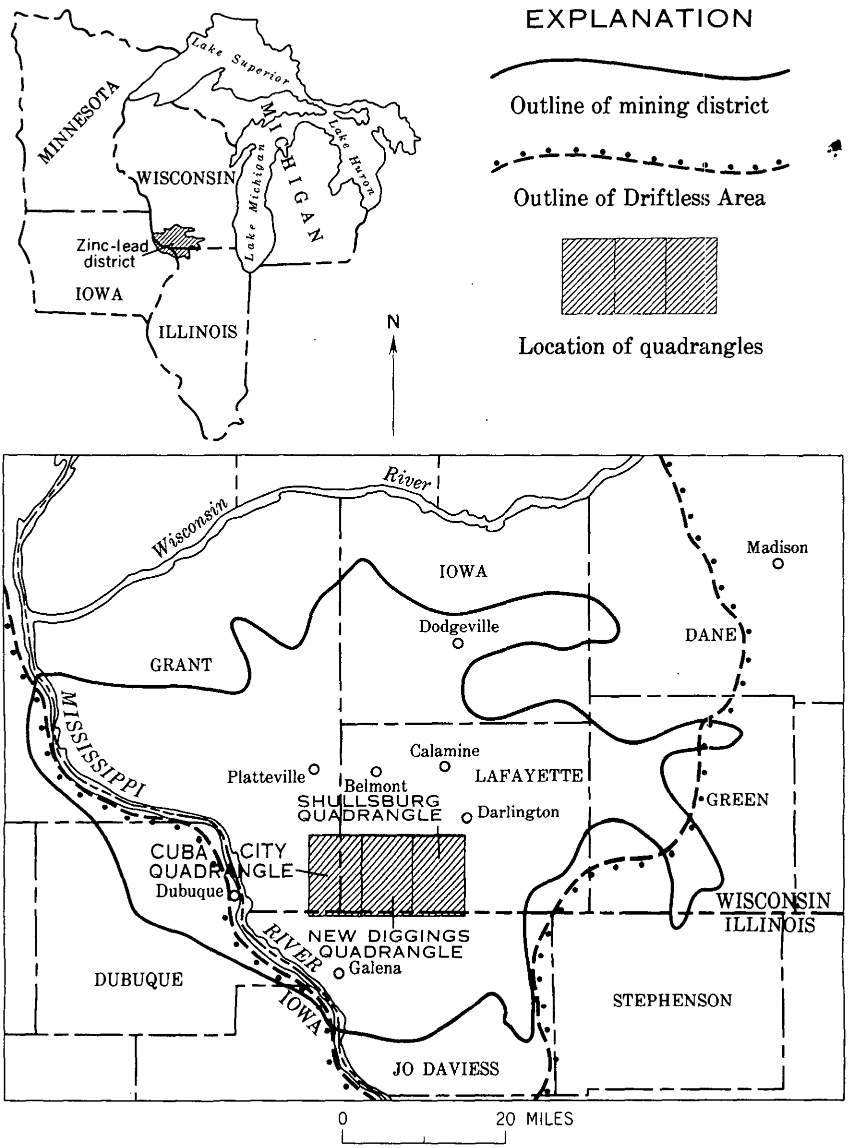

FIGURE 51.—Index map showing outlines of the mining district and the Driftless Area, and location of Cuba City, New Diggings, and Shullsburg quadrangles.

PRESENT INVESTIGATION

The present investigation of the Cuba City, New Diggings, and Shullsburg quadrangles was done in cooperation with the Wisconsin Geological and Natural History Survey and is part of a program of regional study of the occurrence and origin of the ore deposits in the Upper Mississippi Valley zinc-lead district. The purpose of the present investigation was to prepare maps that show the geologic setting of the zinc- and lead-mineral deposits and to collect and interpret data for appraisal of the zinc and lead resources. Quadrangle mapping has followed detailed study of ore deposits and stratigraphy of the mining district during and shortly after World War II (Agnew and others, 1956; Heyl and others, 1959).

The discussion of mineral deposits in this report has two objectives. The first is to give a general description of the deposits in the quadrangles. This description incorporates data concerning deposits in the upper part of the Platteville Formation that have been developed mainly since World War II. The description does not include details on mineralogy, individual deposits, and distribution of deposits. The reader is referred to Heyl and others (1959) for comprehensive and documented information on these aspects of mineral deposits in the Upper Mississippi Valley district.

The second objective is to present an interpretation that alteration of country rock, mainly solution of carbonate, and subsequent subsidence of overlying beds formed structures and ore receptacles in the larger deposits. This interpretation is controversial, for many geologists have interpreted the structures to be tectonic in origin and the chief factor in localizing the deposits. Because of the controversy, the alteration of country rock, the structures, and a possible method of forming the structures by subsidence are described in detail.

This report is based on field and office work between July 1956 and July 1959. Outcrops and structural control points based on outcrops and data from water wells were compiled on 1:7,920-scale topographic maps. Data from mines and exploratory drill holes were compiled on 1:2,400-scale planimetric maps or on the 1:7,920-scale topographic maps. All pertinent information was then transferred to 1:20,000-scale topographic maps for publication at 1:24,000.

Most of the Cuba City and New Diggings quadrangles was mapped during or shortly after the wartime study (fig. 52). The present study included no detailed fieldwork in the part of the Cuba City quadrangle that is in Grant County, Wis., inasmuch as little new information has become available since this area was mapped by Allingham, Flint, and Agnew (1955). The Grant County part of the geologic map (pl. 25) is a slightly modified copy of USGS map

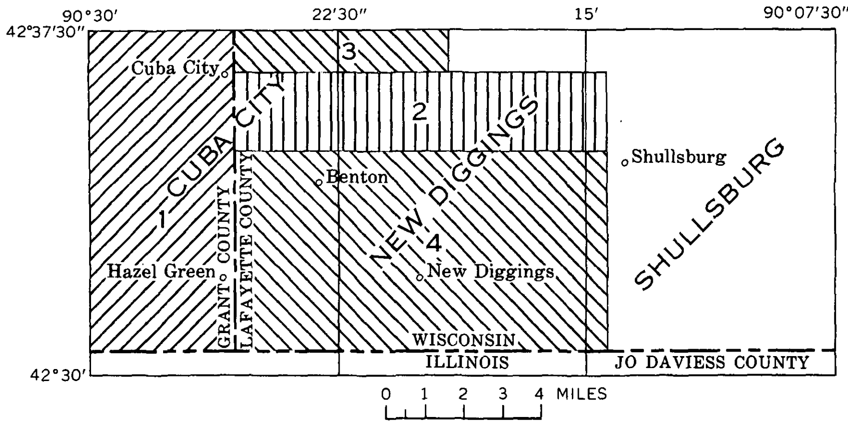

FIGURE 52.—Index map of Cuba City, New Diggings, and Shullsburg quadrangles showing the areas covered by recently published maps. 1, Allingham, Flint, and Agnew (1955) ; 2, Agnew, Flint, and Crumpton (1954) ; 3, Heyl and others, (1959, pl. 3) ; 4, Heyl and others (1959, pl. 5).

MF–40 (Allingham, Flint, and Agnew, 1955) fitted to a topographic base.

Fieldwork in the part of Jo Daviess County, Ill., west of the fourth principal meridian consisted mainly of checking data on aerial photographs and in field notes prepared by Allingham, Flint, and Agnew for overedge control of their map MF–40; this part of plate 25 is based on a compilation of these field notes. All the previously mapped area in Lafayette County, Wis., was remapped in order to incorporate abundant new data obtained from a grid of exploratory drill holes and to transfer the geology onto a modern topographic map.

Contacts of formations and collars of water-well holes that were used for structure control points were surveyed for altitude above sea level with a planetable and telescopic alidade. Most exploratory drill holes used as structure control points had been surveyed by mining companies, but some of the mining company surveys were run from arbitrary bench marks. As a check on surveys made by mining companies, all holes used as control points were plotted on 1:7,920-scale topographic maps. If the altitude of the plotted position of the drill hole was within a contour interval (10 ft) of the altitude given by the mining company, the company altitude was used. If the altitude of the position was not within a contour interval of the company altitude, the hole was, where possible, resurveyed by planetable and alidade. Comparatively little resurveying was necessary in this study, for Agnew and Heyl had tied many of the altitudes based on arbitrary bench marks to sea level in studies made in 1943–46 and 1949–50 (Heyl and others, 1959, pls. 3, 5; Agnew, Flint, and Crumpton, 1954).

DESCRIPTION OF DRILL-HOLE DATA

Because most of the structural and much of the stratigraphic information described in this report is based on drill-hole data, the quantity and quality of such information are described. The logs and locations of about 14,000 drill holes in the mapped area were collected by the U.S. Geological Survey and compiled by the U.S. Bureau of Mines in an unpublished atlas which is on file at the Wisconsin Institute of Technology in Platteville, Wis. About 98 percent of these holes are prospect and development holes in the central two-thirds of the area. The remaining holes are scattered throughout the mapped area; they include prospect holes, water-well holes, and a few holes drilled by companies under contract to the U.S. Geological Survey. The holes drilled for the Geological Survey were for structural and stratigraphic information in areas where surface exposures are poor and other drill-hole information was lacking.

About 10,500 of the prospect and development holes were drilled before 1946 and before the economic potential of ore deposits in the Platteville Formation was fully recognized. Most of these holes were bottomed at the top or at the base of the Guttenberg Member of the Decorah Formation, which is the highest stratigraphic unit in a zone of rocks that are considerably altered and thinned in some zinc-lead ore deposits. The amount of thinning below the top of the Guttenberg Member near zinc-lead ore deposits commonly is 10 to 15 feet, which is in the range of the tectonic structure associated with the deposits. The use of data from pre-1946 holes for structure control points result in showing either structure as modified by solution-thinning and consequent sagging or approximating tectonic structure by interpreting the amount of thinning. Delineations of structural features on the basis of the latter interpretation probably are not consistently accurate within a 10-foot contour interval.

Other factors detract from the value of data from pre-1946 holes for use in interpretation of regional stratigraphy and structure. The major disadvantage is that only "tops" of stratigraphic units and ore and gangue minerals were recorded in the logs. Other disadvantages are that many of the collar elevations were tied to arbitrary bench marks, and most of the holes were concentrated near ore deposits.

From 1946 to 1959 about 3,500 prospect and development holes were completed in the central two-thirds of the area. About one-third of the 3,500 were prospect holes in a regular grid designed to obtain structural information (pl. 25, see secs. 29, 30, 31, and 32, T. 2 N., R. 2 E.); the remainder are development holes. These holes drilled after 1946 were completed in the upper part of the McGregor Member of the Platteville Formation. Because much of the thinned rock associated with the ore deposits is above this member, the holes drilled after 1946 are especially significant for determining tectonic structure. Most of these drill holes were surveyed from a sea level datum.

About two-thirds of the logs of holes drilled after 1946 report lithic characteristics of the rocks penetrated and were of great aid in determining stratigraphic relations.

Only a basic grid of holes is shown on plate 25, for the location of many development holes drilled after 1946 is confidential information of mining companies. However, all drill holes in the mapped area whose collar elevations could be determined within 10 feet were considered in drawing structure contours. Holes drilled after 1946 were so numerous and widely distributed in the central two-thirds of the mapped area that structure contours based mainly on holes drilled before 1946 are used only in secs. 9, 13, 14, 22, S½ sec. 25, N½ sec. 26, N½ sec. 27, secs. 29 and 30, T. 1 N., R. 1 E., and sec. 19 and N½ sec. 30, T. 1 N., R. 2 E.

ACKNOWLEDGMENTS

John W. Reddy assisted in surveying structure control points and in compiling drill-hole data during the 1956 and 1957 field seasons, and Roger M. Borcherding assisted during the 1958 and 1959 field seasons. The assistance of these men is gratefully acknowledged.

Mining companies in the district, the Eagle-Picher Co., the New Jersey Zinc Co., and American Zinc, Lead and Smelting Co. gave full cooperation to the study. Much of the interpretation of regional geologic structure and stratigraphy in this report is based on study of drill-hole data obtained from these companies. Interpretation of the occurrences of mineral deposits in the district was aided considerably by study of mineral deposits in mines operated by the Eagle-Picher Co. and by American Zinc, Lead and Smelting Co. The Illinois State Geologic Survey furnished geologic data on the northwestern part of the State.

The author benefited from many talks with William Arndt, geologist for the Eagle-Picher Co.; W. A. Broughton, professor of geology at Wisconsin Institute of Technology; John Hague, geologist for the New Jersey Zinc Co.; the late Paul Herbert, Jr., geologist for the Tri-State Zinc Co. at the time of this study; M. P. Gronbeck, professor of mining engineering at Wisconsin Institute of Technology; and Allen Heyl of the U.S. Geological Survey. These men, along with the author's colleagues in the Survey office in Platteville, Wis., gave many suggestions about features to observe and much constructive criticism of the author's ideas on the geology of the mining district.

Colleagues of the writer in the regional mapping phase of the work in the mining district were Allen F. Agnew, John W. Allingham, C.

Ervin Brown, John E. Carlson, Harry Klemic, Alfred R. Taylor, Walter West, and Jesse W. Whitlow. Agnew (1963), Allingham (1963), Carlson (1961), Taylor (1964), and Klemic and West (1964) prepared reports on geology of nearby quadrangles in Wisconsin. The geology of the Dubuque South quadrangle, Iowa and Illinois, is described by Brown and Whitlow (1960), and the geology of the Dubuque North quadrangle, Iowa, Wisconsin, and Illinois, is described by Whitlow and Brown (1963).

PREVIOUS PUBLICATIONS

About 200 papers have been published to describe specifically one or several of the following features in the Upper Mississippi Valley zinc-lead district: areal geology, structural geology, stratigraphy, ore deposits, mineralogy, and geomorphology. Heyl and others (1959) give an extensive bibliography for the district, and the complete list of papers will not be repeated here. Several papers, however, were comprehensive reports on the mining district at the time they were written and deserve special mention. These papers are by Owen (1840, 1847), Daniels (1854), Percival (1855, 1856), and Hall and Whitney (1862), who studied the district when lead ore was the chief product; Strong (1877) and Chamberlin (1882), who studied the district when zinc ore was beginning to displace lead ore as the chief product; and Grant (1903, 1906), Bain (1906), and Cox (1914), who studied the district after zinc ore had displaced lead ore as the chief product. Heyl and others (1959), who studied the district during and shortly after World War II, prepared the most comprehensive report and bibliography on the Upper Mississippi Valley zinc-lead district. Their report gives much detail on the general geology, structure, and ore deposits; it also includes a history of the geological work done in the district and summaries of the important earlier reports.

Agnew and others (1956) made a detailed study of the stratigraphy of rocks exposed in the mining district. Their report furnishes information on regional correlation and facies changes of rocks exposed in the Cuba City, New Diggings, and Shullsburg quadrangles. In addition, Reynolds (1958) prepared a report on factors localizing ore deposits in the Shullsburg area, and Bradbury (1959) published a detailed report on joint-controlled deposits in northwestern Illinois.

PHYSIOGRAPHY

RELIEF

Local relief, as measured from the tops of the flat divides to the flood plains of the large streams, ranges from 100 to 200 feet and averages about 170 feet along the Galena River (called the Fever

River by residents of southwest Wisconsin). Maximum relief is about 590 feet. The highest point, White Hill, is about 1,250 feet above sea level; the lowest point, about 660 feet above sea level, is at the Galena River in the southeastern part of the Cuba City quadrangle. Charles Mound, altitude about 1,235 feet, in the southwestern part of the Shullsburg quadrangle, is the highest point in Illinois.

UPLAND

Much of the upland in the Cuba City, New Diggings, and Shullsburg quadrangles consists of flat to rounded divides between streams that form a general dendritic pattern. In general the upland slopes southward and forms two topographic surfaces that are about 180 feet apart vertically. The lower surface is represented by the extensive rounded divides in the Cuba City quadrangle and in the northern and western parts of the New Diggings quadrangle; the higher surface is represented by the top of an irregularly shaped flat-topped hill in the southwestern part of the Shullsburg quadrangle. These surfaces in the mapped area are parts of an extensive upland in the Driftless Area; whether they are structural or erosional in origin is a controversial subject among geologists.

Martin (1916), Trewartha and Smith (1941), and Thwaites (1960) interpreted the southward-sloping surfaces as cuesta-type dip slopes. Grant and Burchard (1907, p. 2) interpreted the lower surface as a peneplain; they named it the Lancaster peneplain and indicated that it is probably Tertiary in age. Trowbridge and Shaw (1916, p. 136–140) concurred with this interpretation and also interpreted the upper surface as a peneplain, which was named the Dodgeville peneplain (Trowbridge, 1921). However, in a communication to C. L. Horberg (Horberg, 1946, p. 185–186) Trowbridge rejected the Dodgeville peneplain. Most of the evidence that the lower surface is a peneplain is found beyond the boundaries of the mining district.

The author interprets the upland as parts of cuestas, although evidence in the mapped area supports each theory about equally.

The upland forms a flat surface that truncates the largest fold in the quadrangles. Near the center of sec. 25, T. 2 N., R. 1 W., the upland surface is 1,020 feet above sea level and is on soft shale near the trough of a syncline. About 1¾ miles east-southeast the upland is 1,030 feet above sea level and is on resistant dolomite near the crest of an anticline. The dolomite is stratigraphically about 160 feet lower than the shale. At the east end of the fold the upland surface maintains an altitude of 1,080 to 1,100 feet in a southeasterly direction from sec. 28, T. 2 N., R. 2 E., to the NW cor. sec. 1, T. 1 N., R. 2 E., although the structural relief between these points is 160 feet.

Possible additional evidence for a peneplain is indicated in the western part of the New Diggings quadrangle where, from the north to the south boundaries, the dip averages about 35 feet per mile and the slope of the upland surface averages about 15 feet per mile.

A structural origin for the upland surface is indicated at several places by the parallelism of the slope of the upland surface to regional dip. For example, in 5.5 miles between the SE¼ sec. 1, T. 1 N., R. 1 W., and sec. 25, T. 29 N., R. 1 W., the topographic surface descends 100 feet and the rocks about 110 feet. In addition, the control of streams by synclines and joints is apparent in all three quadrangles. Shullsburg Branch and some of its southwestward-flowing tributaries parallel small synclines or monoclines in the New Diggings and Shullsburg quadrangles, and the course of an unnamed northeastward-flowing stream in sec. 30, T. 2 N., R. 1 E., in the Cuba City quadrangle possibly is controlled by the upturned edges of northwestward-dipping strata. In most other places in the mapped area the courses of streams in the quadrangles conform to the local joint systems. This close relationship between streams and geologic structure would not be likely if the area had been peneplained.

Evidence that might support a structural origin for the upland surfaces is that the dolomite that caps White Hill and Charles Mound is weathered about the same as the dolomite exposed in the deepest valleys. Grant and Burchard (1907, p. 2) suggested a probable Tertiary age for the Lancaster peneplain. Trowbridge (1954, p. 802–804) concurs with this age designation and also believes that the Driftless Area was uplifted in Pleistocene time. This relation would mean that White Hill and Charles Mound were part of a monadnock of Tertiary age; thus it would be reasonable to expect deep soil or other evidence of long weathering at White Hill and Charles Mound if the peneplain theory is true. No such evidence was found, but it is possible that mass-wasting or downslope movement removes soil and talus as fast as it is formed. C. E. Brown (written commun., 1960) reports a heavy residual red clay formed along the Niagaran cuesta near Dubuque, Iowa.

STREAMS

Nearly all the New Diggings quadrangle, the east half of the Cuba City quadrangle, and the west-central part of the Shullsburg quadrangle are drained by the Galena River and its tributaries. The Apple River and the West Fork of the Apple River drain the southern and southeastern parts of the Shullsburg quadrangle. Tributaries to the Pecatonica River, which in turn is a tributary to the Rock River in Illinois, drain the northern and northeastern parts of the Shullsburg quadrangle. Most of the west half of the Cuba City quadrangle is

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drained by the Sinsinawa River, although some of the northwestern part is drained by tributaries to the Little Platte River. Stream distance that the water flows to the Mississippi River after leaving the mapped area ranges from about 6 miles for the Sinsinawa River to more than 120 miles for the tributaries of the Pecatonica River.

The general pattern of streams and valleys in the mapped area is dendritic. In detail, however, the drainage pattern shows strong joint control; the tributaries join larger streams at 45° or 90° angles.

Most of the large streams in the quadrangles have wide flood plains and steep valley walls. The alluvium on the flood plains is fairly thin; drill holes along the Galena River and Coon Branch indicate a thickness of 10 to 20 feet.

STRATIGRAPHY

Sedimentary rocks exposed in the mapped area have an aggregate thickness of about 600 feet and are of Middle and Late Ordovician, Early Silurian, and Quaternary age. Ordovician and Silurian rocks were deposited in a marine environment and include sandstone, limestone, dolomite, and shale. Quaternary rocks are mainly alluvium and loess that were deposited in a continental environment.

Some of the Ordovician rocks are cut by quartz sandstone dikes, but no igneous rocks are known in the mapped area.

The Ordovician and Silurian rocks exposed in the quadrangles are divided into six formations which are, from oldest to youngest: the St. Peter Sandstone, Platteville Formation, Decorah Formation, and Galena Dolomite, all of Middle Ordovician age; the Maquoketa Shale of Late Ordovician age; and the Edgewood Dolomite of Early Silurian age. An erosional unconformity separates the Maquoketa Shale and Edgewood Dolomite.

The deepest drill hole in the quadrangles, 1,467 feet, shows that sandstone and siltstone of Late Cambrian age and dolomite, shale, and sandstone of Early Ordovician age aggregating about 1,200 feet in thickness underlie the St. Peter Sandstone (unpub. log of the Cuba City No. 2 water well in the SW¼SW¼SE¼ sec. 25, T. 2 N., R. 1 W., by F. T. Thwaites on file at the office of the State Geologist in Madison, Wis.). No drill hole in the quadrangles has penetrated Precambrian rocks. Evidence from the nearest drill holes that penetrate Precambrian rocks indicate Upper Cambrian rocks probably overlie Precambrian rocks at an altitude of 1,000 to 1,500 feet below sea level in the quadrangles. Ten miles north of Cuba City at Platteville, Wis., a drill hole penetrated Precambrian rocks beneath Upper Cambrian rocks at an altitude of 800 feet below sea level (Agnew, 1963, p. 250). At Dubuque, Iowa, which is about 10 miles west of the Cuba

City quadrangle, two drill holes penetrated Precambrian rocks under Upper Cambrian rocks at about 1,200 feet below sea level (Brown and Whitlow, 1960, p. 12).

All rock units except the St. Peter Sandstone are fossiliferous in the mapped area. No systematic study of the fossils was made, and most of the stratigraphic units are based on differences in composition and bedding. However, *Prasopora* at the top of the Decorah Formation and *Receptaculites oweni* Hall, present in several zones in the Galena Dolomite, were useful in establishing stratigraphic position in exposures where the rock composition did not suffice.

The Decorah Formation and the upper two members of the Platteville Formation change from dominantly limestone in the northwestern part of the mapped area to dominantly dolomite in the southeastern part. This change is a part of a regional northwest to southeast facies change of Middle Ordovician rocks in the mining district (Agnew and others, 1956, fig. 34). The general regional facies pattern, as well as the change within the mapped area, is that of progressively older rocks becoming more dolomitic southeastward. In detail, however, individual stratigraphic units contain interbedded limestone and dolomite over relatively wide areas, and islands of limestone occur in the dolomite facies or islands of dolomite occur in limestone facies. In addition to the facies changes, some limestone near zinc-lead mineral deposits is altered to dolomite that cannot be distinguished by field methods from dolomite related to the regional facies change. An attempt was made to establish boundaries between dolomite facies and interbedded limestone and dolomite facies, and between limestone facies and interbedded limestone in each stratigraphic unit. However, data are insufficient to establish exact boundaries, and the ones given in this report are generalized.

Dolomitized rock near zinc-lead deposits is only one of several changes in rock near ore deposits. Other changes include solution, shalification, and silicification. These changes are discussed in detail on pages 489 to 495.

ORDOVICIAN SYSTEM

MIDDLE ORDOVICIAN SERIES

ST. PETER SANDSTONE

The St. Peter Sandstone was named by Owen (1847, p. 170) for exposures along the St. Peter River (now the Minnesota River) near St. Paul, Minn. It crops out only in the northeastern part of the New Diggings quadrangle along the Galena River. (In this report the term "crops out" is used to indicate that a unit forms the surface bedrock. "Outcrop" and "exposure" are used to indicate places where the rock can be seen through the mantle of soil cover.) About 35 feet of St. Peter crops out at the north edge of the quadrangle, but progressively less of the sandstone crops out southward owing to the regional dip; about 1.5 miles downstream it is completely covered by younger rocks.

Most St. Peter Sandstone is friable, and exposures are poor except for local zones where the sandstone is well cemented. The sandstone ranges from very light gray [1] to moderate orange pink and dark yellowish orange. The orange and yellow shades are due to iron oxides that stain or cement grains. The sand is composed of very fine to coarse well-rounded grains of quartz that are either clear or frosted. In general, the sand is poorly sorted, but a few beds 1 to 2 feet thick are composed entirely of very fine grains. Individual beds range in thickness from 0.5 to 5 feet. Most of the thicker beds are cross-laminated, but individual beds are separated by horizontal bedding planes that truncate the cross-laminations in the bed below. The cross-laminations are low angle (less than 10°) and are of the type attributed to deposition on a beach (Thompson, 1937).

A bed about 1 foot thick that contains abundant pyrite is 4 feet below the contact of the St. Peter Sandstone and Platteville Formation in exposures along the Galena River. This pyrite zone is apparently widespread, as most of the drill holes into the St. Peter Sandstone penetrate it. The zone caps most outcrops of St. Peter Sandstone, as iron oxide cement derived from weathering of the pyrite makes it resistant compared to the poorly cemented beds in the rest of the sandstone.

Drill holes show that in some areas clean St. Peter Sandstone overlies dolomite of the Prairie du Chien Group of Early Ordovician age and in other areas it overlies lenses of interbedded quartz sandstone, pale-red and greenish-gray shale, dolomite, and limestone 6 to 110 feet thick. These lenses overlie Prairie du Chien rocks in some places and Upper Cambrian rocks in other places. Some geologists, F. T. Thwaites (unpub. logs of Cuba City, Hazel Green, and Shullsburg city water wells, in U.S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.), and Heyl, Lyons, and Agnew (1951), include the interbedded sandstone, shale, and dolomite in the St. Peter Sandstone; Flint (1956) places these rocks in the Prairie du Chien Group.

If the St. Peter Sandstone is restricted to clean quartz sandstone, its known range in thickness is from 50 feet in the northeastern part of sec. 6, T. 1 N., R. 1 E., to 340 feet in the northwestern part of sec. 11, T. 1 N., R. 2 E. This change in thickness probably is not

[1] Descriptive colors in this report were obtained by comparing the rocks with colors in the "Rock-Color Chart" (Goddard, 1948).

indicative of a regional thickening, because in southwest Wisconsin the St. Peter is known to thicken from 52 to 215 feet in a horizontal distance of 450 feet (Agnew, Flint, and Allingham, 1953, pl. 4). Trowbridge (1917) and Willman and Templeton (1952) report the local abrupt changes in thickness are due to filling by the St. Peter Sandstone of stream channels cut into the top of the Prairie du Chien Group. Flint (1956) believes some of the abrupt changes in thickness are caused by sand that was deposited in depressions caused by solution of carbonate rock of interreef areas in the Prairie du Chien.

The St. Peter Sandstone is overlain conformably by the Glenwood Shale Member of the Platteville Formation in exposures along the Galena River. Templeton (1948), Willman and Templeton (1952), and Bevan (1926) all reported an unconformity at the top of the St. Peter in exposures in Illinois. Possibly this unconformity extends into the southern and eastern parts of the mapped area where the St. Peter is concealed by younger rocks.

The St. Peter does not bear ore, and the mineralizing solutions have not altered it greatly. Lead and zinc minerals in trace amounts occur in the upper few feet of St. Peter Sandstone at the Jack of Diamonds (S½ sec. 22, T. 1 N., R. 1 E.) and Alderson (SE¼ sec. 32, T. 2 N., R. 2 E.) mines (unpub. drill-hole logs, in U.S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.). The pyrite zone is locally thicker under deposits of iron, zinc, and lead minerals in younger beds than in unmineralized areas (Agnew and others, 1956, p. 274; Heyl, Lyons, and Agnew, 1951, p. 5). However, proof that the pyrite is related to sulfide deposits in younger beds is inconclusive.

PLATTEVILLE FORMATION

The Platteville Formation was named by Bain (1905, p. 18–19) for exposures near Platteville, Wis., and the reference section in the mining district selected by Agnew and others (1956, p. 274) is exposed in a roadcut along U.S. Highway 151 in the NW¼ NE¼ sec. 12, T. 2 N., R. 2 W. The Platteville in the mining district is divided into four members, which in ascending order are: the Glenwood Shale, the Pecatonica Dolomite, the McGregor Limestone, and the Quimbys Mill Members. These members are conformable within the formation.

The normal thickness of the Platteville Formation ranges from about 55 feet in the northwestern part of the Cuba City quadrangle to about 75 feet in various parts of the Shullsburg quadrangle. This difference is due to a regional thickening of the Quimbys Mill Member from northwest to southeast. Near lead and zinc deposits the upper members of the Platteville are altered by solutions that leached carbonate rock, left a shaly residue, and thinned the formation as much as 22 feet.

The lithology and regional changes in the Quimbys Mill are well known in the central two-thirds of the mapped area, inasmuch as most prospect holes drilled since 1946 penetrate this member and bottom in the upper part of the McGregor Member. The lithology and regional changes in the lower members are known mainly from exposures along the Galena River and scattered water wells.

GLENWOOD SHALE MEMBER

The Glenwood Shale Member was named by Calvin (1906, p. 60–61, 75) for exposures in Glenwood township, Iowa. In the mining district, the member generally consists of 1 to 4 feet of sandy shale and is considered a part of the Platteville Formation by the U.S. Geological Survey. In parts of Illinois, the Glenwood is considerably thicker and is considered a formation or a group by the Illinois State Geological Survey.

The Glenwood Shale Member crops out above the St. Peter Sandstone along the Galena River in the northwestern part of the New Diggings quadrangle where it is 2 to 3 feet thick. The thickness of the Glenwood increases slightly southeastward. Five drill holes in sec. 22, T. 1 N., R. 2 E., show that it ranges from 3 to 7 feet in thickness.

The member consists of grayish-green and yellowish-green, slightly fissile sandy shale, shaly sandstone, and dolomitic siltstone. Along the Galena River these lithic types are zoned, but the contacts between the zones are gradational. The lowest zone is 0.5 to 1.5 feet thick and is poorly sorted quartz sandstone that contains blebs and lenses of greenish-gray clay and interstitial clay. Sand in this zone ranges from very fine to coarse grains that are rounded, spherical, and frosted; the grains are commonly cemented with iron oxide derived from weathered pyrite. The middle zone, 0.5 to 1 foot thick, is sandy greenish-gray to yellowish-green clay and siltstone that contains abundant disseminated frosted quartz grains and pyrite. Clay and siltstone in this zone is fissile and weathers to chips about $\frac{1}{16}$ inch thick, 1 inch wide, and 1.5 inches long. The upper zone, 0.5 to 1 foot thick, is sandy dolomitic claystone and siltstone in beds 0.5 to 1 inch thick. This zone contains sparse pyrite and abundant phosphatic nodules as much as one-eighth inch long.

Sand grains in the Glenwood are similar to those in the underlying St. Peter Sandstone, and the exposures along the Galena River indicate a conformable and transitional contact between the St. Peter Sandstone and the Glenwood. The upper part of the Glenwood grades into the overlying Pecatonica Dolomite Member.

The Glenwood Shale Member is not normally mineralized with lead or zinc minerals and is not considered a potential ore-bearing zone. Most pyrite in the Glenwood is interpreted by the author as syngenetic; however, trace amounts of lead sulfide (Heyl, Lyons, and Agnew, 1951) may indicate that some of the pyrite came from mineralizing fluids that deposited lead, zinc, and iron minerals in higher beds.

PECATONICA DOLOMITE MEMBER

The Pecatonica Dolomite Member of the Platteville Formation was named by Hershey (1894, p. 175) for exposures east of the mapped area in the Pecatonica River valley. Agnew and others (1956, p. 277) designated the Pecatonica exposed in a bluff at Lattice Bridges (NW¼ sec. 21, T. 1 N., R. 6 E.), Green County, Wis., as the type section.

Pecatonica Dolomite Member crops out along the Galena River in the northwestern part of the New Diggings quadrangle. Complete sections are exposed as far south as the north edge of sec. 3, T. 1 N., R. 1 E.

This member is about 20 feet thick throughout the mapped area. It is composed mainly of dolomite but contains scattered disseminated quartz grains and phosphatic pellets in the basal 18 inches and local brownish-gray dolomitic shale partings. The dolomite is fine to medium grained, yellowish gray to olive gray on fresh surfaces and grayish orange on weathered surfaces. Individual beds of dolomite are 1 to 2 feet thick.

The Pecatonica is a poor host for sulfide mineral deposits in the northern and western parts of the district where it is well exposed. However, the Pecatonica is mainly concealed and its potential is virtually untested in the southern part of the district. Drill holes at the Jack of Diamonds mine (S½ sec. 22, T. 1 N., R. 1 E.) penetrated lead, zinc, and iron sulfide minerals (unpub. drill-hole logs in U.S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.), and drill holes at the Alderson mine (SE¼ sec. 32, T. 2 N., R. 2 E.) penetrated abundant iron sulfide and traces of lead and zinc sulfide minerals in the Pecatonica (Agnew, Flint, and Crumpton, 1954).

MCGREGOR LIMESTONE MEMBER

The McGregor Limestone Member of the Platteville Formation was named by Kay (1935, p. 286) for exposures near McGregor, Iowa. In the mining district it is called the "Trenton lime" by miners and well drillers. Complete sections of McGregor crop out along the Galena River as far south as the N½ sec. 3, T. 1 N., R. 1 E., in the New Diggings quadrangle. The upper part crops out along Shullsburg Branch in the central part of the New Digging quadrangle and along an unnnamed tributary to the Galena River in sec. 33, T. 2 N., R. 1 E., in the eastern part of the Cuba City quadrangle.

The McGregor Member is normally about 30 feet thick and comprises two units of contrasting lithologies. The lower unit is 10 to 15 feet thick, consists mainly of thin- and wavy-bedded limestone, and approximately correlates with the Mifflin Member of Bays (1938). The limestone is light gray to pale yellowish brown and sublithographic. Individual beds are 1 to 3 inches thick and are separated by films of light-gray or pale yellowish-brown shale. The unit contains abundant gastropods and, locally, cephalopods. It is mainly limestone along the Galena River but probably contains considerable dolomite in the eastern part of the mapped area, for it is entirely dolomite in exposures about 6 miles to the east.

The upper unit is 15 to 20 feet thick, consists of medium-bedded limestone and dolomite, and approximately correlates with the Magnolia Member of Bays and Raasch (1935). The limestone is light gray to pale yellowish brown and very fine grained to sublithographic; the dolomite is mainly pale yellowish brown to yellowish gray and noticeably more granular than the limestone, although it also is very fine grained. Individual beds are 6 to 24 inches thick, and only traces of shale separate the beds.

The upper unit of the McGregor is mainly limestone in the western part of the mapped area and mainly dolomite in the eastern part. The gross character of the facies change is a basal limestone zone that pinches out eastward. In detail the change is more complicated, as interbedded limestone, dolomitic limestone, and dolomite occur between the limestone and dolomite facies. The boundaries of this interbedded limestone and dolomite zone cannot be established exactly from available data. The zone probably trends northward, and the east boundary is near Shullsburg and the west boundary near Cuba City.

The upper unit contains scattered nodules of light-gray chert in the Kittoe mine (sec. 15, T. 1 N., R. 2 E.). These nodules probably represent the westward extent of chert nodules that are abundant in exposures of the McGregor Member east of the mapped area (Agnew and others, 1956, fig. 34).

The contact between the upper and lower units, as determined by bedding characteristics, is distinct at individual outcrops; however, thin-bedded units near the contact may grade laterally into thick-bedded units. This lateral change in bedding characterstics is apparently limited to a zone about 10 feet thick near the middle of the McGregor.

Isolated drill holes in the McGregor Member penetrated rock containing zinc-lead minerals of minable grade and thickness (at least 7 feet of rock that averages 3 percent contained zinc or lead) in several places in the mapped area. A few zinc-lead ore deposits in the McGregor have been mined. The McGregor was an ore-bearing zone at the Kittoe (sec. 15, T. 1 N., R. 2 E.), Old Mulcahy (sec. 9, T. 1 N., R. 2 E.), Lucky Hit (sec. 33, T. 2 N., R. 2 E.), Thompson and Temperly (secs. 26 and 27, T. 1 N., R. 1 E.), and James (secs. 8, 9, 16, and 17, T 1 N., R. 2 E.) mines.

Known ore deposits in the McGregor Member are associated with ore deposits in younger rocks, and they occur in erratically sized and distributed pods that contain a few hundred to a few thousand tons of ore. These deposits are near the boundary of the New Diggings and Shullsburg quadrangles and near the town of New Diggings. The general haulage level in most of the mines operated since 1946 is about at the top of the McGregor. To mine the pods of ore, the floor must be lowered; difficulty in road maintenance and pumping results, and consequently the mining companies have been reluctant to follow leads that may indicate pods of ore.

QUIMBYS MILL MEMBER

Agnew and Heyl (1946) named the Quimbys Mill Member of the Platteville Formation for exposures of limestone and dolomite in a quarry in the SE¼SE¼ sec. 11, T. 1 N., R. 1 E., New Diggings quadrangle. This member is known locally as "glassrock" because it breaks with a conchoidal fracture and has a glasslike ring when struck with a hammer.

The Quimbys Mill Member crops out along the Galena River and Shullsburg Branch in the New Diggings quadrangle and along an unnamed tributary to the Galena River in secs. 32 and 33, T. 2 N., R. 1 E., in the Cuba City quadrangle. It is about 12 feet thick at the type section. Northwest of a line that trends south-southwest through the type section, the Quimbys Mill thins progressively to about 2 feet thick in the northwest corner of the mapped area. Southeast of the type section Quimbys Mill thickens slightly but not uniformly. It is 14 to 16 feet thick in sec. 22, T. 1 N., R. 2 E., and 18 to 20 feet thick at the southeast corner of the mapped area. East of the type section it thickens to 22 feet in sec. 3, T. 1 N., R. 2 E., but thins farther east and is about 15 feet thick in the northeastern part of the mapped area.

At the type section the Quimbys Mill Member consists of 6 feet of limestone overlain by 6 feet of dolomite. The limestone is separated from the underlying McGregor Member by 0.2 foot of carbonaceous brownish-gray shale that is locally fissile. The limestone is brownish gray when wet and pale red purple when dry, sublithographic, dense, and in 6 separate beds that range from 0.5 to 1 foot in thickness. Each limestone bed is separated from adjacent beds either by brownish-gray shaly limestone or by fissile carbonaceous shale from 0.1 to 0.5 foot thick.

The dolomite is very pale orange to grayish yellow, fine grained, and dense. It occurs in irregular wavy beds 2 to 6 inches thick that are locally separated by dolomitic and carbonaceous shale partings $\frac{1}{16}$ to $\frac{1}{4}$ inch thick. The dolomite is separated from the limestone by a foot of limy dolomite.

The Quimbys Mill Member changes from limestone in the western part of the mapped area to dolomite in the eastern part. The boundaries between dominant limestone and interbedded limestone and dolomite cannot be determined exactly, but it probably is near the Grant County-Lafayette County line. The boundary between the dominant dolomite facies and interbedded limestone and dolomite extends southeastward from about sec. 30, T. 2 N., R. 2 E., to about the southeast corner of the Shullsburg quadrangle. In the interbedded facies, limestone is more abundant near the base of the Quimbys Mill than near the top.

Agnew and others (1956, p. 262) report that a regional disconformity separates the Quimbys Mill from the overlying Spechts Ferry Member of the Decorah Formation. Evidence for this unconformity is that the top of the Quimbys Mill is pitted and corroded. The pits are as much as 1 inch deep, and some contain involutions of sedimentary rock of the Spechts Ferry. The pitted upper surface was seen in a few places in the mapped area, but the author does not interpret the surface as representing a regional disconformity.

The Quimbys Mill Member contains ore deposits in most mines that were operated between 1956 and 1959. In addition, it is known to be mineralized at many places where mining and drilling into the Quimbys Mill were not done on a systematic basis.

DECORAH FORMATION

The Decorah Formation was named by Calvin (1906, p. 60, 84) for exposures near Decorah, Iowa. In the mapped area it is divided into three members, in ascending order: the Spechts Ferry Shale Member, the Guttenberg Limestone Member, and the Ion Dolomite Member. The author interprets the contact of the Decorah Formation and the underlying Platteville Formation and the contacts of the three members as conformable in the mapped area.

The thickness of the Decorah Formation ranges from about 40 feet in the northwestern part of the mapped area to about 25 feet in the southeastern part. The range in thickness is due to regional thinning of the Spechts Ferry and Guttenberg Members. Near lead and zinc deposits the limestone is leached and compacted and the thickness of the Decorah Formation is commonly reduced by 6 to 10 feet.

SPECHTS FERRY SHALE MEMBER

The Spechts Ferry Shale Member was named by Kay (1928) for exposures near Spechts Ferry, Iowa. This member is known locally as the "claybed."

The Spechts Ferry crops out along the Galena River, along Shullsberg Branch, and along an unnamed tributary to the Galena River in sec. 4, T. 1 N., R. 1 E., and secs. 23 and 33, T. 2 N., R. 1 E., in the Cuba City quadrangle. The Spechts Ferry Member is thin, not resistant to erosion, and forms few natural exposures. Drill-hole data indicate that the Spechts Ferry thins uniformly from about 5 feet of green and white clay and limestone in the western part of the Cuba City quadrangle to a film of green clay in the western part of the Shullsburg quadrangle. The west-to-east thinning, in part, complements the east-to-west thinning of the underlying Quimbys Mill Member of the Plateville Formation.

Along the Galena River the Spechts Ferry is about 3 feet thick and contains about three times as much limestone as clay. The limestone is in beds 1 inch to 2 feet thick, but in most places the major part of the limestone is in one or two beds that are from 8 to 18 inches thick. The limestone is uniformly gray to light gray; however, other characteristics of the limestone vary with the thickness of the beds. Beds 1 to 3 inches thick commonly contain abundant fossils and pale-green clay blebs; thicker beds commonly are dense and sublithographic, contain only fragments of fossils, and have pale-green clay partings instead of isolated blebs. Locally the limestone beds contain lenses of dolomite 1/8 to 1/2 inch thick and 1 to 4 inches long.

Clay in the Spechts Ferry is light gray to white, and pale green. The light-gray to white clay is a bed 2 to 4 inches thick in the basal 1 foot of the member and is probably metabentonite. Allen (1932) identified a similar clay in the Spechts Ferry Member as bentonite or metabentonite, which contained crescent-shaped shards, apatite, and sanidine; he believed it originated mainly as a volcanic ash fall. Taylor (1964) reports that white clay at the base of the Spechts Ferry Member in the Rewey and Mifflin quadrangles is a mixed-layer montmorillonite-illite.

The pale-green clay occurs in beds that range from a film to 4 inches in thickness and as blebs in the limestone. Beds of clay thicker than one-fourth inch are generally fissile in outcrops, but they are only slightly fissile in exposures in mines.

In the western part of the mapped area where the Spechts Ferry Member is about 5 feet thick, the ratio of limestone to clay and shale is about 1 to 1. As compared to the Spechts Ferry along the Galena River, the western part has a threefold increase in clastic content and only a one-fifth increase in carbonate content. The slight increase westward in limestone content is accompanied by a slight decrease in the average thickness of individual limestone beds.

The method of thinning of the Spechts Ferry east of the Fever River is not known at the present. It seems paradoxical that the average thickness of individual limestone beds increases eastward and reaches a known maximum just before they pinch out. Possibly some of the limestone merges with the overlying Guttenberg Member. A vertical gradation between these members is indicated at an outcrop about 600 feet south of the bridge on State Highway 11 in sec. 10, T. 1 N., R. 1 E., where the basal limestone bed in the Guttenberg is 8 inches thick, the lower 4 inches of the limestone greatly resembling limestone in the underlying Spechts Ferry.

The Spechts Ferry Member contains disseminated zinc, lead, and iron sulfide minerals in places where overlying or underlying beds are mineralized. It is too thin, however, to be considered an important ore-bearing unit.

In and near zinc-lead ore bodies, the limestone in the Spechts Ferry Member is commonly leached, and the insoluble residue compacted and shalified. W. A. Broughton (oral commun., 1959) reported that in one place in the West Blackstone mine (sec. 28, T. 1 N., R. 2 E.) the matrix in a thin bed of coquinoid limestone had been completely dissolved and that the fossils were replaced by iron sulfide and silica.

GUTTENBERG LIMESTONE MEMBER

The Guttenberg Limestone Member of the Decorah Formation was named by Kay (1928) for exposures near Guttenberg, Iowa. In the mapped area it crops out along the Galena River, Shullsburg Branch, and an unnamed tributary of the Galena River in sec. 4, T. 1 N., R. 1 E., and secs. 32 and 33, T. 2 N., R. 1 E. It is not particularly resistant to erosion and forms few outcrops.

The Guttenberg Limestone Member is 12 to 14 feet thick in areas west of Shullsburg and slightly thinner in areas southeast and east of Shullsburg. It is about 10 feet thick in sec. 36, T. 1 N., R. 2 E., and sec. 3, T. 1 N., R. 3 E., and 6 to 8 feet thick along the Apple River in the southeastern part of the Shullsburg quadrangle. The thinner Guttenberg in the eastern part of the area corresponds with the regional southeastward thinning reported by Agnew and others (1956, fig. 34).

Typical Guttenberg Member in the New Diggings and Cuba City quadrangles comprises wavy beds of pale-brown limestone separated by brownish-gray to brownish-black shale. The limestone is in beds 1 to 4 inches thick, and grades into shale at the bottom and top. Some beds are extremely fossiliferous and crystalline, whereas nonfossiliferous beds are sublithographic. The shale partings are carbonaceous and petroliferous and range in thickness from a film to 2 inches.

The Guttenberg Member is pale-brown, very fine grained dolomite and limy dolomite in the eastern part of the Shullsburg quadrangle, and is probably interbedded dolomite and limestone in the central part of the quadrangle. (No samples of Guttenberg from the central part of the quadrangle were available for study, and logs of drill holes in this area do not include descriptions of rock types.)

The Guttenberg contains scattered nodules of chert in outcrops along the Galena River. North of State Highway 11 these nodules form a discontinuous layer about 3 feet from the top, but in the southeastern part of the Cuba City quadrangle they are mainly in the lower half of the Guttenberg.

The contact of the Guttenberg Member and the overlying Ion Member is transitional through a zone 8 to 18 inches thick. The zone contains pale-brown limestone and shale typical of Guttenberg rocks and irregular patches of olive-gray limestone and blebs of greenish-gray shale typical of the overlying Ion. The patches of olive-gray limestone have distinct color boundaries, but no other change in adjacent rock is apparent.

Near mineral deposits, part of the limestone in the Guttenberg is dissolved, and insoluble argillaceous material is compacted to brownish-black shale. This shale is carbonaceous and petroliferous, and some of it will burn. Early miners called this shale and similar shales in the Quimbys Mill Member of the Platteville Formation "oil rock." More recent usage is to equate "oil rock" with Guttenberg Member. The change causes some confusion in interpreting logs of holes drilled between 1920 and 1940, for "oil rock" on the log may mean "dark-brown shale" or it may mean "Guttenberg Member."

The Guttenberg Member contains zinc and lead ore in most of the zinc mines shown on plate 25. Most of the ore consists of sphalerite and galena disseminated in shaly Guttenberg strata, but veins of minerals occur locally.

ION DOLOMITE MEMBER

The Ion Dolomite Member of the Decorah Formation was named by Kay (1928) for exposures near Ion, Iowa. The type section was later redescribed by Paul Herbert, Jr. (In Agnew and others, 1956, p. 293), to include 4.5 feet of rock Kay had included in the Guttenberg Member. Drillers and miners in the district subdivide the Ion into the "blue" and "gray" beds, contrary to the local general rule that geologists subdivide rocks more than drillers and miners.

The Ion Member crops out along the Galena River, Shullsburg Branch, and Coon Branch, and it is probably concealed by alluvium in the small gully in the northeastern part of sec. 28, T. 2 N., R. 3 E.

The Ion is about 20 feet thick and comprises two distinctive units. The lower unit, the "blue" of local usage, is 6 to 7 feet thick, and along the Galena River it consists of olive-gray and greenish-gray dolomite and limestone and greenish-gray shale. The dolomite is medium grained, in beds 4 to 18 inches thick, and sparsely fossiliferous. The limestone is coarsely crystalline, is most abundant in the basal 2 feet, and is very fossiliferous locally. The shale occurs as blebs and films in the dolomite and limestone, as shale partings, and in beds as much as 3 inches thick. Typically, however, only two or three shale beds in the lower unit are more than 1 inch thick, and shale is not a major constituent of the lower unit. West of the Galena River the lower unit changes to limestone, and it is probably all limestone at the west edge of the mapped area. East of the river, the sparse limestone at the base grades into dolomite, and the lower unit is all dolomite near Shullsburg.

Rounded fine to medium-fine grains of clear quartz are sparsely disseminated in the basal 1 foot of the lower unit. These sand grains are an excellent stratigraphic marker in studies of small samples of drill cuttings with a binocular microscope.

The upper unit, the "gray" of local usage, is 13 to 14 feet thick, and along the Galena River and in areas east of the river it consists of yellowish-gray dolomite that contains sparse greenish-gray shale. The dolomite is medium grained and occurs in beds 6 inches to 3 feet thick. The shale occurs mainly as small blebs disseminated in dolomite and as films between beds, but forms a bed ½ to 1 inch thick at the top of the upper unit. The upper unit contains more limestone and more argillaceous material near the west edge of the mapped area.

The Ion Member grades upward into the Galena Dolomite. The rocks in the Ion contain slightly more greenish-gray argillaceous material and are slightly finer grained than rocks in the Galena Dolomite. The bryozoan *Prasopora insularis* Ulrich marks the top of the Ion (Agnew and others, 1956, p. 295) but is uncommon in the mapped area.

The Ion Member contained ore in many of the zinc mines shown on plate 25.

GALENA DOLOMITE

The Galena Dolomite, named by Hall (1851, p. 146) for exposures near Galena, Ill., forms the surface rock in about three-fifths of the mapped area. The Galena is about 220 feet thick and is subdivided on faunal criteria into three members which, in ascending order, are: Prosser Member, Stewartville Member, and Dubuque Shaly Member.

Agnew and others (1956, p. 259, 267) divided the Galena by lithic criteria into two subdivisions of about equal thickness: a lower cherty unit and an upper noncherty unit. The lithic subdivision, which is used in this report, is better suited for mapping units in the mining district because of the general scarcity of outcrops and the difficulty in recognizing faunal zones in drill cuttings.

The Galena Dolomite is the principal host rock for lead and zinc minerals in the mapped area. Abundant galena deposits associated with vertical joints occur in the upper two-thirds, and the top of sphalerite deposits associated with inclined joints occur in the lower third. In addition, Galena Dolomite is extensively quarried for use as road metal and agricultural limestone.

CHERTY UNIT

The cherty unit of the Galena Dolomite, locally called the "drab," is about 105 feet thick throughout the mapped area. It consists mainly of grayish-orange dolomite that contains white and gray chert. Northeast of Benton light-brown fine-grained limestone occurs locally in the basal 10 to 30 feet (in secs. 2, 3, 4, 9, 10, and 11, T. 1 N., R. 1 E., and secs. 32, 33, 34, and 35, T. 2 N., R. 1 E.) The dolomite is medium grained and in beds that range from 3 to 18 inches in thickness. Some beds are separated by yellowish-gray silty dolomite zones as much as 1 inch thick, but shale is scarce along most partings. The basal 6 to 8 feet contains sparse blebs of greenish-gray clay, and a 1-inch-thick bed of silty dolomitic clay is about 32 feet below the top. This clay probably correlates with a bentonite at the same stratigraphic position west of the mapped area (Agnew and others, 1956, p. 297). Most of the chert occurs in irregular globs and nodules that are as much as 12 inches long, 10 inches wide, and 3 inches thick but average about 5 inches long, 3 inches wide, and 1 inch thick. The long dimensions parellel bedding, and the nodules are concentrated in layers along, or parallel to, bedding surfaces. In a few places, the chert forms continuous, even beds as much as 3 inches thick. At certain zones in the cherty unit, layers of nodules occur every 4 to 12 inches, and in these places nodules in the layers are abundant. In other zones the layers are farther apart, and the nodules in them are sparse.

All chert nodules in dolomite have smooth but irregular surfaces that show small knobs and depressions. The contact of dolomite and chert is sharp, and the nodules are loosely attached to the enclosing rock. Nodules in limestone have the same general form as nodules in dolomite, but the contact of chert and limestone is transitional and the nodules cannot be removed easily from limstone. Some nodules contain fossils and irregular inclusions of limestone, but no nodules observed in the mapped area contained crystalline quartz.

Apparently the formation of chert nodules preceded dolomitization, because fossils in chert nodules are well preserved but fossils in the dolomite are poorly preserved.

Biggs (1957) made a detailed study of nodular chert in several limestone and dolomite formations that included the Galena Dolomite. He concluded that the chert nodules are epigenetic concretions formed during diagenesis, and that the chert is derived from silica originally deposited with the host rock.

Some beds in the cherty unit in sec. 29, T. 2 N., R. 1 E., are silicified limestone that retains the texture of the original rock. Whether these beds were silicified by processes related to the formation of chert nodules is not known. It is possible that the silica is related to other processes, such as emplacement of sulfide mineral deposits.

The limestone near the base of the cherty unit in the area northeast of Benton grades laterally into medium-grained dolomite. The limestone is abundantly fossiliferous locally, but where fossiliferous limestone grades into dolomite the fossils are destroyed.

Outcrops of the cherty unit are distinctive. The rock is granular, porous, and pitted because of selective solution of the intergranular calcareous cement. The outcrops give the impression that the cherty unit is a permeable zone; however, work by C. R. Holt (oral commun., 1959) has shown that the dolomite in the Galena is relatively impermeable.

The cherty unit is subdivided into four zones based on the abundance of chert and the presence of the fossil *Receptaculites oweni* Hall (Agnew and others, 1956, p. 296–297). The zones are of great value in determining stratigraphic position in outcrop study but are of lesser value in study of drill cuttings as the fossils are destroyed. In ascending order the subdivisions are:

Zone	*Description*
D	About 10 feet thick; does not contain chert or *Receptaculites*. Locally called the "lower buff."
C	About 11 feet thick; contains abundant layers of nodular chert but not *Receptaculites*.
B	About 14 feet thick; contains sparse chert nodules and abundant *Receptaculites*.
A	About 70 feet thick; contains local zones of chert nodules and *Receptaculites*. This zone can be used for stratigraphic control in limited areas, but it is not as persistent or distinctive as zones B, C, and D.

The cherty unit conformably underlies the noncherty unit of the Galena Dolomite, and except for the presence of chert, dolomite in the two units is similar. The top of the cherty unit is marked by a discontinous layer of chert nodules that is 4 to 5 feet above a zone that contains abundant nodules in several layers 4 inches to 2 feet apart.

NONCHERTY UNIT

The noncherty unit of the Galena Dolomite, locally called the "buff," is 115 to 120 feet thick in the mapped area. The lower 75 to 80 feet includes part of the Prosser Member and all of the Stewartville Member; the upper 35 to 40 feet correlates in general with the Dubuque Shaly Member. The noncherty part of the Prosser Member and the Stewartville Member consists of grayish-orange medium-grained dolomite in beds that range in thickness from 6 inches to 3 feet and it is difficult to place the contact between the members either by rock type or by faunal content. In areas of good exposures the contact can be located by a zone that contains abundant *Receptaculites* about 35 feet above the top of the cherty unit. However, *Receptaculites* are sporadically scattered in dolomite below this zone, and the contact cannot be determined with certainty in small outcrops. The dolomite in the basal 75 to 80 feet of the noncherty unit is similar to dolomite in the cherty unit, but typically the outcrops weather to a slightly lighter color and are more porous. This weathering effect may reflect a slight change in composition, or it may reflect a longer period of weathering because of the generally higher topographic position of noncherty rocks.

The contact between the Dubuque Member and the Stewartville is placed at the lowest distinctive and persistent shale bed (Brown and Whitlow, 1960, p. 22; Willman and Reynolds, 1947, p. 9). The beds about 3.5 to 9 feet above this shale are locally called the "caprock" unit and are remarkable for their persistence in the mining district. Near Dubuque, Iowa, the unit consists of the following dolomite beds in ascending order: a 1.7-foot bed, a 0.5-foot bed, and a 3.2-foot bed (Brown and Whitlow, 1960, p. 22). This unit can be recognized at the base of the quarry in the NW¼ sec. 23, T. 29 N., R. 3 E., in the Shullsburg quadrangle, and the individual beds are within 0.1 foot of the thicknesses reported by Brown and Whitlow. Allingham (1963, p. 197) reports that the caprock unit maintains its constant thickness in exposures near Dodgeville, Wis., which is about 40 miles northeast of Dubuque and 30 miles north of the quarry.

Above the caprock unit the Dubuque consists of argillaceous fine-grained dolomite that grades upward from very pale orange to yellowish gray. The dolomite is in beds 4 to 18 inches thick, and the beds are separated by clayey to silty dolomitic shale zones that are apparently only ¼ to ½ inch thick at fresh exposures. Weathering of these beds, however, produces shaly zones as much as 2 inches thick which indicates the dolomitic shale is gradational with the dolomite. Some dolomite beds contain abundant brachiopods, and the beds in

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the upper 5 to 10 feet of dolomite contain abundant small (1/10 to 1/5-in.) segments of crinoid stems.

The noncherty unit of the Galena Dolomite underlies the Maquoketa Shale of Late Ordovician age. The scattered exposures of this contact observed in and near the mapped area indicate the contact is conformable. Agnew and others (1956, p. 259) report that in the mining district the contact is conformable, but that regionally the contact seems to be disconformable.

UPPER ORDOVICIAN SERIES

MAQUOKETA SHALE

The Maquoketa Shale of Late Ordovician age was named by White (1870, p. 181) for exposures along the Little Maquoketa River in Iowa. A thick cover of this formation is preserved in the southern part of the Shullsburg quadrangle and on the hill in sec. 28, T. 1 N., R. 2 E., in the New Diggings quadrangle. In other parts of the mapped area the Maquoketa forms a thin cap on major divides.

The Maquoketa Shale is 185 feet thick at the drill hole a few hundred feet northeast of the crest of White Hill in sec. 23, T. 1 N., R. 2 E., and about 200 feet thick near Charles Mound in the southwestern part of the Shullsburg quadrangle. Outcrops are not common, in spite of the large area covered by Maquoqeta and its relatively great thickness, and they occur mainly in the steep gullies north of Charles Mound and in roadcuts.

The lower 30 to 40 feet of the Maquoketa is mainly dark-gray dolomitic and clayey siltstone. Weathered siltstone is slightly fissile, but in fresh outcrops it occurs in beds 1/2 to 4 inches thick. The basal 2 feet contains abundant depauperate fossils, disseminated pyrite, and phosphatic nodules. The fossils are pelecypods and brachiopods less than one-half inch long, BB shot-sized sponges, and pencil-lead-sized cephalopods. Many fossils are replaced by phosphatic material, and some are replaced by pyrite. The phosphatic fossils are more resistant to weathering than the siltstone and consequently are common in soil near the contact of the Maquoketa Shale and Galena Dolomite.

The upper 160 to 170 feet of Maquoketa Shale consists of clayey siltstone and silty dolomite. The clayey siltstone is similar to siltstone in the lower part of the Maquoketa and occurs in zones 2 inches to 5 feet thick. These zones are separated by dark grayish-orange silty dolomite that occurs in beds 1/4 to 2 inches thick. Cuttings from drill holes indicate that siltstone is about twice as abundant as dolomite in the upper part of the Maquoketa, although dolomite is more conspicuous than siltstone at outcrops.

A conspicuous dolomite bed that ranges from 3 to 13 inches in thickness locally occurs about 175 feet above the base of the Maquoketa Shale. The bed is grayish orange and grayish yellow, granular, contains abundant bryozoa fragments, and is the only ledge-former in the Maquoketa. The dolomite bed is present near White Hill, Charles Mound, and the hill in sec. 28, T. 1 N., R. 2 E.; it probably supports the knobs on the ridges in the southwestern part of the Shullsburg quadrangle. In short distances the bed thickens from 5 to 13 inches, and it is possible that the dolomite occurs as lenses in a restricted zone instead of as a single extensive bed.

The Maquoketa Shale unconformably underlies the Edgewood Dolomite of Early Silurian age. Brown and Whitlow (1960, p. 33) report that the unconformity is erosional and that as much as 135 feet of Maquoketa was eroded in the Dubuque South quadrangle, Iowa and Illinois.

The Maquoketa Shale locally contains minor amounts of sphalerite and barite. At the Glanville prospect (sec. 24, T. 29 N., R. 2 E.) sphalerite crystals and aggregates of crystals associated with barite and iron sulfide occurred throughout a 150-foot drift (Cox, 1914, p. 84). Small disseminated grains of sphalerite were observed in dolomite 35 to 50 feet below the top of the Maquoketa penetrated by the drill hole a few hundred feet northeast of the crest of White Hill. Pyrite is locally abundant in the basal 2 feet of the Maquoketa, but this pyrite probably is related to deposition of shale instead of emplacement of mineral deposits.

SILURIAN SYSTEM

LOWER SILURIAN SERIES

EDGEWOOD DOLOMITE

The Edgewood Dolomite of Early Silurian age overlies the Maquoketa Shale at Charles Mound, secs. 13 and 24, T. 29 N., R. 2 E., and at White Hill, sec. 23, T. 1 N., R. 2 E. About 50 feet of Edgewood is preserved at Charles Mound and about 20 feet at White Hill. Scattered cobbles and small boulders of dolomite similar to dolomite in the Edgewood Dolomite are on the small hill in the SE$\frac{1}{4}$ sec. 25, T. 1 N., R. 2 E., and the hill in the E$\frac{1}{2}$ sec. 34, T. 1 N., R. 2 E. The Edgewood Dolomite shown at these hills on plate 25 is inferred from these boulders.

The only outcrops of Edgewood Dolomite in the mapped area are on Charles Mound where grayish-orange and olive-gray medium-grained dolomite that contains light-gray chert nodules is exposed at the northwest and southeast ends. The dolomite is thin bedded and slightly wavy bedded. Irregular chert nodules 1 to 3 inches thick and as much as 8 inches long occur along some bedding surfaces. The nodules do not coalesce to form layers of chert. The outcrops are small, and it is possible that the rock exposed in them is not typical of the entire Edgewood Dolomite. Thicker sections of Edgewood Dolomite exposed a few miles south of Charles Mound show some zones of rock similar to that exposed at Charles Mound and some zones of thicker bedded rock. The boulder and cobble float at the three other places where Edgewood Dolomite was mapped indicates slightly thicker bedded rock than that exposed at Charles Mound.

The drill hole a few hundred feet east of the summit of White Hill penetrated 15 feet of Edgewood Dolomite. The cuttings of the Edgewood are grayish-orange fine-grained dolomite that contains sparse to abundant bryozoan fragments. No chert was noted in the cuttings.

The Edgewood Dolomite in the mining district is not considered an ore-bearing unit, although rocks of Silurian age contain small veins of galena and iron sulfide in Iowa (Heyl and others, 1959, p. 291–292, fig. 101).

DEPOSITS OF UNKNOWN AGE

SANDSTONE DIKES

Quartz sandstone dikes have been reported in several places in the mapped area. The occurrences are listed below:

Location	*Stratigraphic position*	*Reported by—*
Trewartha mine, S½ sec. 20, T. 1 N., R. 1 E.	Guttenberg Member of Decorah Formation.	Behre, Scott, and Banfield (1937, p. 793).
Mullen mine, NE¼ sec. 17, T. 1 N., R. 2 E.	Quimbys Mill Member of Platteville Formation and Guttenberg Member of Decorah Formation.	A. F. Agnew and A. V. Heyl (1943, field notes, U.S. Geol. Survey files in Beltsville, Md.).
Vertical churn drill hole, 660 ft south of center of north boundary of sec. 36, T. 2 N., R. 2 E.	Contact of Galena and Decorah Formations.	R. R. Reynolds (1950, unpub. log, in U. S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.).
Barite and galena prospect shaft near center of SW¼ sec. 34, T. 2 N., R. 1 E.	Cherty unit of Galena Dolomite.	C. V. Laird, property owner and prospector (1959, oral commun.).
Vertical churn drill hole near center of SW¼ sec. 34, T. 2 N., R. 1 E.	-----do--------------	A. E. Flint (1950, unpub. log, in U. S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.).

None of these dikes were observed by the author. The dikes in the mines were reported to be as much as 8 inches thick and to consist of rounded and frosted quartz grains similar to grains in the St. Peter Sandstone. The sandstone is poorly cemented and is intruded along joints. The vertical drill hole in sec. 34, T. 2 N., R. 1 E., penetrated about 12 feet in the Galena Dolomite, a zone that contained disseminated quartz sand grains and local small blocks of sandstone. The drill hole in sec. 36, T. 2 N., R. 2 E., penetrated 5 feet of quartz sandstone between the Galena Dolomite and Decorah Formation; no other sandstone is mentioned in the log.

Cobbles and boulders of quartz sandstone similar to that in the St. Peter Sandstone, but in an abnormal stratigraphic position, occur on the surface at several places in the mapped area. The positions are abnormal because the boulders occur well above the St. Peter Sandstone, and no sandstone is known to crop out upstream. Known and reported occurrences of these boulders are shown on plate 25 at the following locations in T. 1 N.: SE¼ sec. 1, NE¼ sec. 2, and NE¼ sec. 3, all in R. 1 E.; SE¼ sec. 4 SE¼ sec. 5, NE¼ sec. 5, and NE¼ sec. 8, all in R. 2 E.

A rounded elongate boulder of sandstone at least 2 feet wide and 4 feet long was embedded in alluvium in a small tributary to Shullsburg Branch near the structure control point shown on plate 25 in the NW¼ NE¼ sec. 8, T. 1 N., R. 2 E. Numerous rounded subspherical sandstone boulders as much as 3 feet long and 14 inches thick are in a gully in the NW¼ NE¼ sec. 3, T. 1 N., R. 1 E. Strong (1877, p. 667) reported sandstone boulders that weighed several tons on the ridge in the NE¼ sec. 5, T. 1 N., R. 2 E., but no boulders were observed in this area by the author.

All large boulders have well-cemented outer shells and are poorly cemented beneath the shell. Some boulders contain fragments of chert similar to the chert in several of the formations exposed in the area.

The sandstone boulders are believed by the author to be float from sandstone dikes, but their size indicates dikes much thicker than any actually observed. These large boulders are probably derived from sand injected into vugs or caves along joints. Black (1960) believes that southwest Wisconsin was glaciated and that abnormal stratigraphic positions of boulders of local formations may be due to uplift by ice advance.

Similar sandstone dikes or sandstone boulders in abnormal stratigraphic position have been reported in several other places in the mining district (Agnew, 1963, p. 258; Allingham, 1963, p. 199; Taylor, 1964).

The sandstone dikes are interpreted as injections of St. Peter Sandstone into joints in overlying formations. The St. Peter is generally friable, and under hydrostatic or compressional forces it probably would be injected into open spaces. Thom (1927, p. 737) reports that great quantities of sand have been thrown out of uncontrolled oil and gas wells. According to Thom, a well in Trinidad ejected thousands of tons of sand which covered the adjacent area to depths of 5 feet. If such quantities of sand can be ejected through a drill hole, it seems reasonable to assume that under certain pressures St. Peter Sandstone could be injected into joints or faults.

Sandstone dikes intrude well up into the cherty unit of the Galena Dolomite (Agnew, 1963, p. 258), and sandstone boulders have been found near the upper part of the Galena Dolomite (W. A. Broughton, oral commun., 1959). The probable maximum age for the intrusion is therefore post-Galena, but the minimum age is not known. Possibly all dikes were not injected at the same time.

EXOTIC GRAVEL

Pebbles and cobbles of hematite are scattered sporadically in gullies on the west side of Scrabble Branch in secs. 30, 31, and 32, T. 1 N., R 1 E., but are more abundant in the upper half of the gullies than in the lower half. The hematite is hard and dense, and each fragment has a polished but slightly pitted surface. The fragments are rounded, but only the pebble-sized ones are spherical. The largest cobble observed by the author was about 4 inches long, 3 inches wide, and 2 inches thick, and weighed about 5 pounds. W. A. Broughton (oral commun., 1959) found irregular cobbles about 8 inches in maximum dimension. Cobbles and pebbles of hematite observed by the author were in streams, but Broughton (oral commun., 1959) found that some hematite gravel underlies loess.

The Hazel Green city water well east of the junction of State Highways 11 and 80 in sec. 25, T. 1 N., R. 1 W., penetrated 5 feet of gravel mainly composed of pebbles of igneous rock at a depth of 15 feet below the surface (unpub. log by F. T. Thwaites and J. B. Steurwald, on file in Wisconsin Geol. and Nat. History Survey office in Madison, Wis.). The gravel is overlain by loess, but because no samples were collected from 20 to 30 feet below the surface it is not known whether the gravel is underlain by loess or by bedrock or whether the gravel is more than 5 feet thick. This gravel consists of subrounded and subspherical pebbles of granite, quartzite, diabase, rhyolite, quartz, and chert similar to chert in the Prairie du Chien Group. The pebbles are less than 1 inch long. Similar gravel as much as 1 foot thick and between loess and Maquoketa Shale was reported in several auger holes drilled along State Highway 80 from the Wisconsin-Illinois boundary to about a half mile north of State Highway 11 (unpub. logs by J. W. Allingham, 1950, in U.S. Geol. Survey files at Wisconsin Inst. Technology, Platteville, Wis.).

The fragments of hematite along Scrabble Branch and the pebbles beneath the loess do not resemble other rocks exposed in the mapped area. Because the fragments of hematite are polished and rounded, they are assumed to have been transported into the area from northern Wisconsin or Minnesota where similar rock occurs in iron-bearing formations. The pebbles of igneous rock are also assumed to be derived mainly from Precambrian rocks exposed in northern Wisconsin and Minnesota.

The gravel probably was deposited during Quaternary time, although the exact method and time of transporting them to the mapped area is unknown. The gravel has been used as evidence that glacial ice covered southwestern Wisconsin (Black, 1960). On the other hand, it is possible that ice-fed streams from glaciers near the Driftless Area transported the gravel, or that the gravel is the cap on remnants of a preglacial erosion surface.

QUATERNARY SYSTEM

LOESS

Loess forms an extensive cover as much as 20 feet thick on the upland surfaces in the western part of the area. The cover becomes progressively thinner eastward and no extensive deposits of loess are east of the Galena River. Most of the loess is on upland surfaces where it overlies a residual soil, but some loess remains in stream valleys. The distribution of loess in stream valleys indicates that the drainage pattern in the mapped area was about the same before loess was deposited as it is now. The loess is composed of grayish-orange calcareous silty clay and was derived from glacial outwash and flood plains of glacial-fed streams west of the mapped area. The precise assignment of the loess to the Pleistocene ice sheets is not known, but it should probably be assigned to the Wisconsin Glaciation, inasmuch as the drainage pattern has not changed materially since before the loess was deposited.

ALLUVIUM

Alluvium occurs along most streams in the mapped area. Where these deposits are more than 200 feet wide they are shown on plate 25.

Alluvium generally ranges in thickness from 10 to 20 feet in the large stream valleys and from 2 to 10 feet in the small valleys. It consists of brownish-black, grayish-brown, and dusky yellowish-brown silty clay. Sparse lenses of gravel composed of angular fragments of chert are interbedded in the clay, and a layer of chert gravel as much as 1 foot thick is at the base of the alluvium.

In many places along the Galena River and large streams farther west the alluvium is zoned vertically. The lower part is brownish-black and dusky yellowish-brown, and the upper 1 to 8 feet is grayish brown. The distribution and the lighter color of the upper alluvium indicate that it is mainly reworked loess.

Many of the small intermittent streams in the mapped area have level flood plains 20 to 100 feet wide that slope downstream as much as 200 feet per mile. These flood plains apparently are not built by overflow of the streams but by slope wash that is particularly effective where the rounded divides are cultivated and spring or winter plowing leaves bare soil exposed to spring rainstorms. No quantitative data are available for the rate of erosion of soil in the three quadrangles. Artifacts such as coal-oil lamps, automobile parts, and early type dry cells covered by as much as 18 inches of slope wash indicate considerable erosion in the quadrangles in the 20th century. In Iowa County, Wis., which is immediately north of Lafayette County, one rain in June 1959 eroded an average of 80 tons of soil per acre from unprotected fields (Bjorklund, 1959).

STRUCTURE

Geologic structures in the mapped area are those caused by regional stress in the crust of the earth and those probably caused by subsidence in localized zones of leached rock. The regional forces caused typical folds, faults, and joints, and subsidence caused the inclined fractures and shallow synclines and basins, as expressed at some stratigraphic zones.

Only features believed to result mainly from regional stress will be discussed here. Structural features that result mainly from subsidence are associated with some sulfide mineral deposits, and are discussed in the section on "Mineral deposits," pages 479 to 527.

Interpreting the inclined fractures and shallow synclines and basins as resulting from subsidence is controversial. Features that many geologists (Chamberlin, 1882; Grant, 1903 and 1906; Spurr, 1924; Scott;[2] Behre, 1937; and Heyl and others, 1959) have cited as prime examples of those caused by lateral compression are believed by the author to have been caused by subsidence. The discussion of structure in this report, therefore, is not compatible with most earlier reports on the area.

Structure of the mapped area is shown on plate 25 by structure contours. The trends of the larger structural features are shown on figure

[2] Scott, E. R., 1934, The structural control of ore deposition in the Upper Mississippi Valley lead-zinc district: Evanston, Ill., Northwestern Univ. unpub. M.S. thesis.

53. The features shown on figure 53 have a length of a mile or more, or cover more than a square mile; a minimum size was used to avoid the complex modifications by subsidence. Some smaller features undoubtedly also were caused by regional stress in the crust, but figure 53 probably shows the essentials of structure caused by regional stress.

In the central two-thirds of the mapped area, exposures of the Platteville Formation along the Galena River and Shullsburg Branch and abundant drill holes that bottomed in the upper part of the McGregor Member make it feasible to draw structure contours at the top of the McGregor Member of the Platteville Formation. This horizon is below most of the solution-thinned rocks, and structure contours of the top of the McGregor Member represent the best approximation of tectonic structure that can be made with available data. The McGregor Member is buried by 100 to 400 feet of younger rocks in the eastern and western parts of the mapped area, and few drill holes penetrate it. In these areas structure contours were drawn at the top of the cherty unit of the Galena Dolomite. The normal strati-

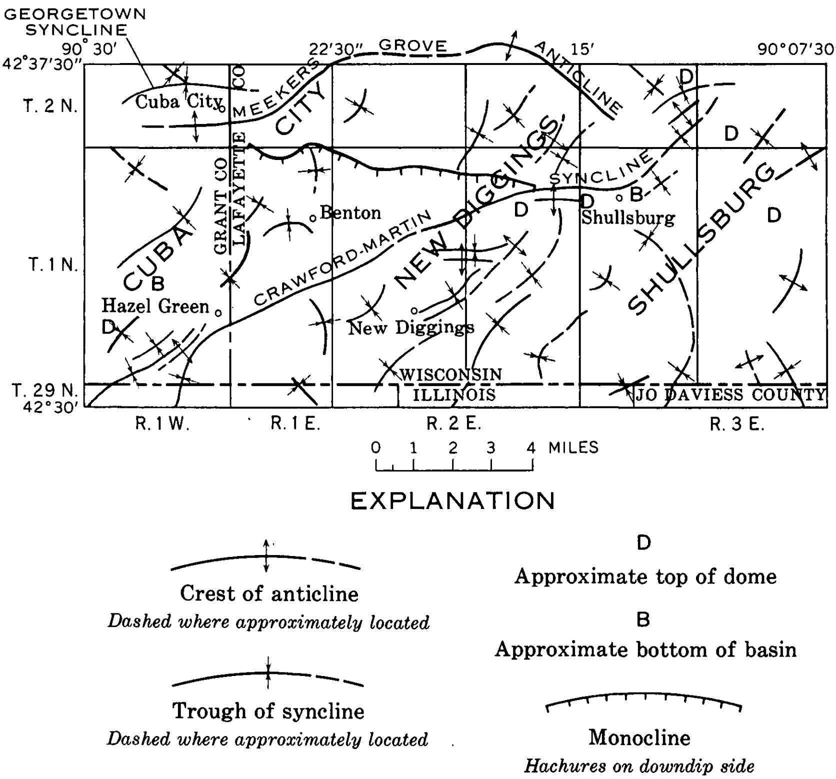

FIGURE 53.—Index map of Cuba City, New Diggings, and Shullsburg quadrangles showing major structural features. Poorly defined structural highs between some synclines omitted.

graphic interval between the top of the McGregor Member and the top of the cherty unit of the Galena Dolomite is about 150 feet, but thinning in this zone commonly totals 20 to 30 feet near sulfide mineral deposits. Whether or not such thinning has greatly modified tectonic structure in these parts of the mapped area is not known.

The Upper Mississippi Valley zinc-lead district is in a roughly rectangular area of uplifted but slightly deformed rocks outlined by the Wisconsin dome on the north, the Wisconsin arch on the east, the Savanna-Sabula anticline on the south, and the Forest City basin on the west. In general, the rocks in the district dip south-southwestward about 17 feet per mile, but this southward dip is interrupted locally by folds. The large folds in the district trend eastward and are 20 to 40 miles long, 3 to 6 miles wide, and 100 to 200 feet in amplitude. The small folds trend eastward, northeastward, and northwestward and are generally 1 to 5 miles long, ½ to 1 mile wide, and less than 60 feet in amplitude (Heyl and others, 1959, p. 27–35).

Geologic structure in the mapped area in general conforms to the district pattern. The dominant structural features are a southward regional dip that averages about 20 feet per mile and an eastward-trending anticline of about 130 feet local structural relief. Most small folds in the area trend northeastward, but a few trend eastward or northwestward. In addition to the folds and regional dip, other tectonic features are vertical joints and a few faults.

FOLDS

The fold of largest amplitude in the mapped area is an asymmetric anticline that extends from sec. 35, T. 2 N., R. 2 E., in the Shullsburg quadrangle to sec. 34, T. 2 N., R. 1 W., in the Cuba City quadrangle. Because the axis of the anticline bows northward, it is ⅓ to ½ mile north of most of the New Diggings quadrangle (fig. 53). Heyl and others (1959, p. 30) named this fold the Meekers Grove anticline.

In the New Diggings quadrangle, the axis of the Meekers Grove anticline trends southeastward and plunges southeastward from sec. 28, T. 2 N., R. 2 E.; in the Cuba City quadrangle it trends southwestward and plunges southwestward from sec. 21, T. 2 N., R. 1 E., to sec. 36, T. 2 N., R. 1 W. West of sec. 36 the axis of the anticline apparently dies out. The length of the fold as described is about 15 miles; however, the trend of the fold and local highs along the trend extend westward for 10 miles (Heyl and others, 1959, p. 30, fig. 13).

The Meekers Grove anticline is asymmetric, having a steeper northern limb. In the mapped area, the steeper limb is 1 to 2 miles wide from the axis of the anticline to the axis of the adjoining syncline and has an average dip of about 1.5°, although the dip is more than 4° in places. Just north of the New Diggings quadrangle, the steeper limb is about one-half mile wide and has an average dip of about 2° (Klemic and West, 1964). The south limb of the anticline is considered by the author to extend to the top of a poorly defined monocline that extends east-southeastward from Cuba City (fig. 53). This monocline is considered the boundary of the fold because it corresponds with a change in slope in contours based on aeromagnetic data (Dempsey and Kirby, 1958). The width of the south limb from the axis of the anticline to the top of the monocline ranges from less than 1 mile to about 3 miles. Dip along this part of the south limb averages about 35 feet per mile, or less than 0.5°. The monocline is $\frac{1}{8}$ to about 1 mile wide, and dips along it range from 1° to 4°.

Maximum structural relief of the Meekers Grove anticline is about 260 feet as measured from the crest of the anticline in sec. 24, T. 2 N., R. 1 E. (Klemic and West, 1964) to the trough of the syncline in sec. 25, T. 2 N., R. 1 E. Typical structural relief, as measured from the crest of the anticline to the trough of the syncline on the north side, is about 130 feet. The maximum closure on the anticline is about 110 feet, for the 950-foot contour does not close on the northeast side.

The cherty unit of the Galena Dolomite is bedrock over most of the Meekers Grove anticline. The noncherty unit of the Galena Dolomite crops out along the north, northwest, and northeast flanks, and a few remnants are near the crest of the anticline in the New Diggings quadrangle. Rocks of the Decorah, Platteville, and St. Peter Formations are exposed where the Galena River and its larger tributaries cross the anticline.

The syncline north of the Meekers Grove anticline is well defined only in the Cuba City quadrangle. In other places, the syncline contains irregular highs that interrupt the symmetry (Agnew, 1963, pl. 19; Klemic and West, 1964), and the syncline is more accurately described as a "synclinal trend." Heyl and others (1959, p. 30) named this trend the "Georgetown syncline."

In the Cuba City quadrangle, the Georgetown syncline is deepest near the boundary between secs. 25 and 26, T. 2 N., R. 1 W. East of this lowest part the axis of the syncline diverges about 45° from the steep flank of the Meekers Grove anticline instead of paralleling it. West of the central low the axis of the syncline bifurcates. One branch extends west-southwestward about 2 miles; the other branch, which is equally well formed, extends about 1 mile north of the mapped area (Agnew, 1963, pl. 19). Although some sulfide mineral deposits are in rocks folded along the Meekers Grove anticline and Georgetown syncline, these structural features apparently do not localize sulfide mineral deposits in the mapped area.

The Crawford-Martin syncline, named by Heyl and others (1959, pl. 5), trends northeastward from sec. 23, T. 29 N., R. 1 W., in Illinois, to sec. 30, T. 2 N., R. 3 E., in Wisconsin. In general, the northwest limb of this syncline is better formed and has more relief than the southeast limb. Maximum structural relief on the southeast limb is about 50 feet in the area northeast of Shullsburg and about 40 feet in the area east of Hazel Green; the relief is 10 to 30 feet in other places. Although the maximum structural relief is only 50 feet, the fold is about 15 miles long in the mapped area and it continues several miles southwestward (Bradbury, Grogan, and Cronk, 1956, pl. 1). The syncline is about one-fourth mile wide along the boundary between secs. 5 and 9, T. 1 N., R. 2 E.; upper limits on width are indefinite, because the north or northwest limb merges with the regional dip.

Several large mineral deposits and many small ones are near the trough of the Crawford-Martin syncline. Of the deposits in the syncline, the Crawford, Cleveland, Badger, and Martin each probably produced more than 500,000 tons of zinc ore (Heyl and others, 1959, p. 78–79). The best example of mineral deposits clearly localized along tectonic folds in the mapped area are the numerous small lead ore deposits along the Crawford-Martin syncline northeast of Shullsburg.

The Meekers Grove anticline and the Georgetown and Crawford-Martin synclines are the best-defined folds, in terms of length and structural relief, in the mapped area. Smaller or poorly defined folds consist of irregular domes and basins, and anticlines and synclines less than 5 miles long (pl. 25, fig. 53). Typical folds that extend more than 1 mile but less than 5 miles have about 20 feet of structural relief and are ⅓ to 1 mile wide. The axis of the folds are curved, and most folds plunge southwestward. Traces of well-defined synclines are about three times as abundant as well-defined anticlines. This predominance probably indicates that some synclines shown on figure 53 are due to or accentuated by solution thinning and subsidence and that anticlines separating synclines have been modified by the same process.

About three-fourths of the small folds trend northeastward, and only three trend eastward. This trend is considerably different from the dominant eastward trend of third-order folds (1 to 2 miles in length and 20 to 60 feet in amplitude) reported by Heyl and others (1959, p. 34–35 and figs. 19 and 20) for the Hazel Green-Shullsburg area. The difference in trends of folds shown on figure 53 from those shown by Heyl and others is mainly due to different interpretations of minor structures associated with east-trending ore deposits. In this report these minor structures are interpreted as having been caused by subsidence.

Some sulfide mineral deposits associated with fractures inclined to bedding are in the troughs of small synclines shown on figure 53. Similar deposits are on the crest of the anticline extending from sec. 26, T. 1 N., R. 1 E., to sec. 8, T. 1 N., R. 2. E., and several deposits are on the crests of domes that cover less than 1 square mile. These domes may be parts of anticlines that are modified by solution thinning. Mineral deposits associated with vertical joints are as abundant on anticlines and domes as in synclines and basins.

FAULTS

The author saw in the mapped area only one fault of more than 1 foot displacement that was interpreted as due to regional stress in the crust. Exposures of two other faults that are probably due to regional stress (Heyl and others, 1959, pl. 5) have been concealed by talus in the last 15 years.

The observed fault is the southwest one of the two shown in the NW¼ sec. 8, T. 1 N., R. 2 E. (pl. 25). In 1958 the evidence of faulting at this locality consisted of a small block of basal Galena Dolomite exposed in a caved shaft at about the same altitude as the base of the Ion Member of the Decorah Formation exposed in the cliff along Shullsburg Branch. These outcrops were about 25 feet apart, and the Galena was northeast and updip from the Ion. The fault surface was not exposed; however, northwestward-trending vertical joints and the lack of inclined joints indicated a probable northwestward trend and a vertical dip for the fault.

This fault and a parallel one about 300 feet northeast were first mapped by Heyl and others (1959, pl. 5). Their field notes show that five outcrops, now concealed, aided in determining the position and strike of these faults. The strike and location of these faults and the displacement of the northeast fault as shown on plate 25 are taken from their map.

Displacement is about 20 feet at the southwest fault and about 15 feet at the northeast one; the northeast block is displaced downward at each fault. A tectonic origin for the faults is indicated because the displacements are about double the average maximum displacements of faults in solution-thinned zones; and the fault planes are probably vertical, whereas fault planes in solution-thinned zones are generally inclined. The monocline that marks the south boundary of the Meekers Grove anticline is possibly offset by the faults as much as 600 feet horizontally. If horizontal movement is interpreted, the northeast side has moved northwestward relative to the southeast side. Heyl and others (1959, p. 39) report that the faults in sec. 8, T. 1 N., R. 2 E., are possibly shears, and horizontal movement would be expected. Several faults in the mining district have offset beds horizontally (Heyl and others, 1959, p. 35–39).

The author does not believe that the faults have an appreciable component of horizontal displacement. Vertical displacement in inclined beds could produce the structural pattern indicated by the contours.

Heyl and others (1959, pl. 5) show a vertical fault that displaces beds about 5 feet in the NE¼NW¼ sec. 33, T. 1 N., R. 1 E. This fault was concealed by talus in 1958, and the position and strike as shown on plate 25 were taken from their map. The displacement of the fault is within the general range of displacement due to solution thinning, but the rocks exposed along the river near the fault are not altered.

Heyl and others (1959, pl. 5) show a fault of about 20 feet displacement (based on drill-hole data) in the NW¼ sec. 29, T. 1 N., R. 1 E. This fault is not shown on plate 25 because surveys by the author indicate that the drill holes on which the fault is based were incorrectly surveyed by a mining company.

The steep flank of the Meekers Grove anticline is faulted in two places just north of the mapped area by high-angle reverse faults that dip southward (Heyl and others, 1959, p. 35, fig. 14, pl. 3). These faults have 20 to 30 feet of vertical displacement, but the horizontal displacement is not known. Probably similar faults along the steep flank of the anticline are concealed by soil cover in the mapped area.

F. T. Thwaites (1931) infers that a fault known from exposures in Green County, Wis., extends south-southwestward to near Shullsburg, Wis.; similar data are shown on a nunpublished map, compiled by Thwaites in 1957, on file at the office of the State Geologist in Madison, Wis. No evidence of this fault was found in the mapped area, but the northeast end of the Crawford-Martin syncline approximately coincides both in trend and location with the inferred extension. Heyl and others (1959, fig. 12) show the same fault in Green County; they do not infer a south-southwestward extension, but they show that the fault is north of an extension of the Meekers Grove anticline.

JOINTS

The Platteville, Decorah, and Galena Formations are cut by well-formed vertical joints throughout the mapped area and locally by inclined joints. The St. Peter Sandstone is locally well jointed by both vertical and inclined joints, but in about one-third of the exposures of St. Peter Sandstone no joints can be observed. The author believes that most vertical joints are formed by tectonic movement and that most inclined joints are formed by adjustment of rock over and near solution-thinned areas. The inclined joints in the St. Peter Sandstone are probably tectonic but do not continue into the overlying limestone and dolomite beds.

The strike and dip of all joints measured are shown on plate 25 by joint symbols. Diagrams of the general trends of vertical joints are shown in figures 54 and 55. The diagrams of the trend of vertical joints apparently show conjugate systems, but the type of stress to which the systems are related is not clearly defined. The conjugate system in the southern part of the area has one set of joints that strikes from N. 75° E. to S. 75° E. and another set that strikes from N. 5° W. to N. 15° E. (fig. 54). In this system, joints that trend nearly eastward are slightly more abundant than those that trend northward. The eastward-trending joints are generally more open, more conspicuous, and can be traced farther along strike than other joints. Eastward-trending joints locally bifurcate vertically and laterally and then join again to enclose irregular blocks of rock. Lead, zinc, and iron mineral deposits occur in both sets of joints but are more abundant and larger in the eastward-trending set.

The open space and larger and more abundant mineral deposits in the eastward-trending joints may be related to orientation of the tectonic forces. On the other hand, the open space and larger receptacles for mineral deposits along east-trending joints are possibly due to the

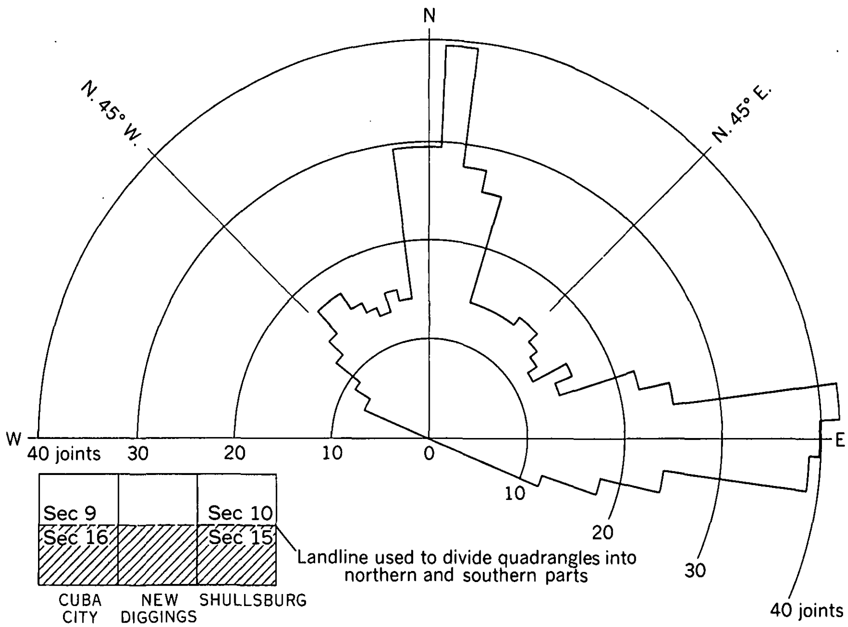

FIGURE 54.—Diagram showing strikes of 680 vertical joints in the southern part of Cuba City, New Diggings, and Shullsburg quadrangles. Each 5° segment represents the average of the number of joint readings in that segment and the adjacent segments.

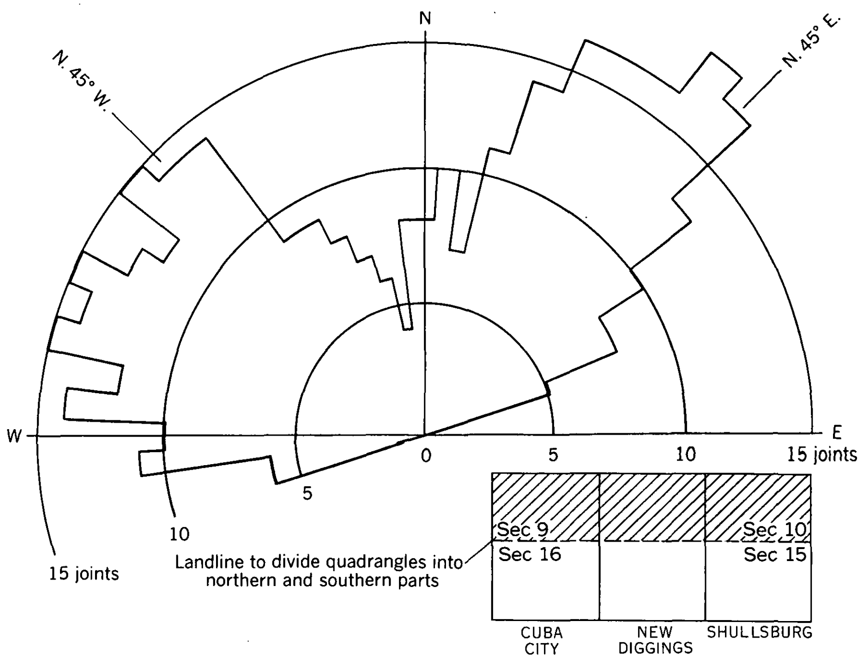

FIGURE 55.—Diagram showing strikes of 400 vertical joints in the northern part of Cuba City, New Diggings, and Shullsburg quadrangles. Each 5° segment represents the average of the number of joint readings in that segment and the adjacent segments.

fact that caves are more likely to form along joints parallel to the strike of beds than along joints not parallel to strike (Bretz, 1942, p. 759).

The conjugate system in the northern part of the mapped area has one set of joints that strikes between N. 15° E. and N. 60° E., and another set that strikes between N. 40° W. and S. 80° W. (fig. 55). In this system, lead, zinc, and iron minerals are more likely to occur along northwestward-trending joints than along northeastward-trending joints. Both sets of joints in this system are tighter fractures than the eastward-trending joints in the south part of the area.

ORIGIN AND AGE OF DEFORMATION

The type of stress that caused the tectonic structures in the mapped area was not determined. The conjugate joint system in the southern part of the area diverges by about 45° from the dominant northeastward-trend of the local folds; the system in the northern part diverges by about 45° from the eastward trend of the Meekers Grove anticline. The conjugate joint systems, therefore, may be interpreted as shear pairs. This interpretation of joints coupled with the asymmetric character of the folds can be used to support a lateral compressive theory. On the other hand, the joint pattern and the folds can also be interpreted as having been caused by vertical adjustments in the basement rocks. Heyl and others (1959, p. 56–60) favor lateral compressive forces to explain the structure in the mining district; Thwaites (1931, p. 735-736), Reynolds (1958, p. 150-152), and Allingham (1963, p. 209) favor vertical adjustments in the basement rocks.

The time of deformation within the quadrangles cannot be dated more closely than post-Early Silurian and pre-Quaternary. Heyl and others (1959, p. 54-56) believe that the principal deformation is related to the closing phase of the Appalachian orogeny during late Paleozoic time. Evidence to support or refute this age of deformation was not recognized by the author.

MINERAL DEPOSITS

The discussion of mineral deposits in this report has two objectives. The first is to give a short history of development and general information on the size, habit, mineralogy, and localization of the deposits. The general description incorporates some new data, but it does not repeat the details reported by Heyl and others (1959). The new data concern deposits in the upper part of the Platteville Formation that have been mainly developed since completion of fieldwork on which the report by Heyl and others is based.

The second objective is to present an interpretation that alteration of country rock, mainly solution of carbonate, was the chief agent in forming structures and ore receptacles in the largest deposits. The structures include synclines as expressed at certain stratigraphic zones, inclined fractures, bedding fractures, breccia zones, and contorted bedding. Most geologists who have studied the area have interpreted these structures as tectonic in origin and as the chief factors in the localization of some deposits.

Mineral resources of the quadrangles include zinc, lead, rock for road metal and agricultural lime, iron sulfide, and barite. Zinc is by far the most important; in southwest Wisconsin the value of zinc mined from 1949 to 1958 totaled about $25,767,000, whereas the value of lead totaled about $2,885,000 (Rand, 1959, table 6). More than two-thirds of the lead and zinc produced in southwest Wisconsin during these years came from mines within these three quadrangles. The value of rock quarried for road metal and agricultural lime is not known, but in normal years it probably would not exceed one-hundredth of the value of the zinc produced. Iron sulfide associated with lead and zinc deposits was recovered from zinc mining and milling operations and treated to make sulfuric acid from about 1899 to 1949, but it is not recovered in present operations. Small quantities of

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barite associated with lead and zinc deposits were produced from 1919 to 1930, but none has been produced since (Heyl and others, 1959, p. 80).

Plate 25 shows 142 named mines and numerous unnamed localities in the mapped area where lead or zinc minerals associated with vertical joints have been mined, but only the following mines produced ore from 1956 to 1959:

Mine [1]	Location			History of operation, 1956–59
	Sec.	T. N.	R.	
1. Kittoe	15	1	2 E.	Opened Aug. 1957.
2. North Hayden	22	1	2 E.	Operated continuously.
3. South Hayden	22	1	2 E.	Do.
4. North Gensler	27	1	2 E.	Do.
5. South Gensler	27	1	2 E.	Do.
6. Hancock	28	1	2 E.	Closed Sept. 1957; reopened Nov. 1959.
7. West Blackstone	28	1	2 E.	Closed Sept. 1957; reopened Nov. 1957.
8. James (Doyle-Harty shaft)	9	1	2 E.	Closed Apr. 1957.
9. Thompson	26	1	1 E.	Opened Sept. 1956; closed Sept. 1957; reopened Nov. 1959.
10. Temperly	27	1	1 E.	Do.
11. Teasdale	21	1	1 E.	Opened Nov. 1956; closed Sept. 1957.
12. Birkett	18	1	1 E.	Closed Aug. 1958; reopened July 1959.
13. New Birkett	18	1	1 E.	Do.
14. Jefferson	13	1	1 W.	Do.

[1] Mines 1–5, 6–7, 9–10, and 12–14 worked from central shafts or inclines.

Of the mines listed above, deposits in the Platteville Formation were available for study only in the first 10.

CLASSIFICATION OF THE DEPOSITS

Known lode mineral deposits in the mapped area contain virtually the same principal primary minerals—sphalerite, galena, marcasite, pyrite, calcite, and locally, barite. Most of the minerals were deposited in space formed directly or indirectly by solution of carbonate rock, although metasomatic replacement of wallrock occurred locally. For purposes of description, the lode deposits are classified as: (1) deposits associated with vertical joints, (2) deposits associated with inclined fractures and bedding-plane fractures, and (3) deposits that are not associated with obvious fracture control. Deposits associated with vertical or near-vertical joints occur mainly in the upper two-thirds of the Galena Dolomite and in the Quimbys Mill and McGregor Members of the Platteville Formation. The deposits in the Galena Dolomite are known as "gash veins" (Whitney, 1862, p. 225) and have been mined chiefly for the contained galena. Deposits in the Quimbys Mill and McGregor Members have been mined chiefly for the contained sphalerite. Deposits associated with inclined fractures and bedding-plane fractures are mainly in the Decorah Formation and lower one-third of the Galena Dolomite. These are known as "pitch-and-flat" deposits (Percival, 1855, p. 55); they are the largest mineral deposits in the area and are mined chiefly for the contained sphalerite. The origin of the inclined fractures and bedding fractures, as well as other structures associated with pitch-and-flat deposits, is discussed in some detail (p. 513–521).

Residual and placer deposits are abundant in the mapped area. These deposits contain mainly lead ore, and they formed in places where mineral-bearing rock was eroded.

HISTORY OF DEVELOPMENT

Lead ore in the Upper Mississippi Valley was known as early as 1658, and by 1690 French explorers established a temporary trading post near the present site of East Dubuque, Ill., to obtain lead ore from the Indians (Thwaites, 1895, p. 272). The earliest systematic mining and smelting of lead ore started about 1790 near the present site of Dubuque, Iowa, and was done by Indians under the supervision of Julien Dubuque. White miners who settled near White Hill (formerly called Gratiot's Grove) just south of the present town of Shullsburg, Wis., in 1819 were apparently the first permanent American settlers in the area (Bain, 1906, p. 3). Discovery of rich galena deposits led to the settlement of Hazel Green and New Diggings in 1824. Meeker (1872, p. 272) reported most of the important lead-producing areas were discovered by 1830. From 1830 to 1871 the amount of lead produced in the Upper Mississippi Valley district exceeded that produced in any other district in the United States (Winslow, 1894, p. 254).

The first miners were interested only in galena, which occurred mainly in gash veins and in residual deposits where galena-bearing rock had been weathered. Gash veins locally also contain smithsonite and sphalerite, which at first were considered a nuisance by miners. By 1859, however, technological improvements in smelting zinc ore made it profitable for miners to save the smithsonite mixed with the galena as well as to develop deposits that contained mainly smithsonite. Some smithsonite deposits resutled from oxidation of sphalerite in gash veins, but most resulted from oxidation of sphalerite in pitch-and-flat deposits stratigraphically below the gash veins. By 1867, zinc-smelting methods had been improved so much that miners could also profitably mine sphalerite in pitch-and-flat deposits, which are considerably larger than gash veins. Systematic mining of joint-controlled deposits in the Platteville Formation, which are stratigraphically below pitch-and-flat deposits, started during World

War II. The deposits in the Platteville Formation contain mainly zinc ore and are smaller than pitch-and-flat deposits.

In recent years, 80 to 90 percent of the ore produced has been from pitch-and-flat deposits, 10 to 20 percent from joint-controlled deposits in the Platteville Formation, and very little from gash veins.

Agnew (1956) reports that in 1873 the amount of zinc produced in the district first equaled the amount of lead; from 1873 to 1893 the amounts were roughly the same, and since 1893 the ratio of zinc to lead produced has ranged from 5:1 to 20:1. Most of the lead produced in the district today is a byproduct of zinc mining.

PRODUCTION

The quantity and approximate grade of ore recovered from mines in southwestern Wisconsin from 1949 through 1958 is shown in table 1. All the 1958 production shown in table 1 was from the mapped area, and from 1949 to 1957 mining in the mapped area produced 75 to 90 percent of the total. None of the mines in Illinois shown on plate 25 produced ore during this period. The decline in the amount of ore produced in 1957 and 1958 reflects a decline in the value of zinc and not a depletion of known mineral deposits.

TABLE 1.—*Production of lead and zinc ore, metals recovered, and appoximate grade of ore produced in southwestern Wisconsin, 1949–1958*

[Data adapted from Rand (1959, table 6)]

Year	Total ore treated (short tons)	Metallic lead recovered (short tons)	Recoverable lead (percent)	Metallic zinc recovered (short tons)	Recoverable zinc (percent)	Probable metallic content of ore [1]	
						Lead	Zinc
1949–53 (average per year)	430, 272	1, 375	0. 32	12, 838	2. 99	0. 38	3. 52
1954	563, 554	1, 261	. 22	15, 534	2. 75	. 25	3. 23
1955	615, 562	1, 948	. 31	18, 326	2. 97	. 36	3. 49
1956	967, 925	2, 582	. 26	23, 890	2. 46	. 30	2. 89
1957	727, 842	1, 900	. 26	21, 575	2. 96	. 30	3. 48
1958	468, 822	800	. 17	12, 140	2. 58	. 20	3. 03
Total or average	5, 495, 065	15, 366	0. 28	155, 655	2. 83	0. 33	3. 33

[1] After allowing for milling and smelting loss (total loss 15 percent).

LEAD

Heyl and others (1959, table 1) report that 832,365 short tons of metallic lead was produced from Upper Mississippi Valley ores from 1800 to 1954. The author estimates that about one-third of this total came from the mapped area, and total metallic lead produced from the mapped area through 1958 is therefore about 285,000 short tons. Probably at least 80 percent of this total, or about 228,000 tons, was produced during the 19th century. Peak lead production in the Upper Mississippi Valley district was 27,248 tons in 1845, and more than

10,000 tons was produced each year from 1836 to 1863. Peak production in the 20th century was 5,946 tons of metallic lead in 1918.

There is no valid method of determining the average grade of lead ore produced from the mapped area. Most lead ore produced in the 19th century was galena that was either hand cobbed from gash veins or washed from residual deposits of galena. Few individual gash veins contained more than 2,000 tons of galena, but areas such as Hazel Green, New Diggings, Shullsburg, and Benton, where gash veins were numerous, produced several tens of thousands of tons of galena from veins and residual deposits (Chamberlin, 1882, pl. 10).

Most of the lead produced in the 20th century is a byproduct obtained from mining zinc ore which averages about 0.33 percent contained lead (table 1).

ZINC

Heyl and others (1959, table 2) report that from 1859 to 1952 the Upper Mississippi Valley district produced 44,331,543 short tons of zinc ore that yielded 1,209,965 short tons of metallic zinc. These figures, however, should not be used to compute an average grade of ore produced. A considerable amount of zinc minerals and metallic zinc was lost by the milling and smelting processes in use before 1930. The author estimates that about 60 percent of the total, or about 730,000 short tons of metallic zinc, was produced from the mapped area. From 1953 through 1958, about 88,000 short tons of zinc was produced from the mapped area; hence the total production through 1958 is about 820,000 short tons of metallic zinc.

Peak zinc production in the Upper Mississippi Valley district was 64,027 tons in 1917; only in 1916, 1917, and 1918 has the district produced more than 50,000 tons a year.

The following tabulation of ore produced from 258 zinc-ore deposits or groups of related deposits in the Upper Mississippi Valley district through 1952 is based on data given by Heyl and others (1959, p. 77–79, 175–295):

Deposits or groups of closely related deposits	*Approximate range in size according to tons of ore produced*	*Approximate percent of total ore produced from deposits in district*
12	More than 1,000,000	44
14	500,000–999,999	18
64	100,000–499,999	29
168	1,000–99,999	9

The tabulation approximates a frequency distribution of size of pitch-and-flat deposits. However, factors such as changes in the value of zinc, grade and location of deposit, and method of mining prohibit a direct correlation between tonnage produced and size.

In similar tabulation by size, the name and location of zinc mines in the mapped area that produced more than 100,000 tons of ore are listed below. Except where noted, the mines produced ore mainly from pitch-and-flat deposits. The tabulation is based mainly on data from Heyl and others (1959, p. 77–79, 184–241), but it includes production through 1958.

Probably more than 90 percent of the zinc ore produced from the mapped area came from the 56 mines listed below. The James deposit (secs. 8, 9, 16, and 17, T. 7 N., R. 2 E.) was the largest in the mapped area. It produced more than 3 million tons of ore that averaged from 6 to 8 percent contained zinc and 0.5 to 1 percent contained lead (Heyl and others, 1959, p. 220–221). The deposits or groups of related deposits from each of the following mines probably produced more than 1 million tons of zinc-lead ore.

Mine	*Location*		
	Sec(s).	*T. N.*	*R. E.*
1. Champion	26, 27	1	1
2. Frontier-Calvert-Treganza	8	1	1
3. James	8, 9, 16, 17	1	2
4. Kennedy	29	1	1
5. North Gensler	21, 22, 27	1	2

The deposits or groups of related deposits from each of the following mines probably produced between 500,000 and 1,000,000 tons of ore. Asterisk (*) indicates at least half the or eproduced was associated with vertical joints.

Mine	*Location*		
	Sec(s).	*T. N.*	*R.*
1. Badger	30	1	1 E.
2. Bull Moose-Middie	8	1	1 E.
3. Copeland	15, 16	1	2 E.
4. Crawford	25	1	1 W.
5. Crawhall-Thompson	30	1	2 E.
6. Federal	32	1	1 E.
7. Fox*	21, 28	1	1 E.
8. Hoskins	13	1	1 E.
9. Kittoe*	15	1	2 E.
10. Martin	16	1	1 E.
11. Monroe-Longhorn-Little Joe	25	1	1 E.
12. North Hayden	22	1	2 E.
13. Old Winskell	19	1	2 E.
14. Penna-Benton	24	1	1 E.
15. South Hayden	22	1	2 E.

The deposits or groups of related deposits from each of the following mines probably produced between 100,000 and 500,000 tons of ore. Asterisk (*) indicates at least half the ore produced was associated with vertical joints.

Mine	Location Sec(s).	T. N.	R.
1. Andrews	20	1	2 E.
2. Birkett	18	1	1 E.
3. Drum	14	1	1 E.
4. Blackstone	26	1	1 E.
5. East Blackstone and West Blackstone combined	28	1	2 E.
6. Booty	19	1	2 E.
7. Byrnes	19	1	1 E.
8. Cleveland	30	1	1 E.
9. Coughlin	4	1	2 E.
10. Empress	13	1	1 E.
11. Helena	7	1	2 E.
12. Hancock*	28	1	2 E.
13. Indian Mound	24	1	1 E.
14. Jefferson	13	1	1 W.
15. Kittoe	17	1	1 E.
16. Lawrence	30	1	1 E.
17. Lucky Hit	33	2	2 E.
18. Lucky Twelve	24	1	1 E.
19. Meloy (Fields)	13, 14	1	1 E.
20. Monmouth-North Monmouth	19	1	1 E.
21. Mulcahy	20	1	2 E.
22. New Ida-Blende	15	1	1 E.
23. New Mullen	17	1	2 E.
24. Nightingale	14	1	1 E.
25. North Unity	16	29	1 E.
26. Northwestern	22	29	1 E.
27. Ida-Blende	15, 16	1	1 E.
28. Ollie Bell	22	1	1 E.
29. Pittsburg-Benton-Etna	2	1	1 E.
30. Rodham*	25	2	2 E.
31. Sally Waters	23	1	1 E.
32. South Gensler	27	1	2 E.
33. South Unity-Hughlett-Gray	21	29	1 E.
34. Trewartha	20	1	1 E.
35. Wilkinson	32	2	1 E.
36. Wipet	17, 18	1	2 E.

Table 1 shows that zinc ore produced in recent years averages about 3.33 percent contained-zinc. Ore produced during and before World War II commonly averaged more than 6 percent contained zinc (Heyl and others, 1959, p. 186–241). The difference in grade of ore probably is due entirely to mining methods. A large part of the zinc ore is along inclined fractures or along roughly horizontal zones not more than 7 feet high. During and before World War II, the general mining practice was to remove ore along the inclined fractures through inclined stopes and to keep drifts less than 7 feet high. Since World

War II, most mining has been done by heavy machinery that requires a modified room-and-pillar mining plan and drifts about 10 feet high. This method produces diluted ore as compared to previous methods.

MINERALOGY

All lode deposits contain about the same principal primary minerals, but the relative amounts of each depend on factors such as composition of host rock and type of occurrence. Sphalerite and galena are the chief primary ore minerals; marcasite, pyrite, calcite, and, locally, barite are the chief primary gangue minerals in the mapped area. Primary minerals reported in small quantities in some deposits are dolomite, quartz (cryptocrystalline), wurtzite, millerite, chalcopyrite, and cobaltite (Heyl and others, 1959, p. 84–88). In addition, large quantities of limestone country rock near some mineral deposits have been replaced by dolomite and, locally, silica.

Primary minerals in deposits above the water table alter to secondary oxides and carbonates, principally limonite and smithsonite. Crusts of cerussite form on galena, but in the limestone and dolomite country-rock environment galena remains more or less stable.

A brief summary of the occurrence of the principal primary ore and gangue minerals in mineral deposits is given below. The reader is referred to Heyl and others (1959, p. 83–108) for information on minor minerals present, zoning, paragenesis, and trace elements associated with deposits in the Upper Mississippi Valley district.

Small crystals of marcasite, pyrite, calcite, sphalerite, and galena are sparsely disseminated in all rocks in the mapped area; crystals of sphalerite or galena are common in outcrops far from known mineral deposits. Because the minerals are so widely distributed, the occurrences described below are restricted to places where introduced sulfide minerals form ore deposits.

Sphalerite is deposited as: (1) veins that fill fractures, (2) veins along bedding opened by solution, (3) impregnations and replacements of country rock, and (4) crystals or aggregates of crystals disseminated in altered rock. Most sphalerite is dark reddish brown, but some is light brown, yellow, or purple. Sphalerite in veins generally forms fibrous layers where crystals are elongate at right angles to the surface of the layer.

Galena is deposited as: (1) crystals that line vugs and openings, (2) mutual intergrowths with sphalerite, (3) disseminated crystals in country rock, (4) well-formed crystals embedded in marcasite, calcite, and barite, and (5) veins that range from a film to several inches in thickness. Most galena forms cubes, but octahedral crystals or octahedral faces on cubes are common. Galena in this district contains only traces of silver.

Pyrite is present in all unoxidized deposits and occurs in several forms. All veins of other minerals are separated from the wallrock by films or impregnations of pyrite. Pyrite also occurs in irregular layers of anhedral cubic and octahedral crystals that range from a speck to about 1 inch in size, in reniform masses as much as 1 foot in diameter that are composed of radiating attentuated cubic crystals, and in small euhedral cubic crystals disseminated in other minerals and country rock.

Marcasite occurs in most unoxidized deposits and is in two main forms. One is grayish green, soft, cryptocrystalline, and occurs in veins and irregularly shaped masses; this type of marcasite is locally called "sooty marcasite." The other is crystalline and has a metallic luster; it occurs in veinlets, disseminated crystals, and irregular masses of crystals as much as 6 inches in diameter. Complexly twinned crystals of marcasite are commonly associated with cockscomb-type crystals. Marcasite that has a metallic luster is resistant to oxidation, whereas grayish-green soft marcasite oxidizes readily.

Barite occurs in irregular tabular masses that parallel bedding, in amorphous and fibrous masses, and in veins. It is a common to abundant mineral in some deposits but entirely absent in others. In general, barite is present in deposits near Shullsburg and Lead Mine but absent in deposits near Hazel Green and New Diggings. Most barite in mines that operated from 1956 to 1959 was disemminated in, or formed tabular masses parallel to bedding in altered rocks of the Quimbys Mill Member of the Platteville Formation. The most abundant barite observed during this study was in the West Blackstone mine where white fibrous barite in veins as much as 6 inches thick and 2 to 8 inches apart parallel bedding in the Quimbys Mill through a zone about 6 feet thick. This zone was exposed for about 100 feet along a haulage drift. Blocks of Galena Dolomite that contain barite are common on some mine dumps in the south tier of sections in T. 2 N., Rs. 1 and 2 E. Heyl and others (1959, p. 93) and Agnew, Flint, and Crumpton (1954) report that barite in these mines fills central parts of veins or forms two parallel layers separated by calcite in the central part of veins.

Calcite is generally the most abundant gangue mineral. The central part of veins and vugs that contains sulfide minerals is usually lined with calcite, and many fractures and vugs that do not contain sulfide minerals are lined with calcite. In addition, crystals and masses of calcite are locally disemminated in country rock. Most calcite forms euhedral rhombohedrons and scalenohedrons that range from ¼ inch to more than 1 foot in length. Calcite crystals have the same form and are approximately the same size in a given vein or vug, but the form and size generally differ from vein to vein. Crystals of calcite that show scalenohedron or rhombohedron overgrowths of calcite are common.

Four stages of calcite that are distinguished by crystal habit, color, marcasite or pyrite inclusions, and transparency occur in most ore deposits. The first three stages are scalenohedral in habit, and from first to third stages they become progressively less colored, less cloudy, and contain fewer inclusions. The fourth stage is colorless and transparent, and only locally contains small specks of iron sulfide.

The general sequence of deposition of principal ore and gangue minerals and the sequence of silicification, dolomitization, and solution of carbonate rock that accompanied deposition of ore and gangue minerals are shown in figure 56. No specimens that showed evidence of early barite were observed in mines that operated from 1956 to 1959.

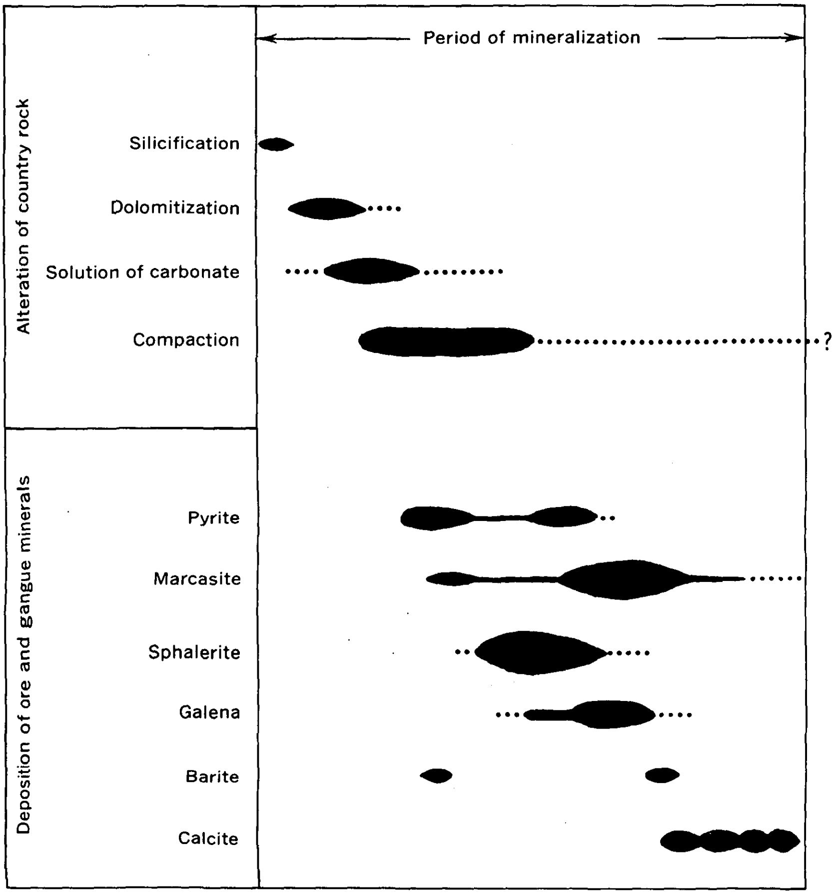

FIGURE 56.—Diagram showing sequence of rock alteration and deposition of principal primary minerals. Position of early barite and indications that it was dissolved. From Heyl and others (1959, p. 99, fig. 58).

ROCK ALTERATION

GENERAL EFFECTS OF ALTERATION

Country rock near mineral deposits in the Upper Mississippi Valley zinc-lead district is commonly altered by the direct effect of chemical action of the mineralizing fluids and an indirect effect of gravity where the physical stability of the rocks was upset by the chemical action. The susceptibility to alteration and the stratigraphic position of altered rock are interpreted as the major controls in forming ore receptacles and structures in mineral deposits. The subdivision of alteration into direct and indirect effects is a necessary corollary to the interpretation of the origin of some structures in pitch-and-flat deposits (p. 513–521).

Dissolving of carbonate rock is the most common of the three types of direct alteration and, in individual deposits, it is the most extensive. It is also most important economically because much of the ore fills spaces caused directly or indirectly by solution of carbonate. Dolomitization is the next most common type and silicification is least common. Cryptocrystalline quartz is the first mineral introduced into country rock, and the silicified rock apparently is not later dissolved or dolomitized. The dissolving and dolomitizing stages are not mutually exclusive; many beds that were originally limestone show effects of both solution and dolomitization. The author interprets most direct alteration as caused by mineralizing fluids, but in some places altered rocks do not contain sulfide minerals. West and Klemic (1961) attribute most of the solution of carbonate to action of ground water.

Composition, bedding, and fracturing of stratigraphic units are the apparent controls of intensity and extent of direct alteration. All or only part of the carbonate rock may be dissolved, but many limestone beds were reduced to argillaceous insoluble residue where superjacent and subjacent beds of dolomite had only intergranular cement removed. Commonly, abundant carbonate was dissolved from thin-bedded units and from highly fractured beds, but relatively small amounts of carbonate was dissolved from thick-bedded units and from unfractured beds. In plan, thin-bedded limestone units had considerable amounts of carbonate disssolved in, and from a few feet to a couple of hundred feet beyond, areas where sulphide minerals are found. Only minor amounts of carbonate, mainly along fractures, were removed from thick-bedded dolomite. The intensity also differs among mineral deposits, probably because of local changes in amounts of mineralizing fluids, fracturing, and stratigraphy.

Gravity enters into alteration as the gravitational stresses previously supported by the dissolved or weakened rock are transmitted to adjacent rock. This transfer of stress causes subsidence, compaction, brecciation, and fracturing in and near the leached rock. Stratigraphic units that are compacted are thinner than normal unaltered sections. This thinning, commonly referred to as "solution thinning," can be used as rough quantitative measurements of the amount and pattern of solution related to mineral deposits. In detail, however, the amount of solution thinning is related to features other than the removal of carbonate. For example, a moderately leached limestone bed 6 inches thick typically has the top and bottom inch reduced to insoluble residue that is succeeded inward by partly leached dolomitic limestone and a center zone of unleached rock 2 inches thick. A moderately leached dolomite bed 6 inches thick typically has most of its intergranular cement removed, but no dolomite grains dissolved and a rigid, porous, framework is left. The altered limestone is compacted to limestone and shale about 4 inches thick, whereas the altered dolomite is not compacted.

In addition to the type of rock, the extent of leached rock and character of overlying rock govern some effects of gravity. Narrow leached zones overlain by strong rock are unlikely to be affected by gravity, whereas broad leached zones are compacted and brecciated by the sagging or collapse of overlying rocks. This effect is analogous to mining problems: the back of a long narrow drift is less likely to collapse than the back of a circular stope that has the same area as the drift.

EFFECTS OF ALTERATION ON STRATIGRAPHIC UNITS

GUTTENBERG LIMESTONE MEMBER OF DECORAH FORMATION

The Guttenberg Limestone Member of the Decorah Formation consists mainly of thin-bedded limestone; it is altered in all pitch-and-flat deposits,[3] above all known joint-controlled deposits in the upper part of the Platteville Formation and under some gash veins. The results are (1) wavy beds of limestone and dolomitized limestone separated by thin dark-brown clay partings of insoluble argillaceous material in slightly altered rock, (2) nodular beds of dolomite separated by 2 to 3 inches of dark-brown clay in moderately altered rock, and (3) dark-brown insoluble argillaceous material in completely altered rock. In most ore deposits the bulk of the Guttenberg Member is moderately altered, but completely altered rock is common. Because altered rocks in the Guttenberg generally form a zone that is wide relative to length, the altered Guttenberg rocks are compacted by the overlying rock. Where all carbonate was removed, the insoluble residue is compacted

[3] Heyl and others (1959, p. 118, 120, 214) report that the Guttenberg Member is not thinned appreciably at the Trego mine near Platteville, Wis., the Hoskins mine (sec. 13, T. 1 N., R. 1 E.), and the Federal mine (sec. 32, T. 1 N., R. 1 E.). This contention is not supported by their field notes and drill-hole logs, which show the Guttenberg to be thinned more than 6 feet in many places in these deposits.

to a dark-brown shale; where about half of the carbonate was removed, the remaining carbonate forms nodules in a matrix of fissile earthy clay; where about a third of the carbonate was removed, the remaining carbonate rocks generally form thin nodular layers that locally were brecciated by compaction. The breccia consists of irregular tabular blocks more or less oriented to the bedding. Individual breccia blocks average about 6 inches in length, 3 inches in width, and 1 inch in thickness. Typically, the normal 12 to 14 feet of Guttenberg is thinned to about 6 feet in pitch-and-flat deposits, and locally it is thinned to as few as 2 feet. These figures represent an average thinning of about 60 percent and a maximum thinning of 85 percent.

Dolomitized rock in the Guttenberg Member retains color and bedding characteristics of the original limestone but has a sugary texture in contrast to the smooth texture of the limestone. Heyl and others (1959, p. 105–214) report that the Guttenberg in the Hoskins and Federal mines is silicified. The original color, texture, and bedding characteristics are preserved in the silicified limestone, and the only megascopic difference between silicified rock and unaltered rock is the hardness. Heyl and others (1959, fig. 66) have shown that the dolomitized and silicified rocks form sharply defined halos around pitch-and-flat deposits.

The compacted insoluble residue in the Guttenberg Member will burn. Bain (1906, p. 25–26) reported that one sample of shale composed of this residue gave 57.46 volumes of gas per volume of rock when heated to a red heat in a vacuum. Gas analysis showed more than 50 percent hydrocarbons and about 7 percent H_2S.

Ore receptacles in the Guttenberg Member consists mainly of spaces in breccia, tiny fractures in the unaltered central part of limestone and dolomite beds, and sparse narrow openings between beds.

QUIMBYS MILL MEMBER OF PLATTEVILLE FORMATION

The Quimbys Mill Member of the Platteville Formation is altered where it contains mineral deposits associated with vertical joints, where it contains or underlies pitch-and-flat deposits, and below some gash veins. Effects of alteration on the Quimbys Mill Member are similar but generally not as intense as in the overlying Guttenberg Member because the Quimbys Mill contains fewer bedding partings than the Guttenberg Member. Where all carbonate is removed the insoluble residue is commonly compacted to a petroliferous brown shale; where only part of the carbonate is removed, the Quimbys Mill is compacted either to irregular wavy to nodular beds of carbonate rock in dark shale or to a breccia consisting of irregular tabular blocks oriented with the general bedding. The breccia blocks average about the size of building bricks; they are slightly larger than blocks in similar breccia in the overlying Guttenberg Member. Limestone is more common near the base of the Quimbys Mill, and the effects of solution of carbonate are more pronounced there. The grayish-brown shale that separates the Quimbys Mill from the underlying McGregor Member is usually 1 to 2 inches thick in unaltered Quimbys Mill; but alteration of limestone and subsequent compaction of the insoluble argillaceous material increases the thickness of the shale to 8 to 15 inches near ore deposits. In a few places solution thinning reduced the thickness of the Quimbys Mill by 80 percent, but a 30-percent reduction in thickness is more typical.

In addition to the solution breccia, unaltered Quimbys Mill rocks are brecciated in some pitch-and-flat deposits. This breccia is generally adjacent to or below dissolved rock and probably occurs where rock fails to support the added stress at the foot of a pressure arch formed over a void or weakened rock.

Near zinc-lead ore deposits most of the carbonate in the Quimbys Mill is dolomite, some of it limestone that was dolomitized by the ore-bearing solutions; other dolomite is related to a regional facies change. It is not possible by field methods to separate the introduced dolomite from the facies dolomite. Sugary texture and treatment with dilute HCl show, however, that the limestone is commonly dolomitized near mineralized joints. The granular texture of dolomite near ore deposits, which contrasts strongly with smooth-textured unaltered dolomite and limestone, is mainly due to an emphasis of fine granularity through intergranular corrosion by mineralizing solutions.

Silicified Quimbys Mill rocks were observed at the dump of the Lucky Hit mine (sec. 33, T. 2 N., R. 2 E.) and Hofer mine (sec. 4, T. 1 N., R. 2 E.). The original texture and color are preserved exactly in the silicified rocks, and the only megascopic difference from unaltered rock is the hardness. Heyl and others (1959, p. 105, 214) report that the Quimbys Mill is silicified at the Federal and Hoskins mines.

Ore receptacles in the Quimbys Mill Member consist of open space in breccia, fractures in partly altered beds, and, where the altered zone is less than 15 feet wide, caves and spaces between beds. These caves and spaces between beds are mainly in the lower, more calcareous part of the Quimbys Mill; the spaces remained open because overlying dolomite beds were relatively unaltered and did not subside.

MCGREGOR LIMESTONE MEMBER OF PLATTEVILLE FORMATION

The effects of alteration in the McGregor Limestone Member of the Platteville Formation have been studied in cuttings from only a few drill holes and from exposures of the top part of the McGregor in mine workings. In all mines examined by the author, the upper part of the McGregor consists of thickly interbedded limestone, limy dolomite, and dolomite. These beds are altered where the McGregor contains mineral deposits associated with vertical joints, and are locally altered under pitch-and-flat deposits. Where beds are altered, much of the limestone is dissolved, and some intergranular cement is removed from dolomite. Locally the insoluble residue is compacted to gray shale, but the altered beds in the McGregor do not form the wavy and nodular beds observed in the overlying Quimbys Mill and Guttenberg Members. The contact of unmineralized and apparently unaltered McGregor and the Quimbys Mill Member locally shows irregular folds as much as 5 feet in amplitude and 200 feet wide under some pitch-and-flat deposits. These irregular folds probably reflect compaction of altered rocks in the lower and unobserved part of the McGregor. Similar but smaller folds occur at this contact in places where the Quimbys Mill and McGregor Members contain deposits associated with vertical joints.

Percy Crosby (1954, unpub. notes, U.S. Geol. Survey files, Beltsville, Md.) determined that the magnesium content of a limestone bed at the top of the McGregor increased sharply at boundaries of the South Hayden and North Gensler mines as compared to practically unmineralized ground between the mines. Undoubtedly, much of the dolomite in the McGregor in and near mineral deposits is related to mineralizing fluids, but it is difficult to determine exactly which dolomite is related to mineralizing fluids and which to facies change.

Most prospect holes drilled in the 1950's stopped at the top of the McGregor Member, but where the upper part of the McGregor was strongly mineralized, the holes continued through the mineralized zone. About 30 holes were drilled through the McGregor in sec. 9, T. 1 N., R. 2 E. These holes showed that the normal 30 feet of McGregor was locally thinned as much as 18 feet and that the average thinning was 12 feet. The drill holes in sec. 9 furnish excellent data of the amount of carbonate dissolved in some mineral deposits. In adjacent unmineralized areas the combined thickness of unaltered McGregor, Quimbys Mill, and Guttenberg Members is about 58 feet, but in the 30 holes that penetrated the McGregor, the combined thickness of these members averaged 31 feet.

Ore receptacles formed by solution of carbonate in the McGregor Member are mainly pore space in altered dolomite and in brecciated zones. The breccia in the McGregor is mainly unaltered crushed rock adjacent to or below leached rock. Solution breccia and space left where beds sagged are scarce in the McGregor Member.

ION DOLOMITE MEMBER OF DECORAH FORMATION

The Ion Member of the Decorah Formation is altered in pitch-and-flat deposits but, compared to the more calcareous underlying rocks, is only slightly altered. The Ion comprises thick-bedded dolomite that contains abundant greenish-gray clay blebs, scattered thin beds of greenish-gray shale, and limestone in the basal few feet. Typically, mineralizing fluids changed the shale and clay from greenish gray to brown, dissolved part of the limestone, and removed part of the intergranular cement in the dolomite. In a few pitch-and-flat deposits, most intergranular cement was removed and some dolomite grains were dissolved. This alteration produced an extremely porous rock that is honeycombed with irregular voids.

In most places the altered rocks in the Ion Member are not compacted, but locally the extremely vuggy rock collapses and forms solution breccia. Horizontally oriented, irregular tabular open spaces form between the overlying unaltered bed and breccias that are compacted by their own weight. Where the porous rock is compacted by overlying rocks, the thickness of the Ion is reduced to about 15 feet. As a general rule, however, the thickness of the Ion is increased in pitch-and-flat deposits. For example, 50 randomly selected drill holes through the Ion in the South Gensler mine showed that the Ion averaged 23 feet in thickness, or about 3 feet more than the Ion not in or near ore deposits. The increase in thickness is caused by slight offset and repetition of beds along inclined fractures and by sagging and pulling apart of beds.

The Ion Member is probably locally dolomitized by the mineralizing fluids, but differentiating dolomite related to mineralizing fluids from dolomite related to regional facies change is not possible by ordinary field methods. Coarse grains of moderate orange-pink dolomite occur in many vugs in altered Ion, but no bed observed by the author was replaced by similar dolomite. No silicified Ion rocks were observed by the author, but Heyl and others (1959, p. 105) indicate that the walls of inclined fractures in the Ion are locally silicified.

Open zones along bedding, fractures, and vuggy and porous zones in dolomite form most of the ore receptacles in the Ion Member. Many of the fractures are steplike and are interpreted as forming where beds in the Ion Member sag into space caused by removal of carbonate in underlying beds.

GALENA DOLOMITE

The Galena Dolomite consists of thick-bedded medium-grained dolomite that contains chert nodules in the lower one-half of the formation and sparse green clay blebs in the lowest 10 feet. The degree of alteration in the Galena near ore deposits ranges from removal of minor amounts of intergranular cement to total removal of rock to form caves along joints. The intermediate stage of alteration produces solution breccias composed of soft porous masses of dolomite crystals that contain irregular cavities as much as 1 inch across. Locally, altered Galena contains films of dark-brown clay that is similar to the insoluble argillaceous material in the Guttenberg and Quimbys Mill Members. In some deposits the greenish-gray clay near the base is altered to dark brown, and the chert nodules are locally selectively mineralized with specks of iron sulfide.

Typical solution thinning in the Galena Dolomite reduced the thickness less than 10 feet, although locally it is thinned as much as 32 feet; the maximum thinning is about 15 percent and the average thinning is less than 5 percent. The amounts of thinning listed are based on drill-hole data; actual amounts of carbonate removed are probably slightly greater, for open space is common in Galena Dolomite in ore deposits. The areal pattern of thinning of Galena in mineralized areas is erratic; isopach maps of the Galena in these areas show isolated patches of thinned rock.

Thinning in the Galena probably represents cumulative slight thinning in many beds, for only films of insoluble residue along bedding planes are known in the Galena. On the other hand, the lack of appreciable concentrations of insoluble material may reflect the lack of insoluble material in normal Galena Dolomite.

Voids directly attributed to solution of carbonate in the Galena Dolomite consist of pore space and irregular cavities in porous dolomite and caves along joints. The spaces are protected from closure because they have relatively little surface area and overlying unaltered Galena beds are strong enough to form roofs. Voids interpreted as indirectly due to solution of carbonate consist of horizontally oriented tabular open spaces above solution breccia that collapses of its own weight and space along stairlike fractures that formed where Galena rocks subsided into underlying altered rocks. Both types of voids serve as receptacles for minerals.

DESCRIPTION OF THE DEPOSITS

DEPOSITS ASSOCIATED WITH VERTICAL JOINTS

GALENA DOLOMITE (GASH VEINS)

The original use of "gash veins" in this district was not restricted to deposits in the Galena Dolomite. Whitney (1862, p. 225) defined gash veins as stratigraphically controlled veins, in contrast to fissure veins which filled fractures that crossed more than one formation and were not restricted to the intersection of a fracture with specific

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beds. Whitney probably would have called some deposits in the Platteville Formation "gash veins" also. Most literature on the Upper Mississippi Valley zinc-lead district, however, restricts the term "gash vein" to joint-controlled deposits in the Galena Dolomite, the usage followed in this report.

No ore was produced from gash veins in the mapped area from 1956 to 1959. The following discussion is based mainly on reports by Heyl and others (1959), Bradbury (1959), Bain (1906), Chamberlin (1882), and Hall and Whitney (1862). It is supplemented by the study of two gash veins about 2 miles south of the mapped area that produced ore in 1956, 1957, and 1959.

Areas worked for gash veins or for residual galena deposits derived from gash veins and, where known, the general strike of the veins, are shown on plate 25. For the most part the data plotted are compiled from Heyl and others (1959, pls. 3, 5), Agnew, Flint, and Crumpton (1954), Allingham, Flint, and Agnew (1955), Grant (1903), Chamberlin (1882, pls. 36–39), and Bradbury (1959, pl. 1).

Some gash veins are several hundred feet from other veins, but most occur in areas where parallel veins are a few feet to 50 feet apart. Closely spaced gash veins are connected locally by gash veins that trend about 45° or 90° to the major trend and, in places, by horizontal veins. Most ore was produced from areas where gash veins are closely spaced, but most of the more spectacular gash veins in terms of length and contained masses of galena or sphalerite are several hundred feet from other veins.

Galena has been by far the chief ore mineral from gash veins, although sphalerite or smithsonite is abundant locally. Barite was an ore mineral in gash veins in secs. 33 and 34, T. 2 N., R. 1 E. (Agnew, Flint, and Crumpton, 1954), but it is not a common constituent in other parts of the mapped area. The ratio of galena to sphalerite and smithsonite produced from gash veins probably is more than 100 to 1, but this ratio reflects a combination of economic and geologic conditions instead of an original abundance ratio. Many gash veins were mined when galena was the only salable mineral produced, and most gash veins mined were above the water table where sphalerite, pyrite, and marcasite were readily oxidized and removed by ground water. The author estimates the original ratio of galena to sphalerite in gash veins as less than 5 to 1.

Minable deposits generally are irregular pods of minerals that fill pore space in altered rock or in solution breccia, form chimneys at intersections of joints, or line walls of caves. In some places, shear zones of closely spaced vertical fractures contained enough thin veins of galena or sphalerite to constitute a minable deposit. Isolated veins along joints furnish little ore, for most veins are less than 2 inches thick; however many isolated veins were worked by early miners. Owen (1840, p. 38) reported that miners could profitably work veins of galena one-half inch thick in unaltered rock and one-quarter inch thick in altered rock.

Most minable deposits are where mineralized vertical joints cut particular stratigraphic zones in the Galena Dolomite. Several of these zones (known as "openings") are present, although not more than three openings are likely to be found in any given vertical section (Cox, 1914, p. 43). Most of the galena produced in the mapped area came from the "caprock" opening and the "upper flint" opening which are about 40 and 120 feet, respectively, below the top of the Galena Dolomite. The caprock opening is most productive near Hazel Green, and the upper flint opening is most productive near Benton, Shullsburg, and New Diggings.

The stratigraphic zones that localized minable deposits are not megascopically different from other zones in the Galena Dolomite. Probably they were more susceptible to attack by mineralizing fluids because of subtle differences in chemical or physical characteristics.

Space that served as ore receptacles where vertical joints intersect the opening zones varies both in cross section and lateral extent. At one extreme, the available space was limited to pore space where cement was removed between grains of dolomite along a joint. At the other extreme, available space was a cave. Typically, the ore zone is podlike in horizontal as well as vertical section, although some zones extend several hundred to several thousand feet along a vertical joint. Bain (1906, p. 54–57) reports that caves 1 to 4 feet wide, 4 to 6 feet high, and as much as several hundred feet long are common along some vertical joints. Chambers 25 to 30 feet wide and 30 to 40 feet high formed locally and particularly at intersections of joints. The caves referred to by Bain mainly are along eastward-trending joints; open spaces are not so common along joints that trend in other directions (Heyl and others, 1959, p. 44). The largest known concentration of ore minerals in gash veins was mined at the Rodham mine (sec. 25, T. 2 N., R. 2 E.). According to Heyl and others (1959, p. 231), the Rodham ore body consisted of a network of intersecting mineralized joints and openings. Thick veins of sphalerite that contained abundant galena were in horizontal zones 10 to 100 feet wide, and vertical chimneys of ore rich in galena occurred at intersections of joints. Total production at the Rodham exceeded 200,000 tons of ore that averaged more than 10 percent contained lead and 10 percent contained zinc. In terms of contained metal, the Rodham deposit was about 10 times as large as galena-lined caves in the district and more than 100 times as large as typical gash veins.

Porous rock in openings ranges from that in which cement was removed from dolomite grains to an irregular coarse filigree of dolomite. Typical solution-altered dolomite is a friable porous crystalline aggregate enclosing irregular cavities as much as 1 inch across. Vuggy altered rock is commonly interspersed with solid unaltered rock. Sphalerite, galena, pyrite, marcasite, and calcite fill the pore space between dolomite grains, form veinlets between blocks, and partly fill the irregular cavities. Ore from these zones is locally termed "brangle." Where the porous dolomite has collapsed by its own weight, horizontally oriented veins of galena occur in the tabular open space above the altered dolomite.

Some caves are lined with galena and they are spectacular examples of mineral deposits. The top and sides of a cave about 6 feet high, 14 feet wide, and 400 feet long lined by a sheet of galena 6 to 12 inches thick were exposed at the Herman Smith 2 mine. This mine is about 2 miles south of the mapped area and was worked in 1956 and 1957. The sheet of galena contained cube terminations as much as 1 foot on edge and the average edge was about 5 inches. At this mine a solution breccia cemented with sphalerite, iron sulfide, and sparse galena veins filled part of the cave under the arch formed by the sheet of galena. Bain (1906, p. 55–57) reports similar galena-lined caves near Dubuque, Iowa; possibly the worked-out Craig level (secs. 25 and 35, T. 1 N., R. 1 E.) was a galena-lined cave (Chamberlin, 1882, fig. 28). Some of these galena-lined caves produced more than 2,000 short tons of galena, but typical gash veins produced considerably less galena, probably about 50 to 100 short tons.

In unoxidized deposits, galena and sphalerite commonly occur along the same joint, but most pods of ore are mainly either sphalerite ore or galena ore. Iron sulfide is scarce in galena ore, but common to abundant in sphalerite ore. Sphalerite is more abundant than galena in porous and brecciated zones, and galena is more abundant than sphalerite as linings of caves and vugs and in openings formed at the intersection of joints. Many gash veins also show a vertical zoning, galena commonly occurring in upper stratigraphic zones and sphalerite in lower zones. Brown and Whitlow (1960, p. 55) report that this vertical zoning is possibly related to the type of ore receptacle. Rock in the lower zones is altered to porous, spongelike masses, whereas rock in the upper zones is commonly completely dissolved and caves have formed.

Unoxidized gash veins commonly are symmetrically zoned. Pyrite and marcasite, the first minerals deposited, form layers as much as one-fourth of an inch thick along the wallrock and locally impregnate the dolomite for as much as 1 inch. Sphalerite overlies the iron sulfide; it forms colloform layers as much as 2 inches thick, but rarely forms euhedral crystals. Galena overlies the sphalerite and commonly occurs as euhedral crystals or sheets that show terminations of euhedral crystals toward the middle of the vein. Pyrite, marcasite, and locally sphalerite were deposited on the galena. Barite, apparently a scarce mineral in most gash veins, probably was deposited after galena (Heyl and others, 1959, p. 99, fig. 58). Calcite in euhedral scalenohedrons or rhombohedrons was the last mineral deposited and partly fills the middle of the vein.

Gash veins above the water table are exposed to oxidizing conditions that alter the composition of the deposit and wallrock adjacent to the deposit. Pyrite and marcasite form hydrated iron oxides, sphalerite alters to smithsonite, and calcite is etched or dissolved. The surfaces of galena crystals alter to cerussite, but otherwise galena is unaltered. Acid formed during oxidation of the sulfide minerals, and it softens or dissolves the dolomite wallrock. As oxidation continues, the wallrock is brecciated by solution or decomposed, and the openings are enlarged. Fragments of wallrock, dolomite sand, insoluble residue, and galena attached to the wall fall to the floor of openings and form a jumbled mass termed "tumble openings" by miners. A stratified deposit of silt, clay, and sand derived from surface materials overlies some tumble openings (Brown and Whitlow, 1960, p. 54). Inasmuch as most gash veins mined in the mapped area were above the water table, a considerable amount of ore came from tumble openings.

Residual soil derived from rock that contained gash veins is colored reddish brown by iron oxides. This soil contrasts strongly with the brownish-gray to black soil derived from rock that does not contain gash veins.

Gash veins are the most abundant mineral deposits in the mapped area, and they were economically the most important deposits until about 1890. The decline in importance of gash veins was caused by depletion of easily found gash veins and an increase in emphasis on pitch-and-flat deposits. Early prospectors found most of the exposed gash veins and most areas where residual galena in soil, ocherous soil, alined vegetation, alined sinkholes, and yellow tinged grass (chlorosis) indicated favorable places to prospect for concealed gash veins. Discoveries of gash veins in the mapped area since about 1890 resulted mainly from activities not directly related to mining or prospecting for them. Some were indicated by residual galena or ocherous soil exposed in cultivating upland surfaces; others were discovered more or less accidentally in prospecting for pitch-and-flat deposits and in drilling of water wells. Prospecting by drilling or current geophysical techniques for gash veins that have no surface indications is prohibitively expensive.

In general, shallow pits served the twofold purpose of recovering residual galena from the soil and exposing veins in bedrock. Where a vein was exposed, the miners sank shafts and drifted along the vein. Other drifts followed caves or altered zones along joints, for these were the most likely places to find ore. Few drifts extended more than 200 feet before another shaft was put down because it was easier to put down a new shaft than to move ore very far through the openings. The additional shafts were also needed to furnish fresh air. Where gash veins were closely spaced, the many shallow pits and shafts pockmark the surface. Modern earth-moving machines made it practicable to reclaim for farming much of the level ground that was worked by early miners, but slopes near New Diggings, Benton, Hazel Green, and Shullsburg are stilled scarred by lead pits.

DECORAH FORMATION

Deposits in the Decorah Formation that are associated mainly with vertical joints are probably scarce. None were mined from 1956 to 1959, and only four are specifically mentioned by Heyl and others (1959) as containing ore principally controlled by vertical joints in the Decorah Formation. These are the Old and New Mulcahy mines (sec. 9, T. 1 N., R. 2 E.), the south prong of the Fox mine (sec. 28, T. 1 N., R. 1 E.), and part of the Blaine and Logan mine (sec. 7, T. 1 N., R. 2 E.). These deposits contained mainly zinc ore in flat veins or solution breccia associated with the joints. Heyl and others (1959, p. 211) report that more than 750,000 tons of ore was produced at the Fox mine, and more than 500,000 tons of this probably came from the south prong.

Some pitch-and-flat deposits in the Decorah Formation contain pockets of ore along vertical joints; these occurrences will be described in the section on pitch-and-flat deposits (p. 503–513).

PLATTEVILLE FORMATION

Vertical joint control of some deposits in the Platteville Formation was recognized by Heyl and others (1959, p. 204–205, 221), but the deposits were not described in detail.

In joint-controlled deposits in the Platteville Formation, minable deposits are in linear altered zones that show a decrease in intensity of alteration away from a central vertical joint. Sphalerite is the principal ore mineral in the deposits, although locally they contain abundant galena. Pyrite, marcasite, and calcite are the principal gangue minerals. Typical deposits contain more pyrite and marcasite than galena and sphalerite, but the relative abundance locally is extremely variable.

Because mineral deposits directly controlled by vertical joints in the Platteville Formation are narrow and thin, the deposits are usually developed only where they are close enough together to form a practically continuous blanket of ore, or where they can be mined with deposits in higher beds. A plan of workings in joint-controlled deposits in the Platteville Formation is shown on plate 26. From 1956 to 1959 only three deposits, the Kittoe (sec. 15, T. 1 N., R. 2 E.), the Temperly (sec. 27, T. 1 N., R. 1 E.), and the Hancock (sec. 28, T. 1 N., R. 2 E.) were worked primarily for deposits associated with vertical joints in the Platteville Formation. Sporadically spaced vertical joint-controlled deposits in the Platteville, however, were recognized in all mines that operated in the mapped area from 1956 to 1960 if the mine workings were as deep as the top of the McGregor Member. In 1956 much ore produced at the James mine (Doyle-Harty shaft) was from joint-controlled deposits in the Platteville, but most of the ore produced previously from the James was associated with inclined fractures in the overlying Decorah and Galena Formations. Heyl and others (1959, p. 221) report that a large part of the ore produced at the Old Mulcahy mine came from joint-controlled deposits in the upper part of the Platteville.

Altered zones that clearly show a central vertical joint range in width from less than a foot to about 20 feet. The width of the altered zone, in general, is proportional to the intensity of alteration; rocks in wide zones are highly altered, whereas rocks in narrow zones are only slightly altered. In narrow zones, only the more calcareous rocks near the contact of the Quimbys Mill and McGregor Members are leached; in wide zones, the dolomitic rocks in the upper part of the Quimbys Mill and the upper part of the McGregor are also leached. The most altered rock is near the joint, and the effects of alteration decrease away from the joint. Linear zones of mineralized rock as much as 35 feet wide that are not associated with a discernible vertical joint locally occur adjacent and parallel to narrower mineralized zones along vertical joints. The effects of alteration in the wider zones are similar but more intense than in the obviously joint-controlled zones. The wider zones were probably also controlled by vertical joints that were obliterated by solution and compaction. Most of the ore produced from the Platteville at the Hancock (pl. 26) and the James mines was in narrow zones, whereas most of the ore from the Kittoe mine was in wider zones that do not show a vertical joint. The ore zones in the Platteville Formation in the Temperly deposit were extremely altered; some showed controlling vertical joints, but most were so close together that it was difficult to identify a particular zone except by a slight sag at the contact of the Quimbys Mill and McGregor Members.

Controlling joints in narrow zones are distinct and extend upward through the Quimbys Mill Member, but cannot be traced through the ubiquitously altered rocks of the Guttenberg or Spechts Ferry Members that overlie mineral deposits in the Quimbys Mill. The depth to which the joints extend is not known, for no mine workings in the mapped area are below the base of the McGregor Member. Indirect evidence indicates that the joint system extends to the underlying St. Peter Sandstone. About 30 percent of all water pumped from mines is artesian flow from the St. Peter Sandstone that enters the mines mainly through joints (C. R. Holt, oral commun., 1959).

Many altered zones 5 to 15 feet wide have a V-shaped collapse structure where the controlling joint intersects the contract of the Quimbys Mill and McGregor Members. These structures range from a few inches to about 3 feet in width and from a few inches to about 2 feet in depth. Small caves and partings along bedding planes in the lower part of the Quimbys Mill Member are associated with many of the V-shaped collapse structures. Altered zones wider than 15 feet generally have an irregular sag as much as 2 feet deep at the contact of the Quimbys Mill and McGregor, but generally no open space is associated with these broad sags.

Mineralized rock associated with the vertical joints is not as extensive as leached rock associated with the joint. Pyrite, marcasite, and calcite occur in the central two-thirds of the altered zone; sphalerite and galena commonly are restricted to the central one-half of the zone. The richest and most persistent ore generally is in the basal 4 to 6 feet of the Quimbys Mill Member in the central part of the zone. Locally as much as 15 feet of the upper part of the McGregor Member contains ore. In slightly leached zones, veins of sphalerite or, locally, galena constitute about 80 percent of the mineral added. These veins are ½ to 8 inches thick, and they fill openings caused in part by solution of rock along bedding planes and in part by breakup of the beds as they responded to gravitational forces. In most deposits the thickest and most persistent vein occurs a few inches above the contact of the Quimbys Mill and McGregor Members. Except for the vein near the contact, veins diminish both in relative and absolute abundance in more leached zones, probably because the more altered beds are too weak to support openings. Relative abundance of gangue minerals generally increases in the more altered zones. Ore and gangue minerals occur mainly as disseminations in the more altered zones, as impregnations, and as veinlets filling spaces in breccia in moderately altered rock. The breccia consists mainly of fragments of dolomite, and it formed where hard ribs of dolomite or dolomitized limestone were fractured when the leached zone was compacted by overlying rock.

The sequence of deposition of ore and gangue minerals in joint-controlled deposits in the Platteville Formation is the same as shown in figure 56.

The longest joint-controlled deposit observed in the Platteville Formation was about 800 feet long and was mined from the northward-trending drift at the west side of the Hancock mine (pl. 26). In most places the sulfide mineral zone was less than 10 feet wide and was mined only because it was along the trend of a planned haulage drift. The typical minable joint-controlled deposits observed by the author were about 300 feet long, and the controlling joints were so close together that the mineralized zones overlapped to form ore zones 20 to 30 feet wide. Ore-grade material associated with the vertical joints generally is less than 10 feet thick, but the drifts used to mine these deposits are about 10 feet high. Typical joint-controlled deposits mined to a height of 10 feet average 3 to 5 percent contained zinc and 0.1 to 0.5 percent contained lead. Total iron sulfide in these deposits probably averages 5 to 10 percent; the total sulfide mineral content therefore generally ranges from about 8 to 15 percent.

DEPOSITS ASSOCIATED WITH INCLINED AND BEDDING-PLANE FRACTURES

The largest mineral deposits in the mapped area contain mainly zinc ore. They are associated with inclined fractures, fractures parallel to bedding, extensive altered zones in the Guttenberg and Quimbys Mill Members, breccia, contorted beds, and synclines or basins as expressed at certain stratigraphic zones. These deposits are known as "pitch-and-flat" deposits, a descriptive term first applied by Percival (1855, p. 55). A "pitch" is a vein of ore or gangue minerals in an inclined fracture; a "flat" is a vein of ore or gangue minerals that parallels the bedding. Some flats fill spaces opened by movement of rock, and others replace rock or fill opened spaces enlarged by solution along bedding surfaces. Cross sections of typical pitch-and-flat deposits are shown in figures 57 and 58. Figure 57 shows a single-pitch deposit—only one system of inclined veins is formed; figure 58 shows a double-pitch deposit—two opposing systems of inclined veins are formed. In double-pitch deposits, one system of fractures is generally better developed than the other. The majority of pitch-and-flat deposits are in fracture systems that extend upward from the Spechts Ferry or Guttenberg Members of the Decorah Formation to 10 to 30 feet above the base of the Galena Dolomite. In some exceptionally large deposits, the fracture systems extend from the top of the McGregor Member of the Platteville Formation to near the top of the cherty unit of the Galena Dolomite, a vertical distance of about 150 feet.

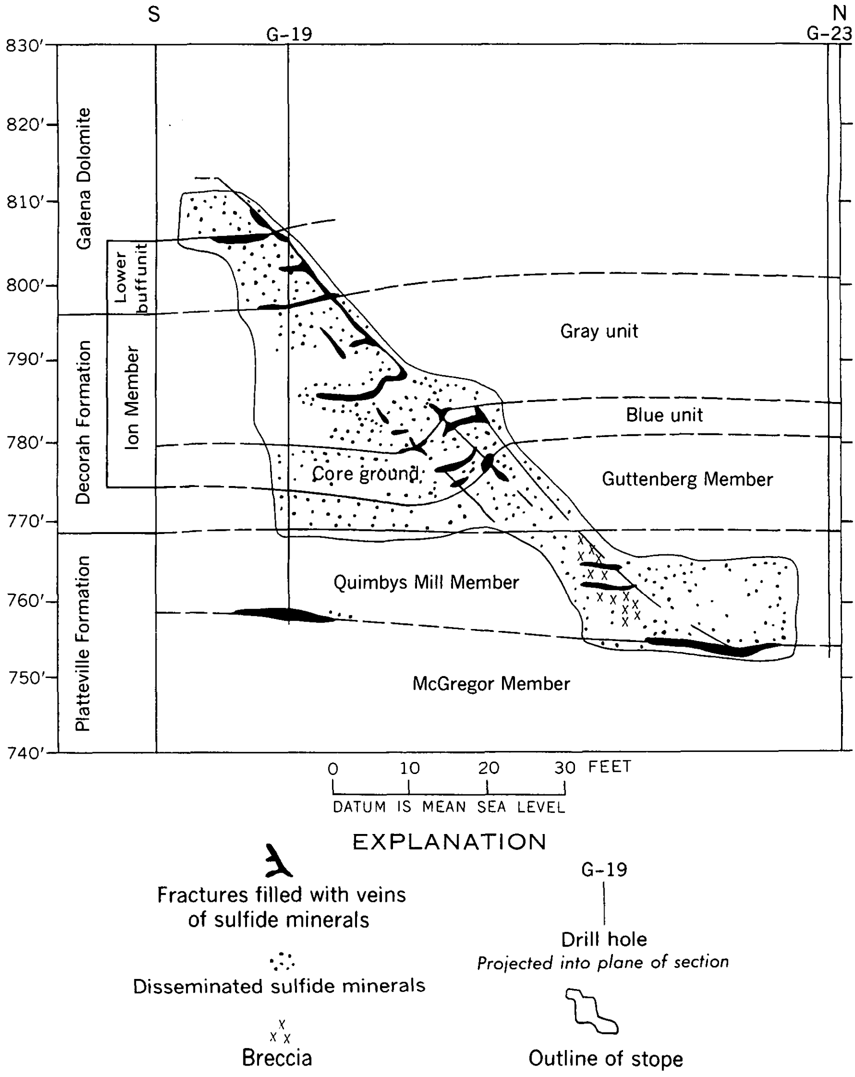

FIGURE 57.—Sketch of pitches and flats in West Blackstone mine near east side of sec. 29, T. 1 N., R. 2 E., Lafayette County, Wis. Inclined veins are pitches; veins parallel to bedding are flats.

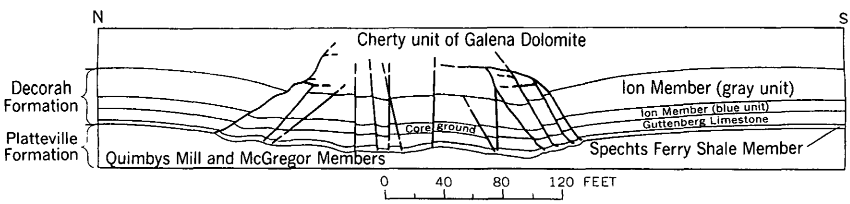

FIGURE 58.—Section across Trego mine near Platteville, Wis., showing pattern of fractures. From Heyl and others (1959, fig. 30).

Pitch-and-flat deposits also contain considerable amounts of ore and gangue minerals as fillings in breccia, as disseminated crystals or aggregates of crystals, and as replacement of country rocks.

The general size range of pitch-and-flat deposits in the quadrangles is given in the section on production (p. 482–486). Individual descriptions of most pitch-and-flat deposits in the mapped area are given by Heyl and others (1959, p. 184–241).

Pitch-and-flat deposits are in areas where altered country rock forms a halo around the part of the deposit that contains pitches and flats. The largest halos are formed by leached rock in the Guttenberg and Quimbys Mill Members; these halos commonly extend 200 to 400 feet into the hanging wall past the base of the pitches. Plan views of workings in typical pitch-and-flat deposits and the extent of the associated altered zone in the Guttenberg and Quimbys Mill Members as indicated by solution thinning are shown on plate 27. An altered zone associated with an elliptical ore body is shown on plate 28.

STRUCTURES ASSOCIATED WITH PITCH-AND-FLAT DEPOSITS

In cross section, the fracture system that contains pitches and flats generally consists of a major open fracture that is inclined to the bedding, several parallel minor open fractures, and open fractures along bedding planes (figs. 57, 58). Tight and generally unmineralized fractures locally intersect the principal inclined fractures at nearly right angles. Typical pitches and flats in minor fractures in the system are shown in figure 59. The major fracture commonly separates the system from unfractured and unmineralized rock in the hanging wall. In many deposits the top of the system is marked by a well-formed bedding-plane fracture that extends over the footwall. Veins in this fracture are called the "top flat." The base of the system is generally not well defined; it consists of poorly formed fractures that decrease in dip and die out along bedding planes. The base of the fracture zone is called the "toe" of the zone, and it is commonly in altered rock of the Guttenberg, Spechts Ferry, or Quimbys Mill.

All major pitches observed by the author were either stairlike or straight above the toe. The stairlike pattern is due to a horizontal or low-angle offset of the inclined fractures along bedding surfaces. Commonly, inclined fractures are offset along bedding at the base of the Ion Member, at the base of the gray unit in the Ion, at the top of the Ion, and at the top of zone D in the Galena Dolomite. Bedding fractures commonly do not extend into the hanging wall at places where the major fracture cuts the Ion Member and the Galena Dolomite. The dips of fractures inclined to bedding range from

FIGURE 59.—Typical minor pitches and flats. End of hammer is about 6 inches above contact of Guttenberg and Ion Members of the Decorah Formation. White mineral in veins and irregular masses is calcite; dark mineral in veins is mainly sphalerite.

nearly vertical to 30° from the horizontal and average about 45°. Fractures near the center of the deposit tend to have steeper dips than those near the hanging wall (fig. 58).

Other geologists report that most major fractures are either straight or stairlike in section but that some are curved. Apparently the curved fractures either steepen or flatten upward. Most cross sections of pitch-and-flat deposits made by Heyl and others (1959) show pitch-bearing fractures that flatten upward; Willman, Reynolds, and Herbert (1946, p. 13) report that the slope of many fractures that contain pitches steepens upward until the fracture is vertical, and Cox (1914, fig. 5 a, b) shows a generalized diagram of pitches in fractures that are concave upward at the base, are convex upward at the top, and join vertical fractures at nearly right angles.

The amount of open space along inclined fractures in the Ion Member of the Decorah Formation and Gelana Dolomite observed by the author was about the same or slightly more than along fractures parallel to bedding in these rocks. Equal importance of inclined and horizontal fractures is probably a characteristic of deposits in and south of the mapped area; Heyl and others (1959, p. 109) report more space along fractures parallel to bedding in mines north of the mapped area.

In many places, beds are displaced a few inches to a few feet along inclined fractures, and most commonly the footwall block is displaced downward. Bedding-plane faults are indicated by abundant slickensides in shaly zones. The slickensides indicate that beds under the incline fractures are displaced toward the hanging wall relative to overlying beds along bedding-plane faults. Technically then, most fracture zones are reverse or thrust-fault zones. This fault zone, however, is a peculiar type that is limited to a certain stratigraphic zone, and commonly is accompanied by a similar zone that dips in the opposite direction.

The height and width of the fracture zone, the number of fractures, the distance between walls along individual fractures, and the amount of displacement differ from place to place along fracture zones, and from deposit to deposit. Large deposits tend to accompany higher and wider zones, more and wider fractures, and greater displacement of beds than do small deposits. At the Kittoe deposit (sec. 15, T. 1 N., R. 2 E.) the fracture zone was about 20 feet high and about 10 feet wide. The major fracture was about 15 feet high and about 3 inches wide, was confined to the Ion Member of the Decorah Formation, and had maximum displacement of less than 1 foot. At the South Hayden deposit, a fracture zone about 50 feet wide contained three parallel fractures that averaged 40 feet in height and 1 foot in width, and many smaller parallel fractures. The major fracture was locally 3 to 4 feet wide and extended from the base of the Quimbys Mill Member to about 30 feet above the base of the Galena Dolomite, a vertical distance of about 70 feet. Maximum displacement along this fracture was 7 feet where it cut the top of the Guttenberg Member. About 5 feet of this displacement, however, was due to abrupt thinning of the Guttenberg at the fracture zone.

The horizontal trace of the fracture zone may be linear, sinuous, arcuate, or even elliptical (pl. 27, fig. 60). Some zones are several thousand feet long, but a few hundred feet is a more common length, and most of the longer zones are sinuous or arcuate. Some fracture zones are discontinuous along the mineral deposit, and in many deposits the major fracture in one part of the zone can be traced into a minor fracture along strike. In some places where the zone changes strike, the major fracture is continuous; in other places the change in strike is marked by slightly curved en echelon fractures.

The footwall block in pitch-and-flat deposits is called core ground. In many double-pitch deposits, the core ground is strongly mineralized

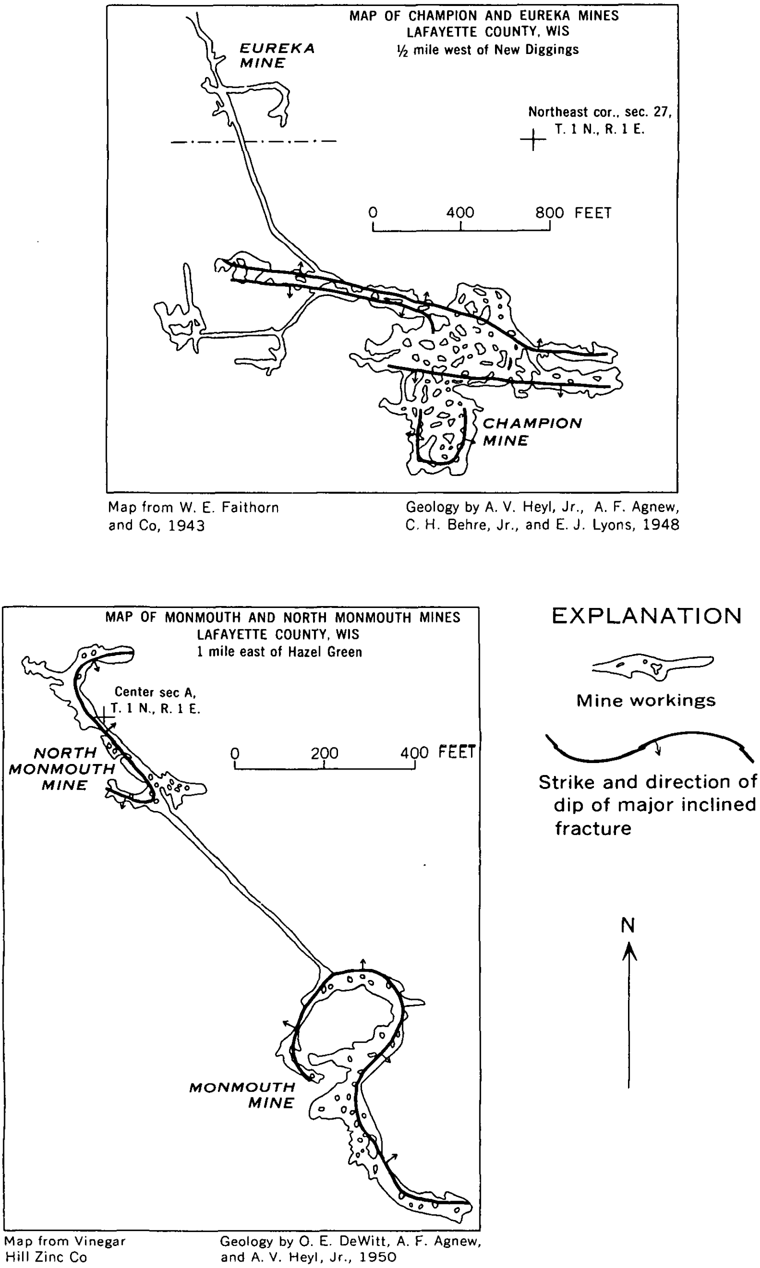

FIGURE 60.—Maps of Monmouth and North Monmouth mines, sec. 19, and Champion mine, secs. 26 and 27, T. 1 N., R. 1 E., Lafayette County, Wis., showing outline of workings and strike and direction of dip of major inclined fractures. From Heyl and others (1959, figs. 82, 83).

and yields a large proportion of the ore; in single-pitch deposits the core ground generally is barren or only weakly mineralized except near curves in the pitch zone. Heyl and others (1959, p. 63–65, figs. 44, 45) report that strata in the core ground commonly are in slight anticlines, which are bounded by small synclines at the base of the fracture zones. The bases of all fracture zones observed by the author were over sags, some as much as 4 feet deep and 30 feet wide. The anticlines in core ground are expressed, however, only in the lower beds (fig. 57). In figure 57 the anticline expressed at the top of the Guttenberg Member in the core ground is an anticline only because the top of the Guttenberg Member sags at the fracture zone.

The Quimbys Mill annd Guttenberg Members are locally altered to shale or very shaly thin-bedded dolomite in the core ground. Commonly the shale and shaly dolomite zones are squeezed, and bedding in them is contorted. The contorted bedding does not extend into overlying beds in the Ion Member or underlying beds in the McGregor Member.

The origin and general characteristics of most breccia in pitch-and-flat deposits were described under "Rock alteration" (p. 289–490). Solution breccia in the Ion Member and Galena Dolomite is mainly in the footwall block, but solution breccia in the Quimbys Mill and Guttenberg Members is is in the hanging-wall block as well as the footwall block. Crushed-rock breccia is mainly in unaltered zones in the Quimbys Mill and McGregor Members. Most of it occurs in the footwall block at or immediately under the base of fracture zones. Zones of crushed rock a few feet in height and thickness and 40 to 50 feet in length are common in some deposits and are entirely absent in others. Fragments of the crushed rock are roughly equidimensional, and they tend to be about the same size in individual breccia zones, but the size of fragments differs from zone to zone. The finest crushed rock observed had fragments that averaged about 1 inch in long dimension, and the coarsest averaged about 8 inches.

A less common breccia consists of large blocks of Galena Dolomite or Ion Member of the Decorah Formation that collapsed into openings in the footwall block. Blocks of Galena Dolomite as much as 6 feet thick, 10 feet wide, and 20 feet long formed a jumbled mass about 100 feet long and 20 feet thick immediately under the major inclined fracture at the west end of the North Gensler ore body. These blocks were coated with ore and gangue minerals in layers as much as 4 inches thick, but the spaces between the blocks were not completely filled.

Vertical joints that extend through more than 6 feet of rock are abundant along walls of barren drifts but scarce in the core ground, where they were apparently obliterated by alteration and subsequent compaction of rock.

Most pitch-and-flat deposits are in shallow basins or synclines as expressed at the top of the Guttenberg Member (pls. 29, 30). The basins and synclines range from a few hundred feet to a mile in length, a few hundred feet to one-third mile in width, and from 10 to 30 feet in amplitude. They are reflected in younger rocks but are subdued or reversed below the top of the McGregor Member of the Platteville Formation (pl. 31, fig. 57).

Inclined joints are common in outcrops of the Decorah and Galena Formations in the basins and synclines above pitch-and-flat deposits. These joints dip toward the edge of the basins. A few joints that curved and conformed with the shape of the basin were observed, but sparse outcrops prohibit a generalization about the relationship between joints and basin shape.

OCCURRENCE OF MINERALS

Typical pitches more than 2 inches thick contain several minerals and are symmetrically zoned in cross section. The general zoning is as follows: Pyrite and metallic-lustered marcasite line and impregnate wallrock in a layer that ranges from a film to 1 inch in thickness. Sphalerite overlies the pyrite and marcasite in a layer that ranges from a film to several inches in thickness. The third layer is discontinuous and consists of pyrite, marcasite (both metallic-lustered and sooty cryptocrystalline forms), galena, and early stages of calcite. Heyl and others (1959, p. 99) report that barite also occurs in this layer. Pyrite, galena, and calcite in the third layer show terminations of euhedral crystals toward the middle of the pitch. The central part of most pitches contains a late stage of calcite that generally does not completely fill open spaces in the middle of the pitch. All pitches more than 1 foot wide observed by the author had open space in the center that limits the total thickness of minerals in pitches to about 2 feet, although some fractures are 3 to 5 feet wide. Usually the part of the pitch attached to the footwall is thicker than the part attached to the hanging wall. The largest pods of ore and gangue minerals in the deposits usually occur where pitches are joined by flats.

Pitches less than 2 inches wide generally consist mainly of one mineral—sphalerite, sooty marcasite, calcite, or galena—that is separated from the wallrock by films of pyrite and metallic-lustered marcasite. Open space is not common in pitches less than 2 inches thick.

Major pitches generally also show a vertical zoning. Galena and calcite are more abundant and form larger crystals near the top of the pitch than near the base. This zoning is particularly common in pitches that have large central voids near the top.

Flats in the Galena Dolomite and Ion Member of the Decorah Formation are similar to pitches in zoning and mineralogic character. Generally, galena is more abundant in the top flat than in other places in pitch-and-flat deposits. Heyl and others (1959, p. 197, 211) report that the top flat in the Kennedy mine (sec. 29, T. 1 N., R. 1 E.) contained 2.5 to 3.5 feet of solid galena and that the top flat in the New Hoskins mine (sec. 13, T. 1 N., R. 1 E.) contained galena crystals as much as 2 feet across.

Flats in the Guttenberg and Quimbys Mill Members were mainly deposited along bedding that was opened by solution or were formed by replacement of rock adjacent to bedding surfaces. These flats range from a film to 10 inches in thickness; they contain mainly one mineral—sphalerite, marcasite, or galena—and open space in the middle is not common. Some flats in the Guttenberg or Quimbys Mill Members extend across the core ground and connect opposing pitches. Many of these flats extend into the hanging wall, whereas most of the stratigraphically higher flats do not.

Locally, minerals or zones of minerals in pitches and flats were fractured. The fractures healed with veinlets of calcite, marcasite, or sphalerite; some movement along the containing fractures during deposition of minerals is thus indicated.

In some deposits, minerals in the pitches and flats are less abundant than those that fill cavities in breccia, fill more or less randomly oriented tiny fractures, fill vertical joints, and are disseminated in country rock. As a general rule, ore minerals in the Galena Dolomite and Ion Member that are not in pitches and flats are confined to the footwall, whereas ore minerals in the Quimbys Mill, McGregor, Spechts Ferry, and Guttenberg Members occur both in the hanging wall and in the footwall. Mineralized rock in the Guttenberg and Quimbys Mill Members forms a halo 20 to 100 feet wide around the base of the pitch and as much as 400 feet beyond the plan projection of pitch zones as at the east and west ends of South Gensler deposit (pl. 27). Mineralized rock in the Guttenberg, Spechts Ferry, Quimbys Mill, and McGregor Members in some places can be related to pitches or flats; in other places it cannot. It is included as part of pitch-and-flat deposits because it is the extensively altered zone associated with pitches and flats.

Much of the space between blocks in breccia in pitch-and-flat deposits is filled with ore and gangue minerals. In breccia composed of blocks less than 6 inches long, the minerals form veinlets or irregular masses that fill most of the open space. Veinlets that contain more than one mineral are crusted in the same way as are pitches. As a general rule, pyrite, marcasite, and calcite are more abundant

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than sphalerite in breccia composed of blocks less than 6 inches long. In breccia composed of blocks more than 6 inches long the minerals commonly do not fill all open space. The blocks are coated with layers of pyrite and sphalerite, and terminations of euhedral crystals of galena as much as 6 inches across project into the open space.

Disseminated minerals in pitch-and-flat deposits form two size classes: (1) small grains of sulfide minerals and calcite that more or less impregnate dolomite and chert and (2) megascopically discrete crystals or aggregates of crystals. Small grains are more abundant in dolomite beds, and discrete crystals or aggregates of crystals are more abundant than grains in shaly rocks in the Guttenberg, Spechts Ferry, and Quimbys Mill Members. The average size of disseminated crystals in shaly rocks is larger than the average size of disseminated crystals in dolomite.

The disseminated small grains of sulfide minerals replace intergranular cement and dolomite grains, but how much of the replacement was metasomatic and how much was deposition of minerals in voids caused by earlier removal of carbonate was not determined. Locally, fossils and as much as 2 inches of dolomite along fractures are replaced by iron sulfide in a manner that retains the original form and texture. Typically, however, small grains of sulfide minerals are sporadically disseminated through dolomite in quantities that range from a trace to about 50 percent of the rock. These disemminated minerals occur behind an irregular front that extends as much as 2 feet from the nearest vein or fracture.

The size of disemminated crystals in the shaly altered rocks in the Guttenberg, Spechts Ferry, and Quimbys Mill Members is governed by the type of mineral. Sphalerite occurs as individual crystals as much as one-fourth of an inch long and as aggregates of crystals as much as 4 inches across. Galena occurs in crystals as much as 2 inches on an edge, but aggregates that contain more than a few crystals are rare. Barite locally occurs as individual crystals, but it mainly forms irregular 2- to 6-inch spherical masses that are made up of lath-shaped to acicular crystals. Some of the spherical masses of barite grew around a core of galena or sphalerite. Pyrite and marcasite are not as abundant in shaly altered strata as sphalerite. Laminations in the shaly strata are commonly draped over crystals, but whether this draping represents crystal growth that forced laminations apart or differential compaction of shale around crystals was not determined.

Some pitch-and-flat deposits, particularly those north of the mapped area, consist mainly of disseminated crystals and aggregates of crystals in the basal beds of the Decorah Formation and the Quimbys Mill Member of the Platteville Formation (Heyl and others, 1959,

p. 134). These deposits are also notable because they contain sparse iron sulfide.

There are two ways of viewing the relative abundance of minerals associated with vertical joints in pitch-and-flat deposits. Minerals in vertical joints in the core ground are not abundant, probably because vertical joints are obliterated in the core ground. However, in the altered Quimbys Mill and Guttenberg rocks that form a halo around pitches and flats, ore is abundant along vertical joints. Most known deposits associated with vertical joints in the Platteville Formation are in areas of altered rock associated with pitch-and-flat deposits.

ORIGIN OF STRUCTURES ASSOCIATED WITH PITCH-AND-FLAT DEPOSITS

Origin of basins and synclines as expressed at the top of the Guttenberg Member, and of fractures, breccia, and contorted beds associated with pitch-and-flat deposits is a subject of controversy among geologists who have studied them. Extreme viewpoints of this controversy are: (1) The features are the result of lateral compressive forces, and geologic structure localized the deposit; (2) the features are the result of subsidence in areas of altered rocks, and emplacements of the deposit caused the structures.

Chamberlin (1882), Jenney (1894), Grant (1906), Spurr (1924), Scott (see footnote 2, p. 470), Behre (1937), Behre, Scott, and Banfield (1937), and Heyl and others (1959) all emphasize the role of tectonic activity in forming the structures associated with pitch-and-flat deposits. Of this group, Heyl and others (1959) prepared the most comprehensive report. These authors believe that the synclines and basins were caused by lateral compressive forces, that the inclined fractures and fractures parallel to bedding are tectonic thrust faults, that the "crushed-rock" breccia is a tectonic breccia, that the contorted folds represent foreshortening by lateral compressive forces, and that the medial anticlines represent areas in which the synclines were so compressed that the middle of the syncline buckled upward (Heyl and others, 1959, figs. 44, 45). These authors recognize that collapse due to leaching of carbonate rocks has modified the tectonic structures.

Bain (1906, p. 38–43) believed that the synclines expressed at the top of the unit now known as Guttenberg Member represented basins in the surface of deposition of the Guttenberg Member. According to Bain, shale was deposited in the basins and limestone was deposited on the interbasin areas. Inclined fractures and fractures parallel to the bedding formed at the edges of the basins when the shale and limestone were differentially compacted. This particular hypothesis has lost favor; the shale that Bain considered sedimentary in origin is now commonly believed to be the insoluble residue of leached limestone in the Guttenberg Member.

Blake (1894), Cox (1914, p. 46), Trowbridge and Shaw (1916), Willman and Reynolds (1947, p. 5), and Reynolds (1958) attributed the structures in pitch-and-flat deposits to a combination of subsidence in altered zones and tectonic activity. The amount of tectonic stress needed ranged from that capable of forming inclined joints to stress capable of forming folds.

Heyl and others (1959, p. 49–52) summarized the opinions and ideas expressed in all the reports listed above except the 1958 Reynolds paper. The reader is referred to the summary of Heyl and others because some of the reports are not easily available.

In the present report the features associated with pitch-and-flat deposits are interpreted as resulting from subsidence in areas of altered rock. Tectonic forces are not needed to form any features of these deposits except the vertical joints that served as passageways for the mineralizing solutions. The inclined fractures and the fractures parallel to the bedding formed because beds overlying places where large amounts of carbonate were removed acted as structural beams or plates and formed a natural arch under pressure. The shattered rock probably results from failure of rock units to support added stress transmitted to a foot of the natural arch. The solution breccia that is widespread in the Quimbys Mill and Guttenberg Members, the contorted folds, and the "shalifying" of beds are probably due to partial or complete failure of the structural plate that allowed overlying rock to compress altered rock.

Subsidence as the cause of shallow synclines and basins as expressed at the top of the Guttenberg Member is demonstrated at the Bautsch [4] and Graham-Snyder [5] deposits near Galena, Ill. These deposits trend northwestward, are 100 to 300 feet wide, and are near the middle of northwestward-trending anticlines which are 800 to 1,200 feet wide and 5 to 10 feet in amplitude as expressed at the top of the McGregor Member. The structure expressed at the top of the Guttenberg Member, however, is a northwestward-trending syncline 400 to 600 feet wide and 5 to 15 feet deep. The reversal in structure correlates with an irregular but progressive thinning in the Quimbys Mill, Spechts Ferry, and Guttenberg Members toward the middle of the deposit (fig. 61). These units thin from a combined unaltered thickness of about 26 feet to about 12 feet in the middle of the deposit.

Subsidence as the cause of the syncline expressed at the top of the Guttenberg was clearly demonstrated only at one place in the mapped area. At the West Blackstone mine (SW¼ sec. 28, T. 1 N., R. 2 E.), a syncline of about 10-foot structural relief at the top of the Gutten-

[4] Unpublished data prepared by Paul Herbert, Jr., geologist for the Tri-State Zinc Co., 1959.

[5] Unpublished data prepared by William Arndt, geologist for The Eagle-Picher Co., 1959.

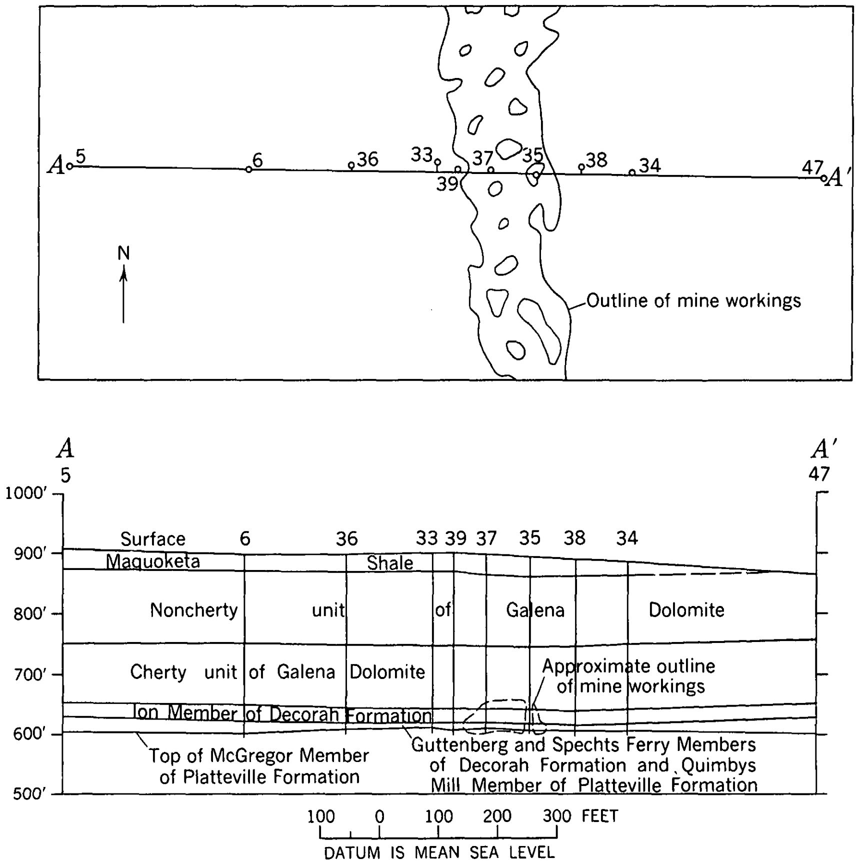

FIGURE 61.—Map of part of the Graham-Snyder mine in sec. 25, T. 29 N., R. 1 W., Jo Daviess County, Ill., and section based on drill holes.

berg Member overlies an anticline of about 5-foot relief as expressed at the top of the McGregor Member. The disharmonic character of the structure is due entirely to thinning in the Quimbys Mill and Guttenberg Members. Part of this structure is shown in figure 57.

In other places in the mapped area the relationship between the syncline at the top of the Guttenberg and subsidence due to compaction of altered rocks is not as clearly demonstrated. The author believes this apparent absence is due primarily to lack of information about thinning of rocks below the top of the Guttenberg Member. Fewer than one-tenth of the pitch-and-flat deposits in the mapped area have been developed in a manner to provide reliable information on the amount of thinning in the Guttenberg, Spechts Ferry, and Quimbys Mill sequence of rocks. No mine or deposit has been developed in such a way as to provide reliable information concerning the amount of thinning in the McGregor Member.

Information on thinning that is available shows that it either caused or emphasized the syncline as expressed at the top of the Guttenberg Member. For example, an anticline at the top of the McGregor Member is indicated at the Kennedy deposit by the drill holes shown in figure 62, but a syncline as expressed at the top of the Guttenberg Member is indicated immediately over the ore deposit by holes 157 and 158. Unfortunately, these are the only holes at the Kennedy mine that are deep enough to give data on the disharmonic folds. At the Thompson deposit, structure contours at the top of the McGregor Member show a well-defined syncline (pl. 30) near the middle of the deposit, but otherwise they do not conform to the contours at the top of the Guttenberg Member. Five drill holes in this deposit penetrated

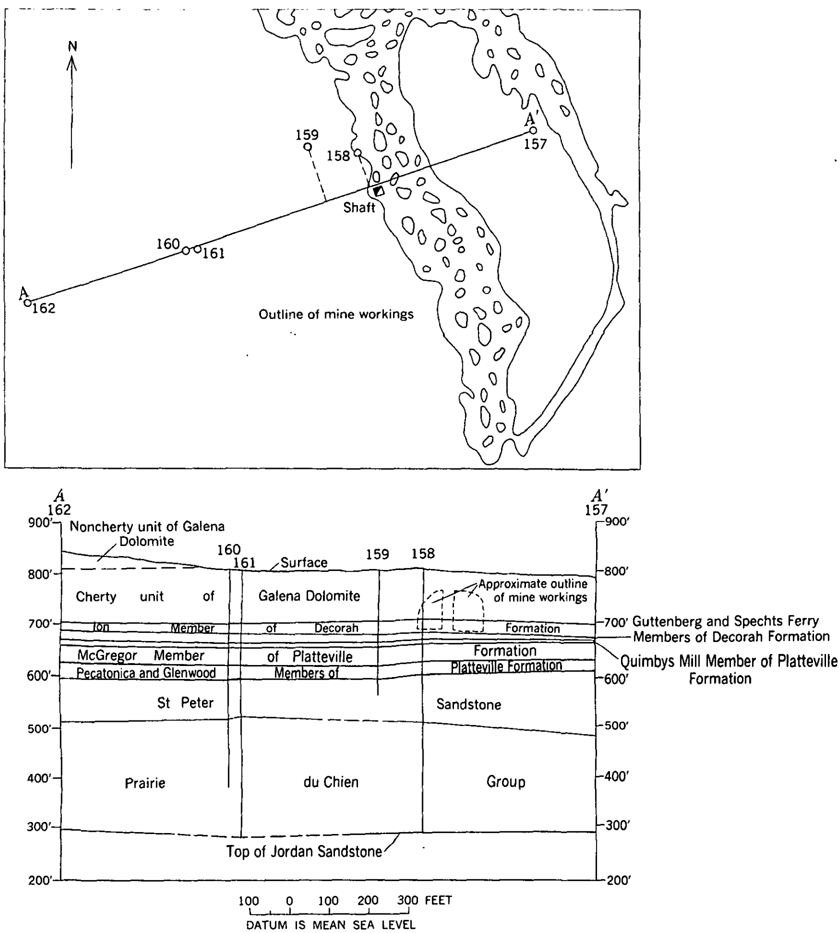

FIGURE 62.—Map of part of the Kennedy mine in sec. 29, T. 1 N., R. 1 E., Lafayette County, Wis., and cross section based on drill holes.

the McGregor Member, which was thinned by 8 to 15 feet from a normal thickness of 30 feet. The syncline expressed at the top of the McGregor Member near the middle of the deposit is about 10 feet deep. Therefore it is possible, and the author believes it is probable, that the syncline at the top of the McGregor represents compaction of altered rock.

Other examples of disharmonic relationships between structure at the top of the McGregor Member and at the top of the Guttenberg Member occur in the ore deposits in secs. 15, 22, and 27, T. 1 N., R. 2 E. As expressed at the top of the McGregor Member, the Kittoe and South Gensler deposits (pl. 31) are in slight depressions, the North Hayden and part of the North Gensler are near the crest of anticlines, and South Hayden is on the flank and in the trough of a syncline. Each of these deposits, however, is associated with a structural low as expressed at the top of the Guttenberg Member (pl. 29). Inasmuch as the McGregor Member is known to be thinned in some of these deposits, the structure shown on figure 18 probably does not represent a true tectonic feature. Reynolds (1958, fig. 58) showed that the Kittoe deposit is on a structural high as expressed at the top of the Pecatonica Member of the Platteville Formation. The author interprets the tectonic structure at the South Gensler as either flat or slightly anticlinal. The syncline at the South Hayden is probably tectonic in part, for the structural relief exceeds the expected maximum thinning between the top of the McGregor Member and the St. Peter Sandstone.

The postulated mechanics of producing fractures inclined and (or) parallel to bedding and "shattered-rock" breccia by subsidence are based mainly on the beam theory of Fayol (see Peele, 1941, p. 520–522) and the pressure arch theory of Randolph (1915). Beam mechanics are applicable where material is able to sag, instead of collapse randomly, into a void. Pressure-arch mechanics are used to calculate the probable points of maximum stress around openings in rock.

It should be understood that the author has no quantitative measurements that would prove or disprove beam-action or pressure-arch theories in pitch-and-flat deposits, and the argument is based entirely on analogy. Subsidence over the chemically stoped area in pitch-and-flat deposits should not be materially different from subsidence over manmade openings in rocks, for which there are abundant quantitative and qualitative data in mining engineering journals. The author obtained most of his information on subsidence from these references: Peele (1941), Stemple (1956), Bucky (1931), Bucky and others (1945), Bucky and Fentress (1934), Crane (1929), and Bucky and Taborelli (1938, 1939). These authors indicate that the occurrence of fractures similar to cracks formed by downward bending of a structural beam is the rule rather than the exception in subsidence.

Figures 63 and 64 show typical sections of fractures caused by downward bending of a structural beam. In plan view, the fractures associated with subsidence due to beam action are linear, curved, and arcuate, and they conform to the shape of the area of subsidence (Peele, 1941, fig. 793). The strike of the crack over a subsided area is a function of the relative width and length of the opening. Where the length is more than 1.5 times the width, the crack trends with the long direction (Bucky and Taborelli, 1938, p. 2). The development

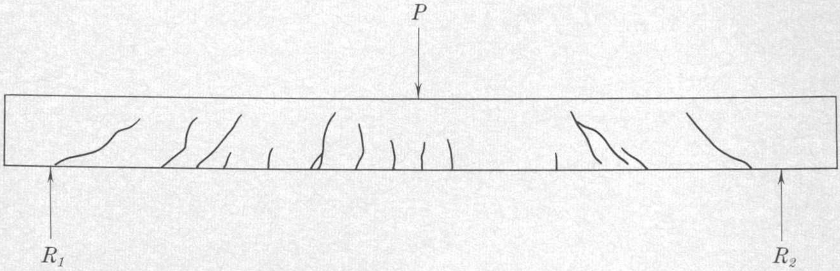

FIGURE 63.—Diagram of cracks formed in a reinforced concrete beam supported at R_1 and R_2 and under load at *P*. Adapted from Hool (1937, fig. 45); published by permission of McGraw-Hill Book Co.

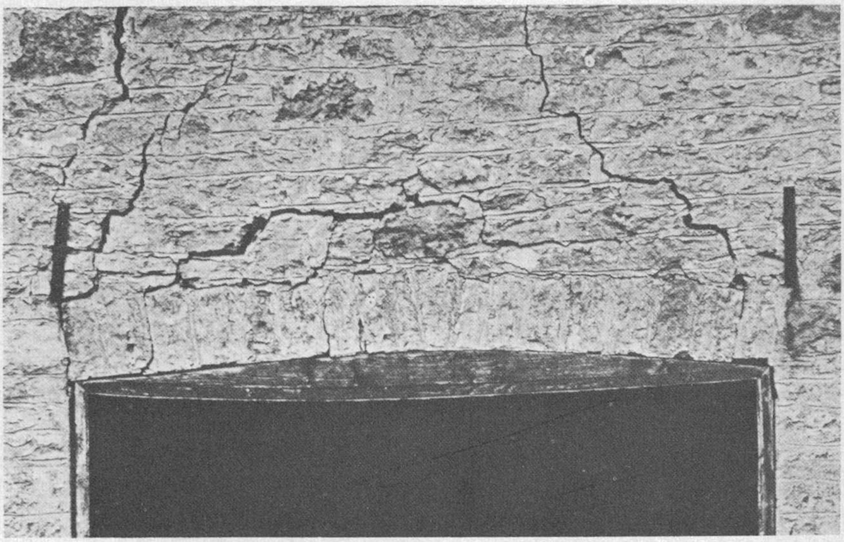

FIGURE 64.—Fractures formed in rock wall where supporting beam has been bent downward by weight of overlying rocks. From Cox (1914, photograph in plate 12; name of photographer not known).

of cracks on both sides of a mined-out area depends on the strength of the rock, pressure, and width of openings (Bucky and Taborelli, 1938, p. 16). If pressure and strength are equal, single cracks form above narrow openings and opposing cracks form above wide openings. Furthermore, early fractures that form above an expanding opening tend to close (Bucky and Taborelli, 1938, p. 8-9); the inner fractures tend therefore to be less conspicuous than the outside fractures.

The proposal that structural features associated with pitch-and-flat deposits resulted from beam-type subsidence is based on three lines of evidence: (1) inclined and bedding-plane fractures resemble fractures known to be caused by subsidence where material at the top of the opening acts as a structural beam, (2) altered and thinned rock in the pitch-and-flat deposits offered the possibility of a beam-type subsidence, and (3) the distribution of "shattered-rock" breccia follows the expected pattern due to transmittal of stresses in an altered zone.

The similarity in section between fractures in a pitch zone and in a sagging beam can be noted by comparing figures 57 and 58 with figures 63 and 64. The probable similarity between strike of the two types of fractures can be extrapolated from data shown on plate 27. Where the thinned area is elongate, the fracture zone strikes with the long direction; where the thinned area is more circular, as in the western part of the South Hayden deposit, the fracture zone is curved and discontinous. In all places the fracture zone would reach its apex over the most thinned area.

In all pitch-and-flat deposits the Guttenberg Member of the Decorah Formation is altered and weakened, and the upper part of the Platteville Formation is similarly affected in many deposits. Rock units above the Guttenberg are thinned in a few deposits, but the pattern of thinning is not as uniform as in the older rocks. In pitch-and-flat deposits, therefore, a natural opening or its equivalent in weakened rock is present immediately below the base of the Ion Member. The weakened rock upsets the equilibrium of gravitational forces established before the alteration. Equilibrium could be restored by one or a combination of several methods: (1) The rocks above the weakened zone might be strong enough to support the added stress, (2) the rocks under the weakened zone might be squeezed upward, (3) the overlying rocks might collapse randomly into the weakened zone, or (4) the overlying rocks might sag into the weakened zone. Sagging is indicated by the type of fractures, the compaction of altered beds, and the probable dynamics of the alteration. In an enlarging zone of altered rocks, the tendency of overlying unaltered rocks to sag would be reached before the zone was large enough to cause random collapse of overlying rocks. Because the sagging-beam type fractures are first to form, they furnish planes of weakness. Where enough rock was leached to cause collapse of overlying rock, the movement would probably be along the first-formed fractures.

Theoretically, the height of inclined fractures formed over openings should be proportional to the height and width of the opening. Reynolds (1958) showed a direct correlation between the height of the inclined fractures and the amount of leaching (solution thinning) in the Quimbys Mill and Guttenberg Members in the deposits in secs. 15, 22, and 27, T. 1 N., R. 2 E. Idealized illustrations of the possible effects of solution thinning are shown on plate 32 in which the lateral extent and amount of thinning shown in the Guttenberg and Quimbys Mill Members are the averages for several large ore deposits in the mapped area. The slight thickening of the Ion Member of the Decorah Formation in the center of the altered zone (pl. 32) is also based on average thicknesses in several ore deposits. The lateral extent and amount of thinning in the McGregor Member shown are extrapolated from scattered holes in several deposits, and they should be considered as interpretations. The slight anticline is included mainly to illustrate possible reversal of dip due to solution thinning, although several ore deposits mined in recent years are known to be on anticlines of about this magnitude.

Plate 32*B* illustrates the possible structure if the stresses caused by thinning the rocks were relieved by simple subsidence. If the effect of offset along inclined fractures is ignored, several ore deposits in the mining district show sections similar to those shown on plate 32B. (For example, compare figs. 61 and 65 with plate 32B.) It should be noted that the cross section through the Bautsch mine (fig. 65) is a selected one. Most other cross sections through the deposit do not show the central syncline as expressed at the top of the McGregor Member, but all sections show the syncline as expressed at the top of the Guttenberg Member.

Plate 32*C* is an idealized diagram of structural and stratigraphic relationships in pitch-and-flat deposits if the stress caused by thinning the rocks were relieved by a combination of subsidence and fracturing.

Most of the shattered unaltered rock in pitch-and-flat deposits is in the footwall at the base of or immediately below the fracture zone (fig. 57). This distribution of breccia is expected if the fractures result from subsidence. The hanging wall becomes a cantilever beam hinged at the base of the fracture. Stress added at the hinge locally crushed unaltered rock near the base of the fracture. This type of crushing is reported in many coal mines (Stemple, 1956, p. 40) and in some deep metal mines (Bucky and others, 1945, p. 568–597).

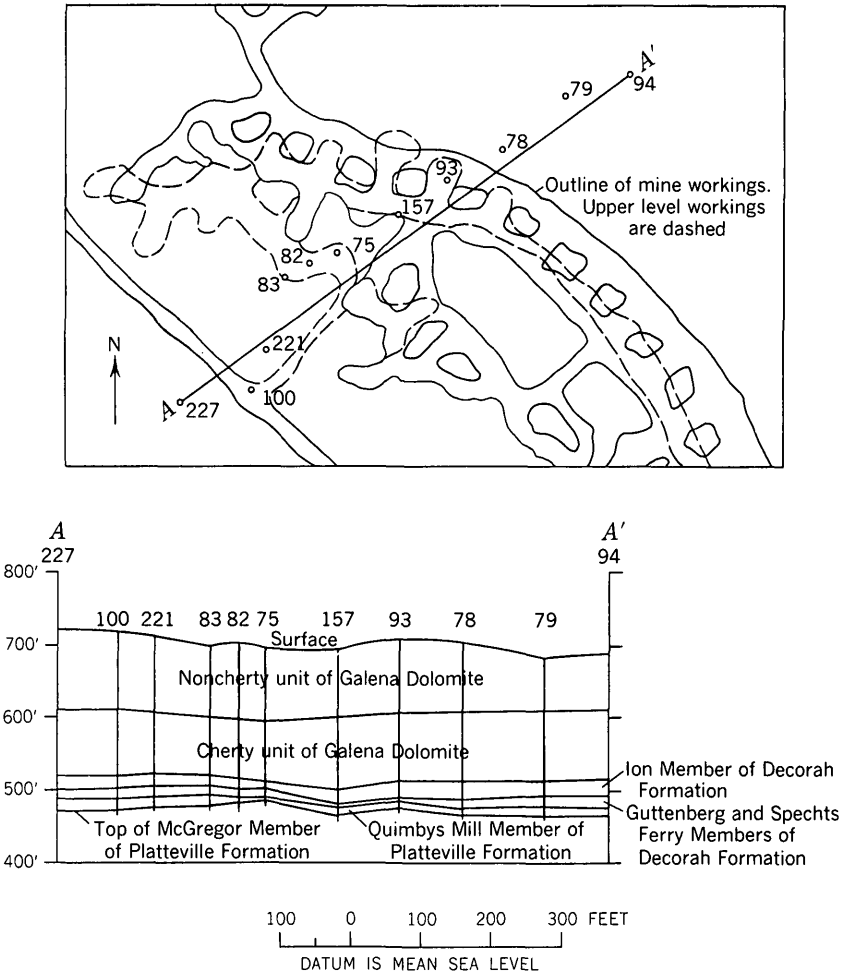

FIGURE 65.—Map of part of the Bautsch mine, sec. 10, T. 27 N., R. 1 E., Jo Daviess County, Ill., and section based on drill holes.

Isolated areas of shattered unaltered rock are mainly surrounded by altered rocks. Apparently this breccia represents incompetent pillars that were crushed by the weight of the subsiding rocks where the structural plate failed. This type of failure of incompetent pillars is also common in mines (Bucky and others, 1945).

Contorted folds found in pitch-and-flat deposits are limited to altered and shalified zones in the core ground. These features are interpreted to be the result of compaction and lateral adjustment of nearly strengthless rock by the subsiding rocks. The folds are irregular because isolated blocks of unaltered or partly altered rocks form buttresses which locally control the shape and size of the folds.

RELATION OF PITCH-AND-FLAT DEPOSITS TO DEPOSITS ASSOCIATED WITH VERTICAL JOINTS

The author interprets pitch-and-flat deposits as a peculiar occurrence of deposits controlled mainly by vertical joints. Pitch-and-flat deposits probably overlie areas where altered zones along vertical joints in the Quimbys Mill and Guttenberg Members overlapped and formed weakened areas so large that overlying rocks were not supported. This explanation is indicated by a few obvious joint-controlled altered zones in pitch-and-flat deposits and by an extrapolation of intensity and lineation of altered zones in Guttenberg and Quimbys Mill rocks in pitch-and-flat deposits as compared to joint-controlled deposits adjacent to pitch-and-flat deposits. The lack of abundant evidence of joint-controlled altered areas in the Quimbys Mill and Guttenberg Members in the core ground is due to the fact that most vertical joints in these members were obliterated by compaction and few pitch-and-flat deposits have been mined at a depth that would expose these members.

The relation between pitch-and-flat deposits and trends of vertical joints can be seen by comparing figure 66 with figures 54 and 55. Elongate pitch-and-flat deposits in the south part of the quadrangles have a dominant eastward trend, and deposits in the north part of the quadrangles have a northwestward trend. The trends in the two parts of the area parallel a set of joints in the locally dominant conjugate joint set, and the change in trend from south to north parallels a similar change in the trend of vertical joints.

Perhaps an additional reason to consider pitch-and-flat deposits as genetically controlled by vertical joints is to simplify geologic explanations. Most pitch-and-flat deposits underlie or are slightly offset from areas worked for gash veins, and most known deposits associated with vertical joints in the upper part of the Platteville Formation are under or adjacent to pitch-and-flat deposits. It seems unreasonable to postulate fold-and-fault control for deposits sandwiched between joint-controlled deposits.

MINERAL DEPOSITS NOT ASSOCIATED WITH OBVIOUS FRACTURE CONTROL

Economically significant mineral deposits not obviously related to a fracture system or to other areas of altered rock that contain ore associated with fractures are probably scarce in the central part of the mapped area. The only ore not associated with fractures or altered rock underlying inclined veins mined between 1956 and 1959 was a typical "brangle" ore as described on page 498. The ore deposit was about 10 feet high, 20 feet wide, and 200 feet long; it was

40 feet above the top flat in the North Gensler deposit (sec. 27, T. 1 N., R. 2 E.) but was not obviously connected to the main ore body by fractures or veins of ore or gangue minerals. Similar runs of ore or mineralized rock possibly overlie or are adjacent to many pitch-and-flat deposits (Reynolds, 1958, fig. 7), but few are mined because they are too small. Some of these runs probably are controlled by

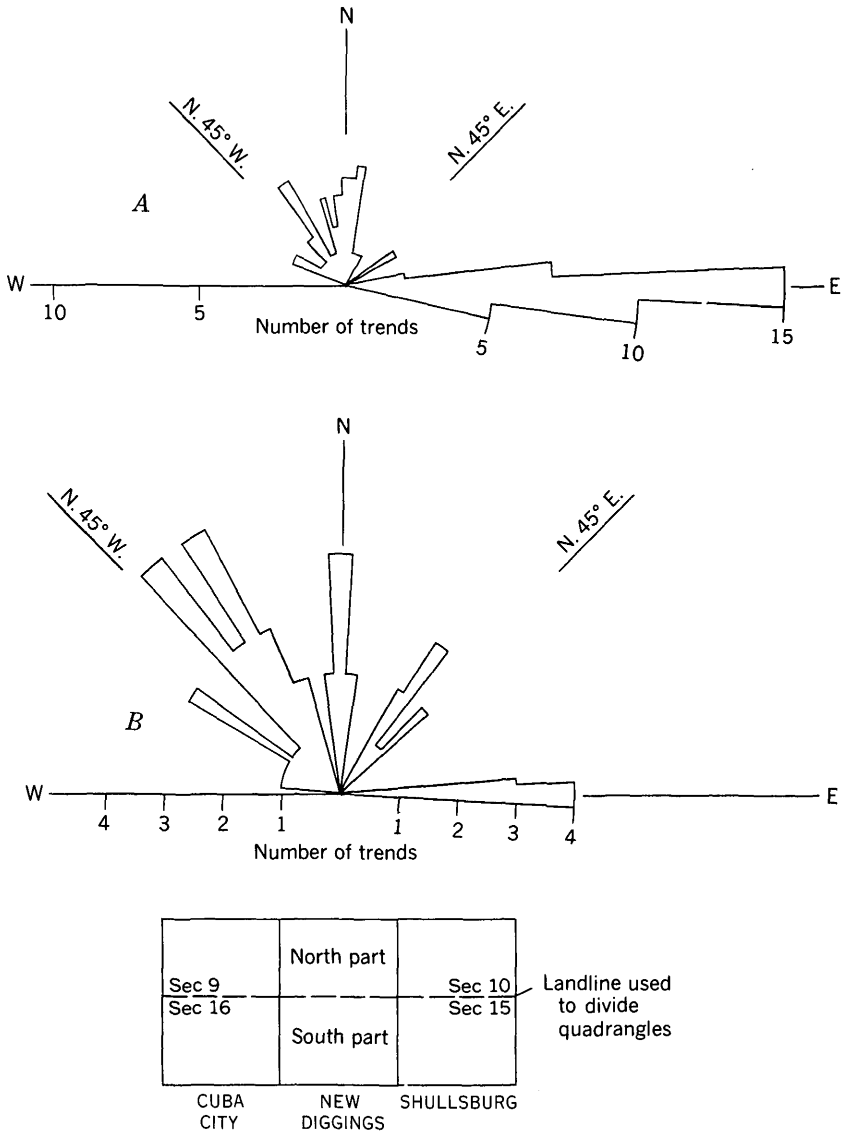

FIGURE 66.—Plot of dominant trends of elongate pitch-and-flat deposits in the Cuba City, New Diggings, and Shullsburg quadrangles, Wisconsin and Illinois. *A*, South part of quadrangles; *B*, north part of quadrangles.

vertical joints. Heyl and others (1959, p. 133–134) report that ore in solution breccia not directly associated with fractures is common, but all specific occurrences of solution-breccia ore in the mapped area described by these authors are associated with fractures or with leached and "shalified" rocks in the Spechts Ferry and Guttenberg Members of the Decorah Formation. In this report, the solution breccia and the disseminated minerals in altered Spechts Ferry and Guttenberg Members are considered part of pitch-and-flat deposits.

The following information about the Luning ore body is based largely on a 1959 oral communication from the late Paul Herbert, Jr., who at the time was general manager of the Tri-State Zinc Co., operations in Galena, Ill.

The Luning ore body in sec. 10, T. 27 N., R. 1 W., Jo Daviess County, Ill., is the only known zinc ore deposit of more than a few thousand tons in the district that is not associated with obvious vertical or inclined fractures. It is also the only known oval-shaped ore body of more than a few thousand tons that does not overlie thinned rocks in the Guttenberg and Quimbys Mill Members. The ore body produced more than 300,000 tons of ore that averaged about 3.5 percent zinc and 0.2 percent lead from "brangle" ore in the basal 18 feet of the Galena Dolomite. The deposit was oval shaped in plan. Sulfide minerals were concentrated near the middle and decreased in abundance progressively toward the outer limits. Mining of the deposit was governed by an assay instead of a geologic wall.

The fact that the deposit did not contain inclined fractures is here interpreted to reflect the lack of thinning in the underlying rocks. This interpretation allows speculation that similar deposits might be found in areas where the Guttenberg Member of the Decorah Formation and Quimbys Mill Member of the Platteville Formation are dolomite and are not particularly susceptible to thinning. These areas are in the eastern part of the Shullsburg quadrangle, where no large ore bodies are known but where zinc and lead sulfide minerals occur along joints and are sparsely disseminated in the Galena Dolomite.

LOCALIZATION OF THE DEPOSITS

The ultimate cause for localizing mineral deposits in the mapped area was not determined. Because the deposits have not succesfully been related to known sources, the features of localization discussed here are areal distribution of the deposits, tectonic control, and stratigraphic control. Information on distribution of deposits associated with vertical joints is mainly based on deposits in the Galena Dolomite (gash veins) which have a wider known distribution than deposits associated with vertical joints in other formations.

Mineral deposits associated with vertical joints in the Galena Dolomite (gash veins) probably occur throughout the mapped area. The more productive veins, however, are in a northeast-trending belt that extends about 2½ miles on either side of a line through Hazel Green and Shullsburg. Within the belt, gash veins are clustered in patches that are more or less isolated by nonproductive areas. The southeast boundary of the belt of more productive gash veins is mainly through ground underlain by the Maquoketa Shale and the upper part of the Galena Dolomite. These rocks are above the most favorable host rocks for mineral deposits and the southeast boundary of the belt of productive deposits therefore probably is more of an erosion boundary than a true mineral-belt boundary. Much of the area northwest of the belt is underlain by the lower and middle parts of the Galena Dolomite, rocks that are favorable hosts for gash veins elsewhere. In terms of natural exposures and intensity of cultivation, the area northwest of the belt is about on par with the area in the belt. Inasmuch as few large deposits have been found northwest of the belt, the northwest boundary probably is a true boundary for large deposits associated with vertical joints.

The reason or reasons that the more productive areas for deposits associated with vertical joints are in the belt is not known. Except for vertical joints, the deposits do not show a preferred association with tectonic features. They occur on flanks of folds, in the troughs of synclines, and at the crest of anticlines and domes. Regional stratigraphic changes probably should be eliminated also as a localizing agent for deposits associated with vertical joints. The distribution in the mapped area is similar to the distribution of dolomite and interbedded dolomite and limestone facies of the Decorah and Platteville Formations. However, gash veins are abundant near Fair Play, Wis. (Heyl and others, 1959, pl. 1), which is about 2 miles west of the mapped area and in an area where the Decorah and upper part of the Platteville are mainly limestone.

Known pitch-and-flat deposits are not as widely distributed as gash veins. They are restricted to the central two-thirds of the mapped area, and the more productive deposits are in the northeast-trending belt of the more productive gash veins. Except for some parallelism between elongate pitch-and-flat deposits and sets of vertical joints in the local dominant conjugate-joint system, no preferred association between pitch-and-flat deposits and other tectonic features was recognized. They, like gash veins, occur on flanks of folds, in troughs of synclines, and at crests of anticlines as expressed at the top of the McGregor Member of the Platteville Formation.

Unlike gash veins, pitch-and-flat deposits probably are localized by regional stratigraphic changes. The interpretation of how structures associated with pitch-and-flat deposits formed (p. 513–521) requires that a more or less specific amount of limestone underlie thick-bedded dolomite. Empirically derived figures from known distribution of pitch-and-flat deposits indicate the amount of limestone should range between 10 and 40 feet. No pitch-and-flat deposits are known in the eastern and northern parts of the Shullsburg quadrangle where the stratigraphic section is mainly dolomite. Neither are pitch-and-flat deposits known in the western part of the Cuba City quadrangle where mineralizing solutions might be dissipated in the 65 feet of limestone in the Decorah Formation and upper part of the Platteville Formation.

The probability that pitch-and-flat deposits will not be found in certain parts of the mapped area does not exclude the possibility that large mineral deposits of different habits are present in these parts. Pitch-and-flat is a specific type of mineral deposit that probably forms under specific stratigraphic conditions. If large quantities of mineralizing solutions passed through rock unfavorable for formation of pitch-and-flat deposits, large deposits of different habit might form. The Luning ore body (p. 524) is an example of a fairly large deposit formed where local conditions were not favorable for a pitch-and-flat deposit.

Most deposits are elongate in a direction that parallels a set of joints in the locally dominant conjugate-joint system. This tendency of mineral deposits is well displayed by gash veins. In the southern part of the mapped area most gash veins trend either eastward or northward; in the northern part most trend either northwestward or northeastward. This change correlates well with the south to north change in the strike of vertical joints (figs. 54, 55). The same tendency to parallel a set of joints in the local dominant conjugate system is also shown by pitch-and-flat deposits. A plot of the dominant trends of pitch-and-flat deposits (fig. 66) shows the change in trend of these deposits from the south to north part of the mapped area.

One set of joints in the local dominant conjugate system generally is more favorable for deposition of minerals than the other set. In the southern part of the area the eastward-trending set was more favorable than the northward-trending set; in the northern part the northwestward-trending set was more favorable than the northeastward-trending set. The reason, or reasons, why one set was more favorable for deposition of minerals was not determined.

ORIGIN AND AGE OF THE ORE MINERALS

Arguments for or against an igneous origin for the mineralizing fluids are based more on theories about the ionic concentration of fluids than on the minerals and temperature of deposition. None of the primary minerals can be considered diagnostic of igneous origin, and studies on the temperature of deposition have been inconclusive. Liquid inclusions indicate that the temperature during deposition of sphalerite ranged from 75° to 121° C, and the temperature of deposition of stage II and stage III calcite deposited on the sphalerite ranged from 50° to 78° C (Bailey and Cameron, 1951, table 1). These temperatures are within range of both telethermal solutions and meteoric water heated by burial at a few thousand feet.

The author interprets the deposits as related to intrusions of igneous rock of Paleozoic or younger age into Precambrian rocks that underlie the mining district, but there is no proof. This interpretation is based mainly on the probable composition of the mineralizing fluids as determined by Garrels (1941). The apparent paradoxical zoning in veins—late deposition of galena in spite of the relative insolubility of lead sulfide—is attributed by Garrels to mineralizing solutions that were rich in chloride ions. The abundance of chloride ions allowed the lead to be transported as a complex chloride; however, iron and zinc do not form complex chlorides. According to Garrels, meteoric water that contains enough chloride ions to cause the zoning should be expected, where as much known hydrothermal water contains sufficient chloride ions. The mineralizing solutions were rich in chloride ions as shown by some liquid inclusions in galena from this district containing about four molar concentrations of NaCl (Newhouse, 1932).

The sulfide minerals and silica in the deposits are interpreted as having been introduced by the mineralizing fluids. The carbonate minerals, calcite and dolomite, are interpreted as having been redistributed by action of the mineralizing fluids on the limestone and dolomite country rock.

Middle Silurian rocks in the mining district contain small veins of galena and iron sulfide; the age of the ore is thus probably post-Middle Silurian. Heyl and others (1959, p. 146) believe that the deposits are closely related to folds of tectonic origin and were emplaced during the latter part of the Appalachian orogeny. The author believes that the folds referred to by Heyl and others are not tectonic and that most mineral deposits are associated with vertical joints. Presumably the joints could act as conduits for mineralizing solutions at any time after they were formed. Therefore the age of the deposits can only be determined as post-Middle Silurian.

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