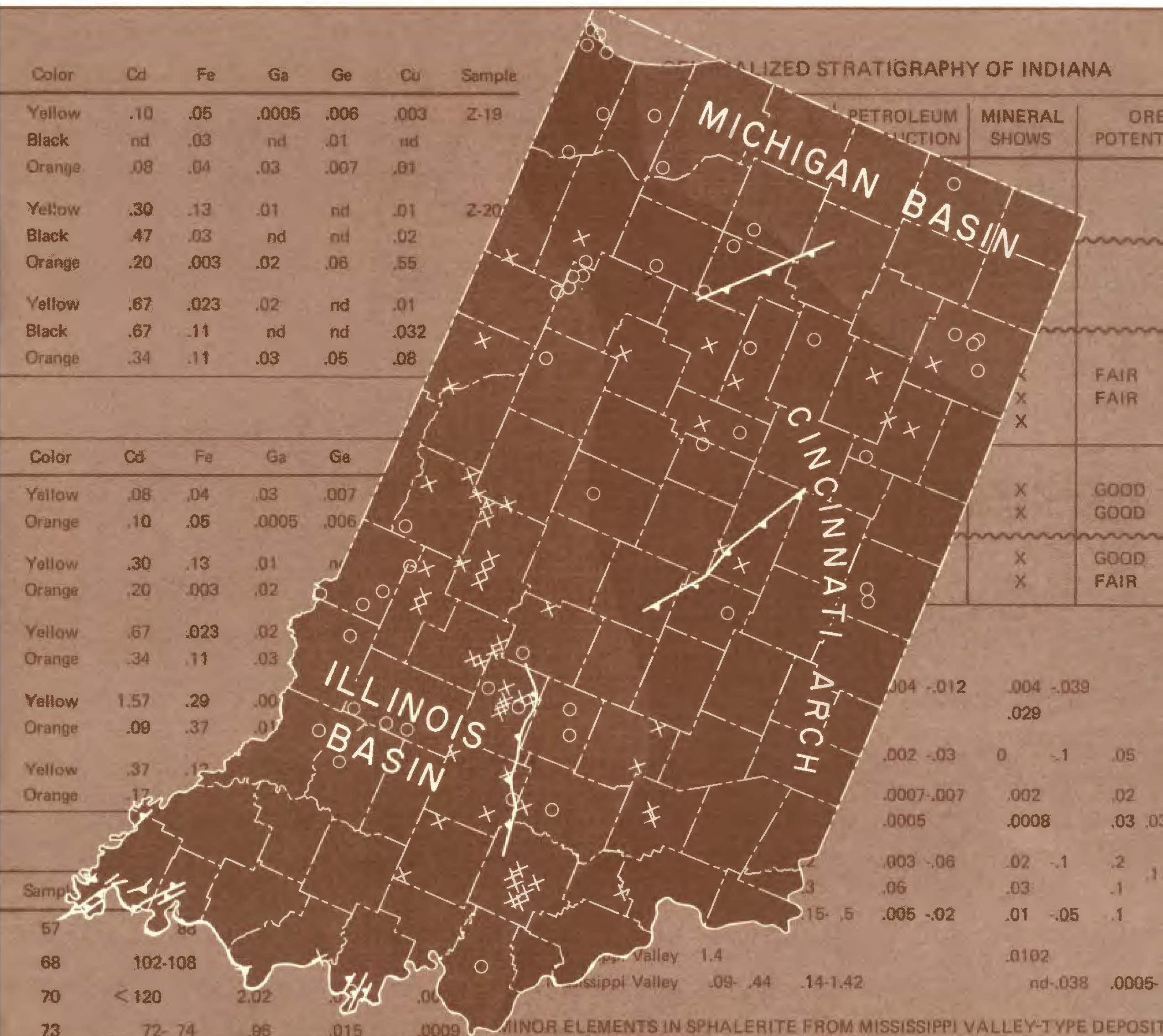
POSSIBILITY OF MISSISSIPPI VALLEY-TYPE MINERAL DEPOSITS IN INDIANA

Special Report 21



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Possibility of Mississippi Valley-Type Mineral Deposits in Indiana

By NELSON R. SHAFFER

DEPARTMENT OF NATURAL RESOURCES
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By NELSON R. SHAFFER

Abstract

The midwestern United States is recognized as a lead-zinc metallogenetic province because of its low-temperature Mississippi Valley-type ore deposits. These deposits are found in Paleozoic dolomitic host rocks, commonly on the flanks of structurally high areas far from areas of igneous activity. They have simple mineralogies, mostly sphalerite, fluorite, galena, or barite, that are believed to have formed at low temperatures (70° to 200°C) from concentrated brines. One commonly accepted explanation of the origin and characteristics of Mississippi Valley-type deposits is that they were the natural consequence of basin development when sedimentary connate waters, the metal-bearing brines, migrated updip from the basin and precipitated ore minerals on encountering sources of reduced sulfur.

Indiana lies within a structural framework and contains many geologic features that appear suitable for the development of Mississippi Valley-type deposits. A structurally high area, the Kankakee and Cincinnati Arches, crosses Indiana from northwest to southeast and separates the Michigan and Illinois Basins. Potential-ore host rock occurs in the Knox Dolomite (Cambro-Ordovician); the Black River and Trenton Limestones (Ordovician); the Salamonie Dolomite, the Louisville Limestone, and the Wabash Formation (Silurian); the Muscatatuck Group (Devonian); and the Sanders and Blue River Groups (Mississippian). Unconformities are at the top of the Knox, the Trenton, and the Wabash. Many occurrences of sphalerite, fluorite, barite, and galena in Indiana had already been noted, and more than 90 new ones were found during this study. Most new occurrences were in the Black River-Trenton section, especially in northern Indiana where the rocks had been extensively dolomitized. In northern Indiana many minerals occur in the dolomitized reef facies of the Silurian System and in the overlying Devonian limestones. In southern and southwestern Indiana sphalerite and fluorite occur in the Salem and Ste. Genevieve Limestones. Preliminary information from fluid inclusions in sphalerite samples indicates that some specimens formed at temperatures within the range reported for Mississippi Valley-type deposits.

Favorable geology, ore minerals in minor amounts, and tentative evidence that ore-type fluids passed through suitable host rocks indicate that undiscovered Mississippi Valley-type ore deposits possibly exist in Indiana.

Introduction

The midwestern United States is generally recognized as a lead-zinc metallogenetic province because of many lead-zinc ore deposits. These deposits, collectively called Mississippi Valley-type, have similar geologic characteristics and, according to many geologists, a similar origin in the Midwest. Deposits of this type occur in southeastern Missouri, the Illinois-Kentucky fluorite district, the tri-state region of Oklahoma, Kansas, and Missouri, the upper Mississippi Valley, eastern and central Tennessee (fig. 1), and foreign countries.

Common features of these deposits, as summarized by Ohle (1959, 1970), Snyder (1968), Heyl and others (1974), and many others, include: (1) occurrence in shallow-water carbonate rocks of Paleozoic age, mostly in dolomitized areas; (2) location on flanks of structurally high areas, mostly far from igneous or tectonically active areas; (3) simple mineralogy of sphalerite, galena,

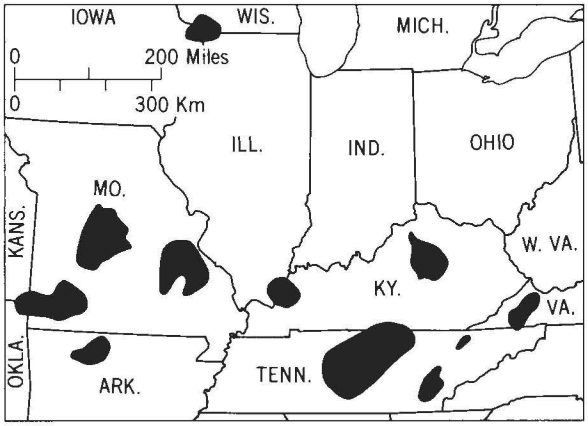


Figure 1. Map of the midwestern United States showing areas with Mississippi Valley-type mineral deposits. Modified from Worl and others (1974); McKnight and others (1962a, 1962b); and Brobst (1965).

fluorite, and barite with carbonate or quartz gangue and traces of asphaltic material; (4) apparent formation in open spaces at low temperatures (70° to 200°C) from highly saline brines; (5) galena with anomalous lead isotopes; and (6) highly variable sulfur isotope ratios. Callahan (1964) pointed out the association of many deposits with unconformities and suggested that unconformities contribute to ore formation, but others dispute the importance of unconformities in localizing ore.

Many explanations of the observed characteristics and the origin of these deposits have been advanced. One explanation by Noble (1963), Jackson and Beales (1967), Beales (1975), and many others is that Mississippi Valley-type ore deposits are formed as a normal step in the evolution of sedimentary basins. As part of this evolution, connate brines in deep parts of the basin become enriched in metals and are heated to moderate temperatures, perhaps as a byproduct of petroleum formation (Dozy, 1970; Macqueen, 1976). The warm, metal-rich brines migrate updip (fig. 2*A*) to structurally higher areas in a manner similar to petroleum migration. Deposits form when the brines encounter suitable traps (fig. 2*B*) and sources of reduced sulfur that cause precipitation of dissolved metals as sulfides. The most likely source of sulfur is H_2S-rich natural gas, but other sources could be oil shales, petroleum, coal, or syngenetic pyrite (Ohle, 1977).

Not all workers agree with this explanation (for example, Ohle, 1977), but it is plausible, and metal-rich subsurface brines do occur (Billings and others, 1969; Carpenter and others, 1974). This and other theories on the formation of Mississippi Valley-type deposits have been summarized by Bastin (1939), Brown (1967, 1970), White (1968), and many others.

If near-surface igneous sources are not needed to form deposits, as most workers will admit, and if brines formed in large sedimentary basins can cause mineralization, then Indiana possibly contains Mississippi Valley-type ores. It lies in the lead-zinc region of the central United States, and it has a structurally high area—the Cincinnati and Kankakee Arches—that trends diagonally across the state and separates two basins containing large volumes of Paleozoic carbonate rocks. Ore deposits occur along this arch in central Kentucky and central Tennessee and along a possibly related feature in northern Illinois. Indiana's proximity to known ore districts, the gross similarities of its geology to that of mineralized areas, and recent theories about the origin of Mississippi Valley-type ores make Indiana a favorable area for these deposits.

Geologic Setting

Indiana occupies about 36,290 square miles of the stable craton in North America, which according to King (1959) has undergone only minor tectonic activity. Unconsolidated glacial materials cover the bedrock in about five-sixths of the state (fig. 3). Bedrock consists of 3,000 to 14,000 feet of Paleozoic sedimentary rocks that fill the Michigan and Illinois Basins and drape over a basement high (fig. 4) that crosses Indiana from northwest to southeast (fig. 5). The structurally high area consists of two parts: the Kankakee Arch, which is a southeasterly extension of the Wisconsin Arch, and the Cincinnati Arch, which is the northwestern part of a structural feature that extends southward through Ohio, Kentucky, and Tennessee, where it is covered by rocks of the Mississippi Embayment. The two arches join near Logansport in northwestern Indiana along a structurally low feature that is marked on its northwest side by the Royal Center Fault (fig. 5).

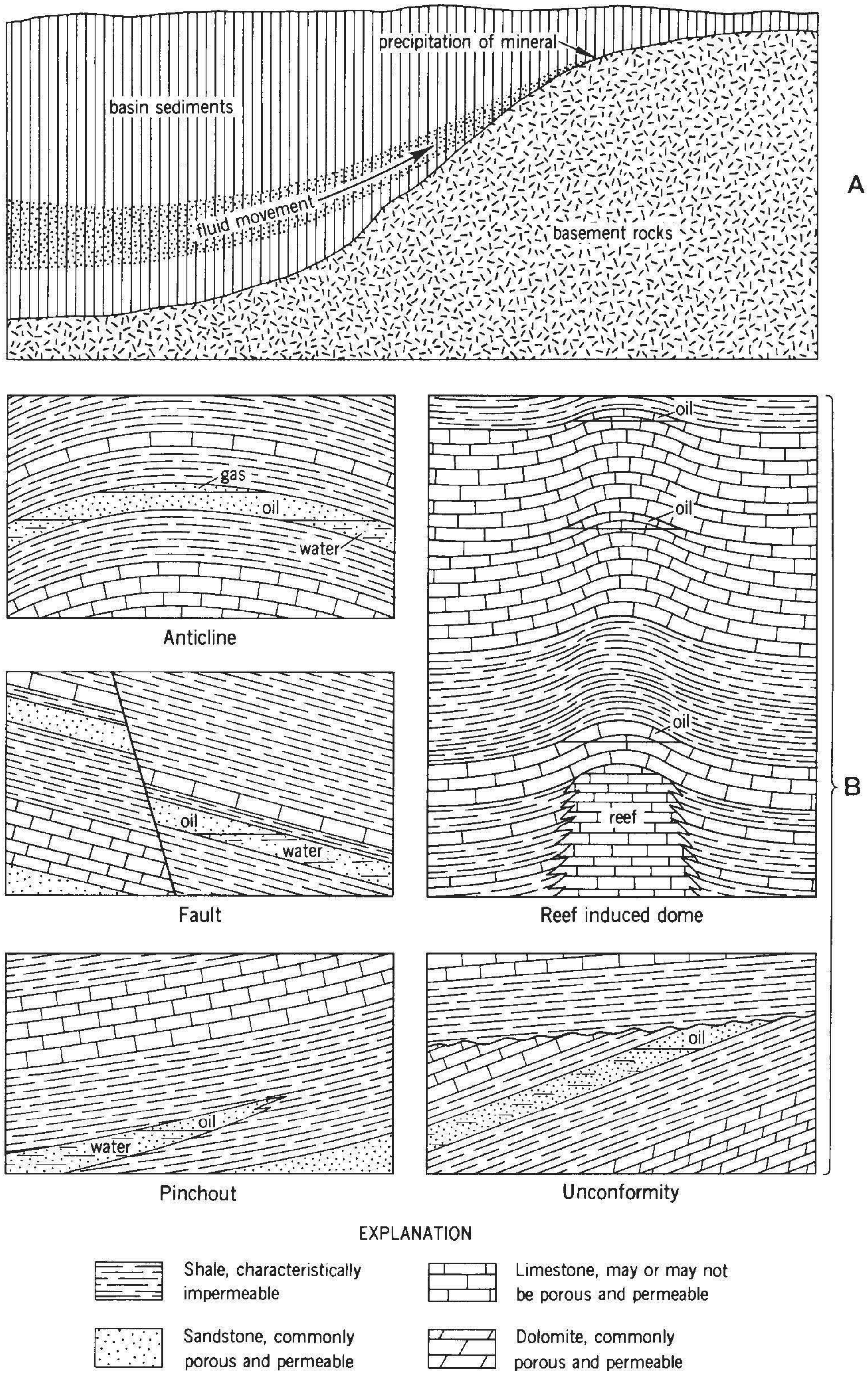


Figure 2. Diagrams illustrating recent theory of origin of Mississippi Valley-type ores (*A*) and possible trapping structures for oil or ore fluids (from Carpenter and others, 1975) (*B*).

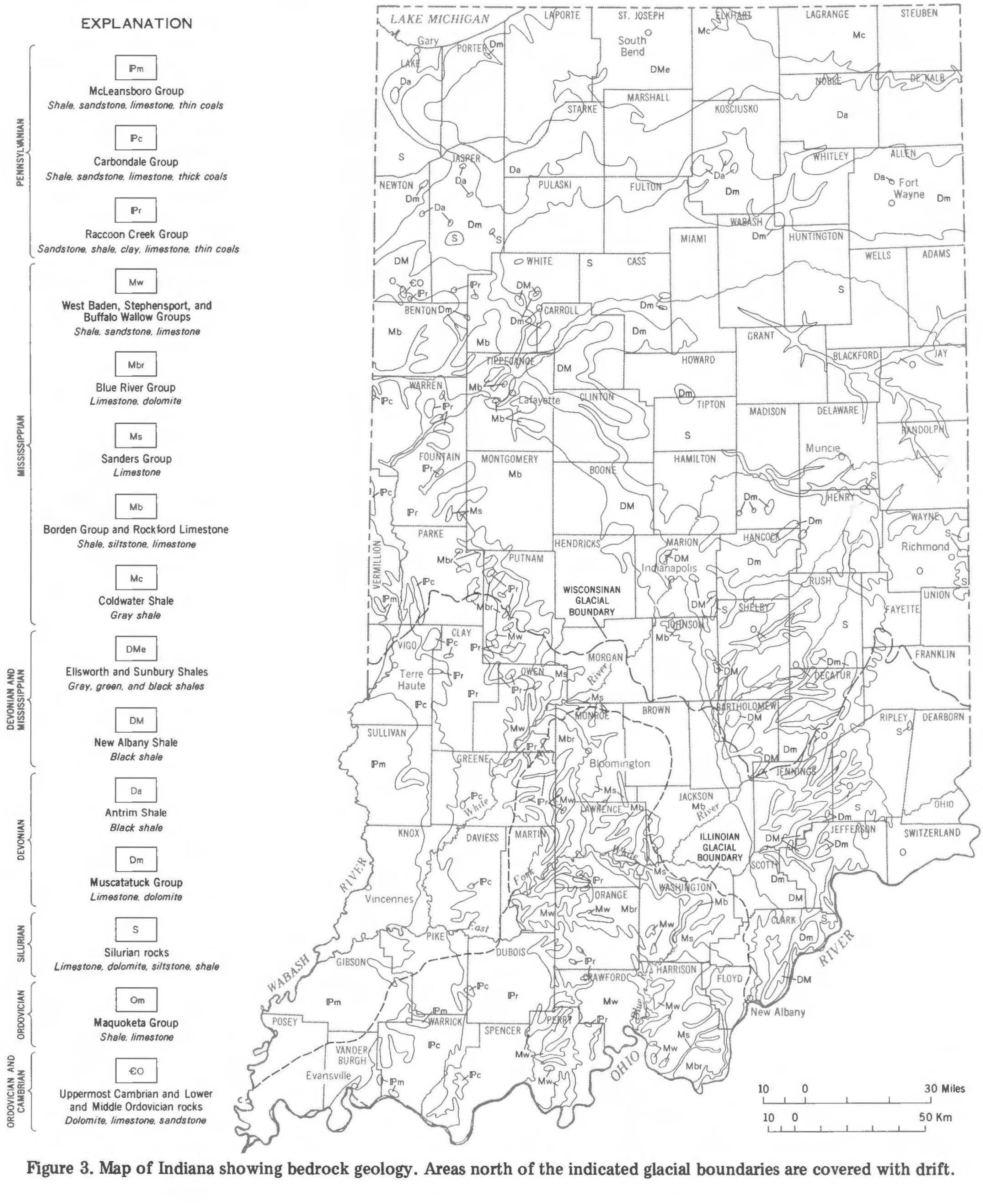


Figure 3. Map of Indiana showing bedrock geology. Areas north of the indicated glacial boundaries are covered with drift.

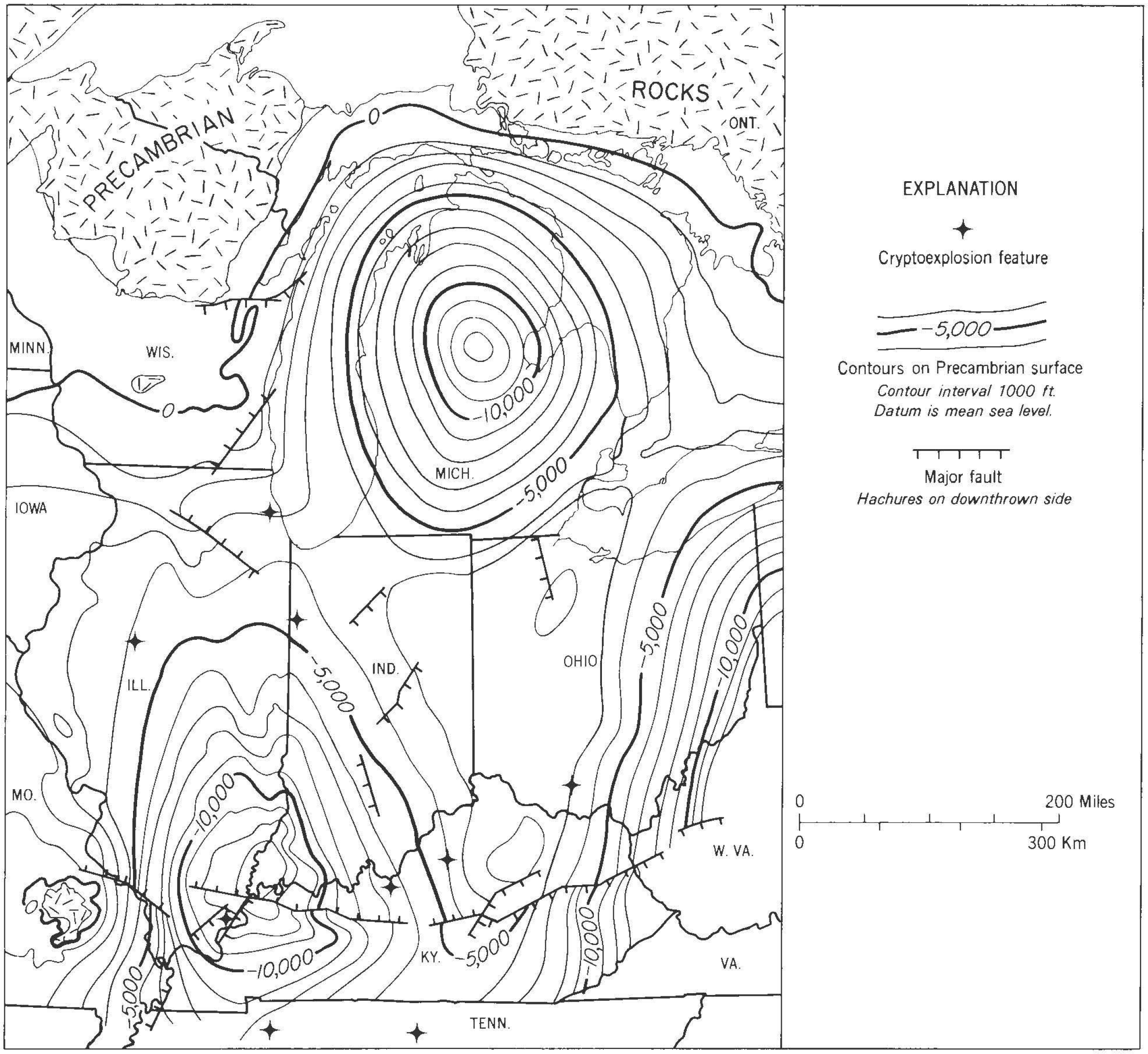


Figure 4. Map showing structural framework and cryptoexplosion features in Indiana and nearby states. Modified from Bond and others (1971).

Ore deposits occur along the Cincinnati Arch in Kentucky and Tennessee and along the Wisconsin Arch in the upper Mississippi Valley district. The arches are not anticlines that resulted from uplift but are areas that remained relatively stable as surrounding basins subsided. They form a broad, relatively flat area of about 10,000 square miles. Sedimentary rocks dip from the ill-defined crest of the arch into the basins at only 25 to 60 feet per mile, but dips steepen toward the center of the basins. Older rocks crop out along the arch area, and younger rocks are exposed in the basin areas (fig. 3).

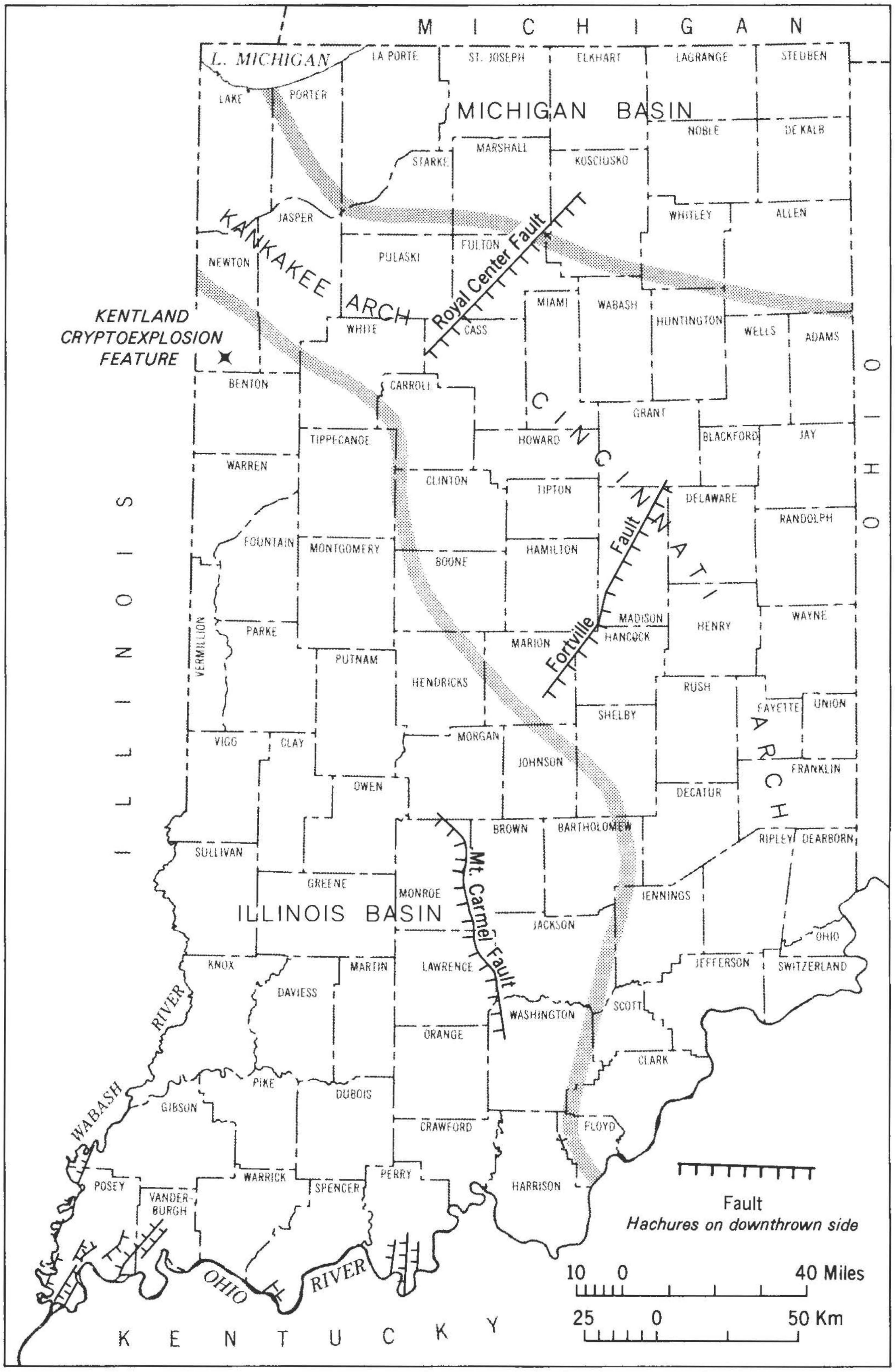


Figure 5. Map of Indiana showing tectonic features and faults. Modified from Blakely and Varma (1976).

The Illinois Basin underlies about 20,000 square miles of Indiana and contains an estimated 108,000 cubic miles of rock (Bond and others, 1971). It is roughly spoon shaped, the deepest point lying about 14,000 feet below the surface in southeastern Illinois. The large structures in the Illinois part of the Illinois Basin and of interest to this study are: the north-southward-trending LaSalle Anticline in the eastern part; mafic igneous dikes in the southeastern part; and the Rough Creek Fault System in the southern part. The latter is a major fault system that has maximum displacements of more than 2,000 feet. It and a northeast-southwestward-trending fault system that extends into the Wabash River valley are closely connected with mineralization in southeastern Illinois. The Rough Creek Fault System can be tied in with other structural features across much of the eastern United States to form the 38th parallel lineament of Heyl (1972). Parts of this system and faults in the Wabash River valley affect southern Indiana. (See figs. 3 and 4.)

The Michigan Basin is roughly circular and contains about 108,000 cubic miles of sedimentary rocks; an estimated 47 percent are carbonate rocks, 23 percent sandstone, 18 percent shales, and 12 percent evaporites (Combs, 1971). Precambrian basement rock is estimated to lie 14,000 to 15,000 feet beneath the surface at the deepest point, which seems to have changed position through time but is presently near the center of Michigan (Ells, 1971). The basin contains northwestward-trending anticlines, some of which are faulted, structures related to buried reefs, and structures related to salt flowage or solution. Oil is produced in the basin, and ascending fluids that caused dolomization are evident (Cohee, 1948). Shawe (1976) suggested that heated ascending fluids caused solution of limestone, dolomitization, and formation of minor sulfides in the Albion-Scipio Trend of Michigan. In Indiana the Michigan Basin is fringed by a large reef bank (fig. 11).

Major faults in Indiana are the Mt. Carmel, Fortville, and Royal Center Faults. The Mt. Carmel in south-central Indiana has been traced 55 miles. It is a normal fault and has a displacement of 80 to 175 feet, and its west side is down (Melhorn and Smith, 1959). Structures associated with this fault have produced gas. The Mt. Carmel Fault and smaller faults in Floyd (Harris, 1948) and Perry (Hughs, 1951) Counties appear at the surface. The Fortville Fault trends northeast-southwestward through parts of Madison and Marion Counties and has displacements of about 100 feet. A similar fault, the Royal Center, is in Cass, Marshall, and Kosciusko Counties. The latter two faults, whose traces at the bedrock surface are covered by glacial drift and were found by drilling, cut across the Cincinnati Arch. Some faults are known to occur in but not above the Trenton Limestone (Rooney, 1966), and a small but complexly faulted area occurs near Kentland in northwestern Indiana. This area, known as a cryptoexplosion feature, has been studied by Gutschick (1976) and Tudor (1971). It is 4 miles across, and the central part of this circular disturbed area contains rocks that have been uplifted more than 1,500 feet. It resembles such structures as those at Serpent Mound, Ohio, Flynn Creek, Tennessee, and Rose Dome, Kansas.

Sedimentologic evidence from facies changes in the Trenton, noted by Rooney (1966), seismic evidence by Woollard (1958), and interpretation of geophysical measurements by Henderson and Zeitz (1958) suggest that a hinge line runs across southern Indiana and connects the faulted and mineralized area in southeastern Illinois and the St. Lawrence River valley disturbances. According to Rooney, this hinge may someway be connected with the Precambrian Grenville boundary postulated by Rudman and others (1965) to occur east of this general region. Possible hinge areas may also be marked by reef banks around the Michigan and Illinois Basins.

Structurally, Indiana appears suited to host ore. It contains a major positive area (Cincinnati and Kankakee Arches). Deep basins on either side of the arches contain thick sequences of potential source rocks that have been buried deeply enough to produce oil or gas and probably also warm mineralizing fluids. Faults occur that could transmit heated fluid upward, even from the Precambrian basement. Potential-ore traps are afforded by these and major unconformities.

Stratigraphy

Potential-ore host rocks occur throughout the stratigraphic section. General information concerning the extent, thickness, lithology, and features pertinent to their potential role as source or host rocks is summarized below for some rock units in Indiana.

The Paleozoic rocks in Indiana (fig. 6) consist mainly of shallow-water carbonate rocks, sandstones, shales, evaporites, and coal. The carbonate rocks are of main concern for this study because most Mississippi Valley ore deposits are hosted by dolomite or limestone. Organic-rich black shales, such as are found in the New Albany Shale, or coals of Pennsylvanian age have some potential for mineralization and should not be overlooked, but carbonate rocks are the mostly likely host rocks. Precambrian basement rocks generally lie too deep below the surface to be considered as reasonable exploration targets, but highs on the Precambrian surface may help channel ore fluids or localize ore.

PRECAMBRIAN

The Paleozoic sedimentary section rests unconformably on Precambrian basement rocks. Only about 20 wells have penetrated this basement, so only broad generalities are known about it. Kottlowski and Patton (1953) and Greenberg and Vitaliano (1962) have described Precambrian rocks of Indiana petrologically, and Rudman and others (1965) have summarized the general distribution of rock types. Bradbury and Atherton (1965) have described Precambrian rocks in Illinois, and Botoman (1975) and Owens (1967) have described those in Ohio. Rudman and others (1965, 1972) have summarized geophysical evidence of the basement rocks in the Midwest and Indiana, and Lidiak and others (1966) have reported isotopic ages obtained from basement rocks of the Midwest. These reports indicate that the basement consists of igneous and metasedimentary rocks about 1.1 to 1.3 billion years old. Igneous lithologies range from abundant granites to sparse basalt, and metamorphic lithologies consist mainly of marble and metasediments. Direct evidence for pronounced highs on the bedrock surface that could help localize ore is lacking, but these highs have been postulated.

Interpretations of the basement surface, based on geophysics and information from a few wells, must be very general (fig. 7), but they are valuable because ore tends to occur around high areas. Because of poor well control, only the broad general form of the Cincinnati Arch and the basins can be clearly proved, but geophysical evidence (Henderson and Zeitz, 1958) suggests several distinct topographic highs on the basement surface. But recent work by Rudman and others (1972) explains that geophysical anomalies are due to intrusives or flows of dense magnetically susceptible materials into lighter acidic rocks rather than to relief on the Precambrian surface. Basement scarps have been observed beneath structures in the sedimentary section, and the basic form of the Precambrian surface is assumed to be reflected by overlying sediments (Bond and others, 1971). Relief on the unconformity at the Precambrian surface should be expected. And although a figure of 1,600 feet of relief over about 45 miles in Ohio (Green, 1957) is suspect, well data indicate nearly 700 feet of relief in western Illinois (Bond and others, 1971).

CAMBRIAN AND CAMBRO-ORDOVICIAN

The first sedimentary unit that overlies the Precambrian crystalline rocks in Indiana is the Mount Simon Sandstone. It is medium- to coarse-grained poorly consolidated sandstone that ranges in thickness from 500 feet in southeastern Indiana to more than 2,000 feet in the northwest; the lower 300 to 400 feet of this unit is reddish because of high feldspar content. It is correlative with the Lamotte Sandstone of Missouri and is called the Mount Simon Sandstone in Illinois, Michigan, and Ohio. This unit probably does not contain ore; but it might act as a permeable bed for transmitting deep fluids from the center of the basin to the margin, and its feldspars might provide a source of metals.

Above the Mount Simon lies the Eau Claire Formation, which is mainly dolomitic sandstones, shales, and silty dolomites containing abundant glauconite grains. It thins eastward from more than 700 feet to 500 feet and correlates with the Franconia Formation or Galesville Sandstone of Illinois. The Eau Claire is a possible source for metal-bearing brines.

The Knox Dolomite of Cambro-Ordovician

age conformably overlies the Eau Claire. It contains an estimated 27 percent of the sedimentary rocks of Indiana and is correlative with ore-bearing rocks elsewhere in the Midwest. The Knox ranges from 500 to 1,500 feet in thickness and is composed mainly of gray, white, or tan finely crystalline dolomite, but in places it contains minor amounts of limestone and chert. A thick (400-foot) bed of clean quartz sand is contained within the Knox in southeastern Indiana (Patton and Dawson, 1969). The Knox thins northward because of depositional thinning and erosional truncation of younger beds (fig. 8). Considerable erosion occurred at the top of the Knox. Patton and Dawson (1969) presented evidence for petroleum accumulations in butte-like erosional remnants of the Knox Dolomite and pointed out excellent conditions for entrapment at the top of the Knox throughout most of central and eastern Indiana.

Gutstadt (1958) correlated Knox rocks with those as young as the Shakopee Dolomite or Prairie du Chien Group of Illinois and the Cotter Dolomite of Missouri. He made no correlation with the Knox Group of Tennessee, but he considered that the Shakopee was lithologically similar to the top of a unit in Kentucky called by Freeman (1953) the Jefferson City-Cotter formation. He doubted that truncation was the sole cause of the Knox thinning northward and stated that the upper Knox equivalents are in northern Indiana and Michigan.

The Knox represents one of the best potential-ore hosts in Indiana because it is mineralized in the Midwest; it has an erosional unconformity at its top; it overlies and even has within itself permeable units; it is known to contain some oil; it has dolomite as the dominant lithology; and it contains a few small shows of sphalerite. It represents a reasonably shallow exploration target along the Cincinnati Arch and is only sparsely drilled in much of Indiana.

ORDOVICIAN

Unconformably atop the Knox lie rocks of the Chazyan Series that contain the St. Peter Sandstone and the Joachim Dolomite of the Ordovician System. The St. Peter is loosely consolidated fine- to medium-grained sandstones, and soft green shale occurs spottily at its base; the Joachim is a tan finely crystalline dolomite (Gutstadt, 1958). Both formations thin eastward and are absent in parts of eastern Indiana. The maximum thickness of the St. Peter is 135 feet, and that of the Joachim is about 70 feet. Although the Joachim may have some ore potential, it is rather thin; the St. Peter is an unlikely host but could have offered avenues for fluid movement.

Overlying the Joachim is a section of Middle Ordovician carbonate rocks—the Black River and Trenton Limestones. The Black River is brown lithographic to fine-grained limestone that has some dolomite or argillaceous units. It ranges in thickness from about 100 feet (fig. 9*A*) in the north, where it is dolomitized, to more than 600 feet in the southwest, where it is limestone with an argillaceous section at the base. Thin bentonitic shales in the upper part of the Black River may represent the Pencil Cave or Mudcave Bentonite of the Tyrone Limestone in Kentucky. Because of its fine grain size and low permeability, the Black River would not likely contain ore. But it is correlative with the Platteville Group of northern Illinois, an ore-bearing rock, and could be a host if fracturing or dissolution produced local areas of increased porosity or open spaces.

The Trenton Limestone (fig. 9*B*) ranges from 0 to about 225 feet in thickness (fig. 9*C*) and thins southward. It consists of tan fine- to medium-grained limestone, but it is extensively dolomitized (fig. 9*D*) in northern and especially northwestern Indiana. Many vugs with dolomite rhombs are present in dolomitized areas, and pyrite is common in the upper parts. These rocks hosted huge deposits of oil and gas in east-central Indiana, and many samples throughout northern Indiana show oil or bituminous residues. Evidence for a widespread unconformity at the top of the Trenton was given by Rooney (1966), who mentioned examples of drilling probably intersecting caves. This suggests that extensive solution and possibly karstification affected the Trenton. The Trenton has good ore-hosting potential because it is correlative with units that contain ore, it is known to have contained fluids capable of dolomitization, and it contains oil. Solution of upper parts of the Trenton probably occurred, and a relatively impermeable shale unit now overlies this upper surface. The Trenton is correlative with the Galena Group of Wisconsin and Illinois.

The Trenton is covered by 200 to 1,000 feet of interbedded shales and limestones of the Maquoketa Group (Ordovician) that is a clastic wedge of rocks whose thickest area is to the east. Calcareous gray or brown shales make up most of this unit, and limestones are only about 20 percent. The limestones have been dolomitized in northwestern Indiana. Gutstadt (1958) and Gray (1972) have described the Maquoketa in detail. This formation shows little promise for ore, but it may have acted as a cap rock that impeded the flow of mineralizing solutions.

SILURIAN

Silurian rocks (fig. 10) unconformably overlie the Maquoketa and consist in ascending order of the thin basal (4- to 14-foot) limestone known as the Brassfield Limestone; the thick (90- to 200-foot) gray fine-grained unit called the Salamonie Dolomite; the thin (10- to 30-foot) argillaceous carbonate or shale called the Waldron Shale or Formation; 50 to 85 feet of mottled brown fine-grained to sublithographic carbonate rocks named the Louisville Limestone; 100 to more than 400 feet of the Huntington Lithofacies (reef facies) and the nonreef facies of the Wabash Formation; and thin (0 to 90 feet) fine-grained limestones or dolomites of the Salina Formation. Rocks of Silurian age are perhaps the most extensively studied rocks in Indiana. They have been studied by Pinsak and Shaver (1964), Shaver (1974a, 1976), Becker (1974), and many others. The Salamonie, the Huntington Lithofacies of the Wabash, and the Salina have some ore potential.

The Salamonie Dolomite is made up of light-gray fine-grained porous dolomite and dolomitic limestone. It contains beds of vuggy dolomite and is cherty in many areas. In southern Indiana it is subdivided into the Osgood and Laurel Members. The Salamonie of northern Indiana correlates with the gray and white rocks of the Niagara Group of Michigan or with the Joliet Dolomite of Illinois. The Salamonie has some potential to host ore because it contains permeable vuggy dolomite, especially in northern Indiana, it is bounded below by an unconformity in much of Indiana, and it is covered by impermeable shale.

Above the Waldron lies light-gray to brown fine-grained argillaceous dolomite or dolomitic limestone known as the Louisville Limestone. This unit is mottled and contains laminae of a black organic component.

Reefs make up a significant part of the Wabash Formation. As previously mentioned, large barrierlike banks occur around the basins. Smaller individual reefs or reef complexes containing several reefs dot the state (fig. 11). Reef rocks are porous, and most of them are almost pure dolomite. They are assigned to the Huntington Lithofacies and are surrounded laterally mainly by fine-grained argillaceous and cherty carbonate rocks of the Mississinewa Shale Member and the Liston Creek Limestone Member. Reefs are valuable sources of dolomite aggregate in northern Indiana, and solution features are commonly observed in places where large sections are exposed in quarries. Several large specimens of sphalerite have been found in these exposures. Silurian reefs have a good potential for being mineralized because they are relatively porous and are surrounded by much less porous rock, many of them are composed of dolomite, many of them contain dead oil, and some of them show solution features below a major unconformity. Reefs host or are associated with Mississippi Valley-type deposits elsewhere, but Silurian rocks throughout the world rarely contain this type of deposit.

DEVONIAN

Overlying Silurian rocks are Lower and Middle Devonian (fig. 12) carbonate rocks. Lower Devonian formations are known to occur only in southwestern Indiana at depth. Becker (1974) noted that Lower Devonian rocks are mainly carbonate rocks or cherty carbonate rocks. Where Lower Devonian rocks are absent, carbonate rocks of the Muscatatuck Group unconformably overlie Silurian rocks.

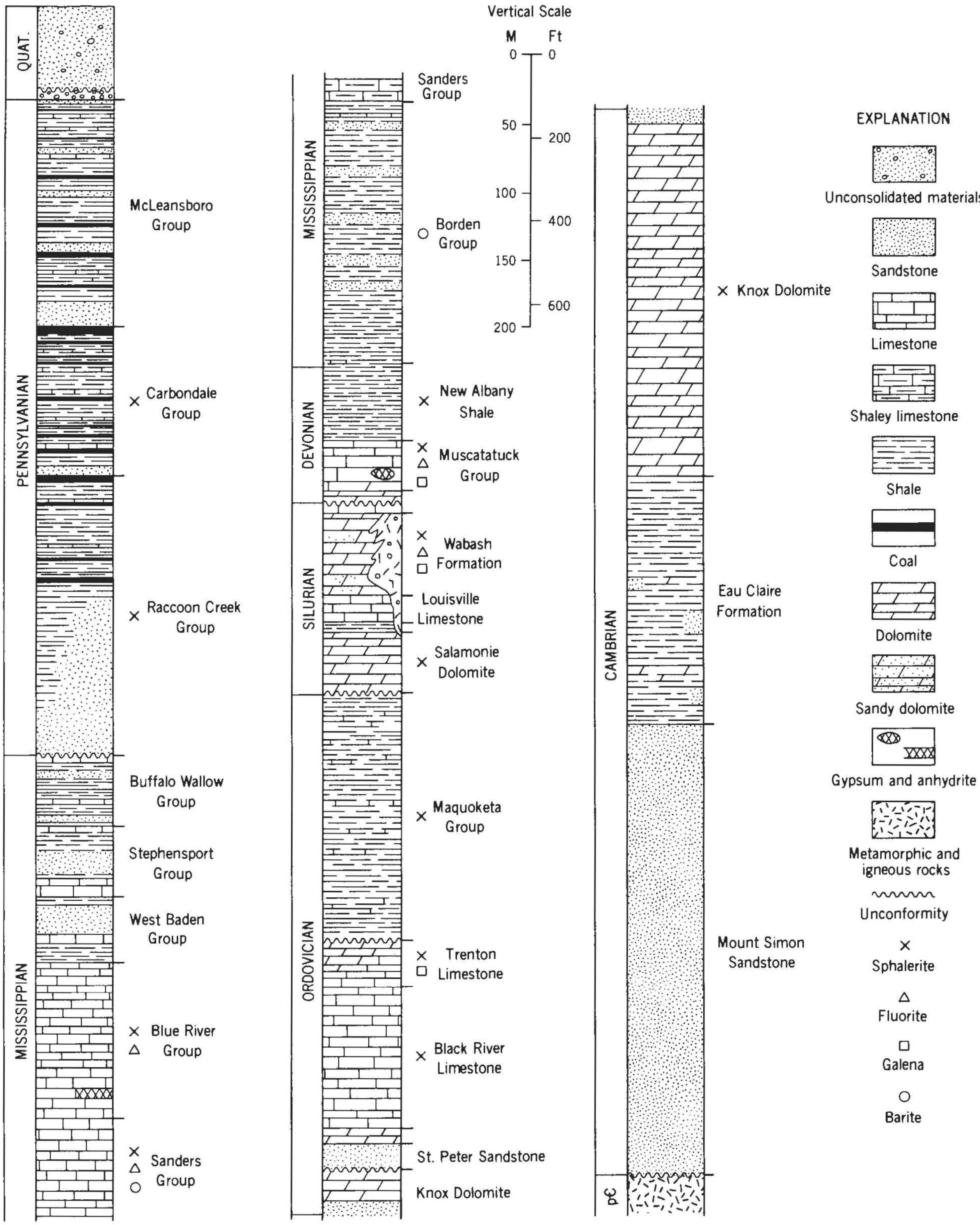


Figure 6. Rock units in which minerals have been found and generalized stratigraphic column of Indiana showing major rock units mentioned in the text. Modified from Shaver and others (1970).

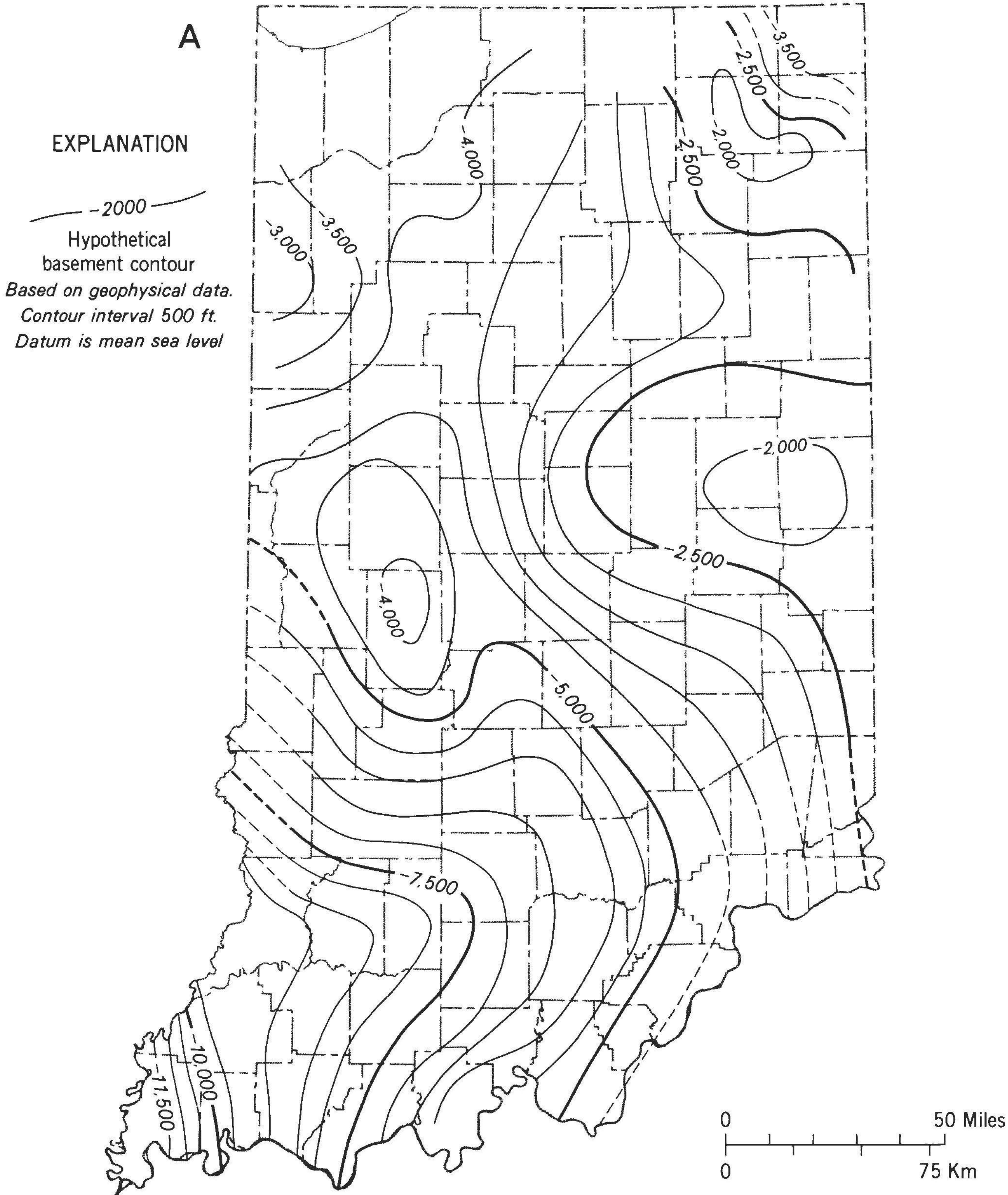
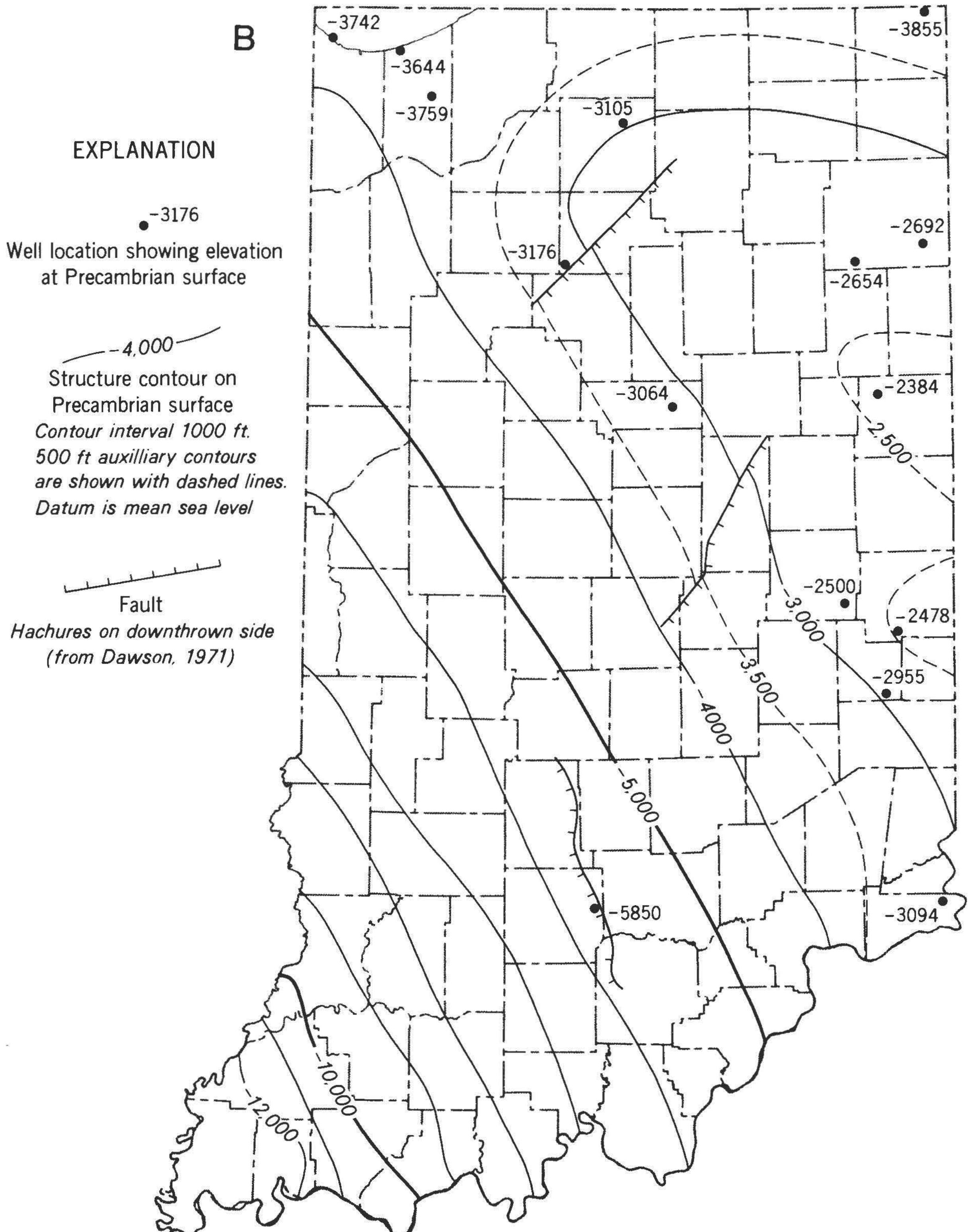


Figure 7. Maps of Indiana showing generalized contours on the Precambrian surface inferred from geophysical measurements (from Henderson and Zeitz, 1958) (*A*) and structure contours on the Precambrian surface and elevations of Precambrian rocks in wells (modified from Bond and others, 1971; Becker and others, 1978) (*B*).



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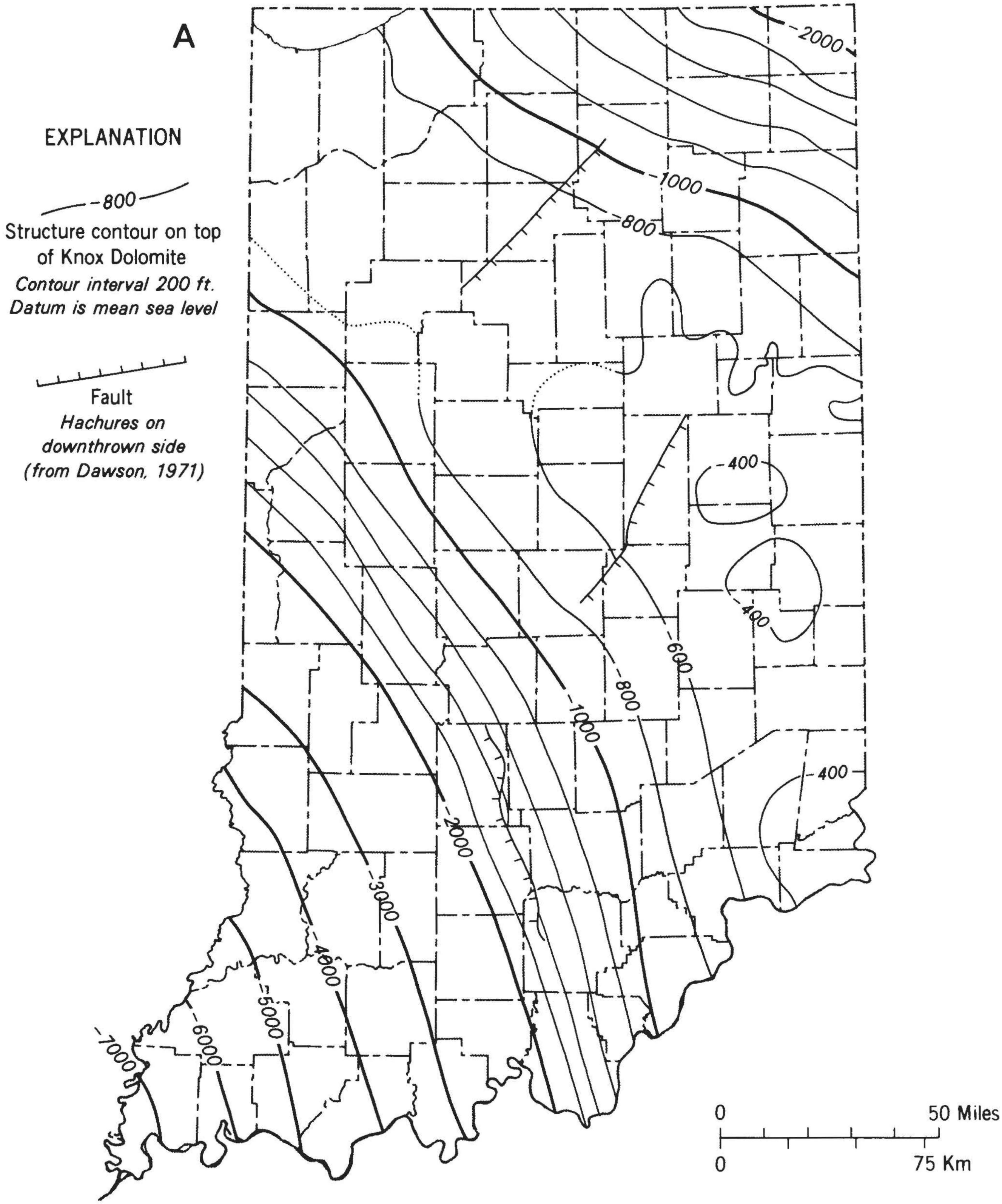
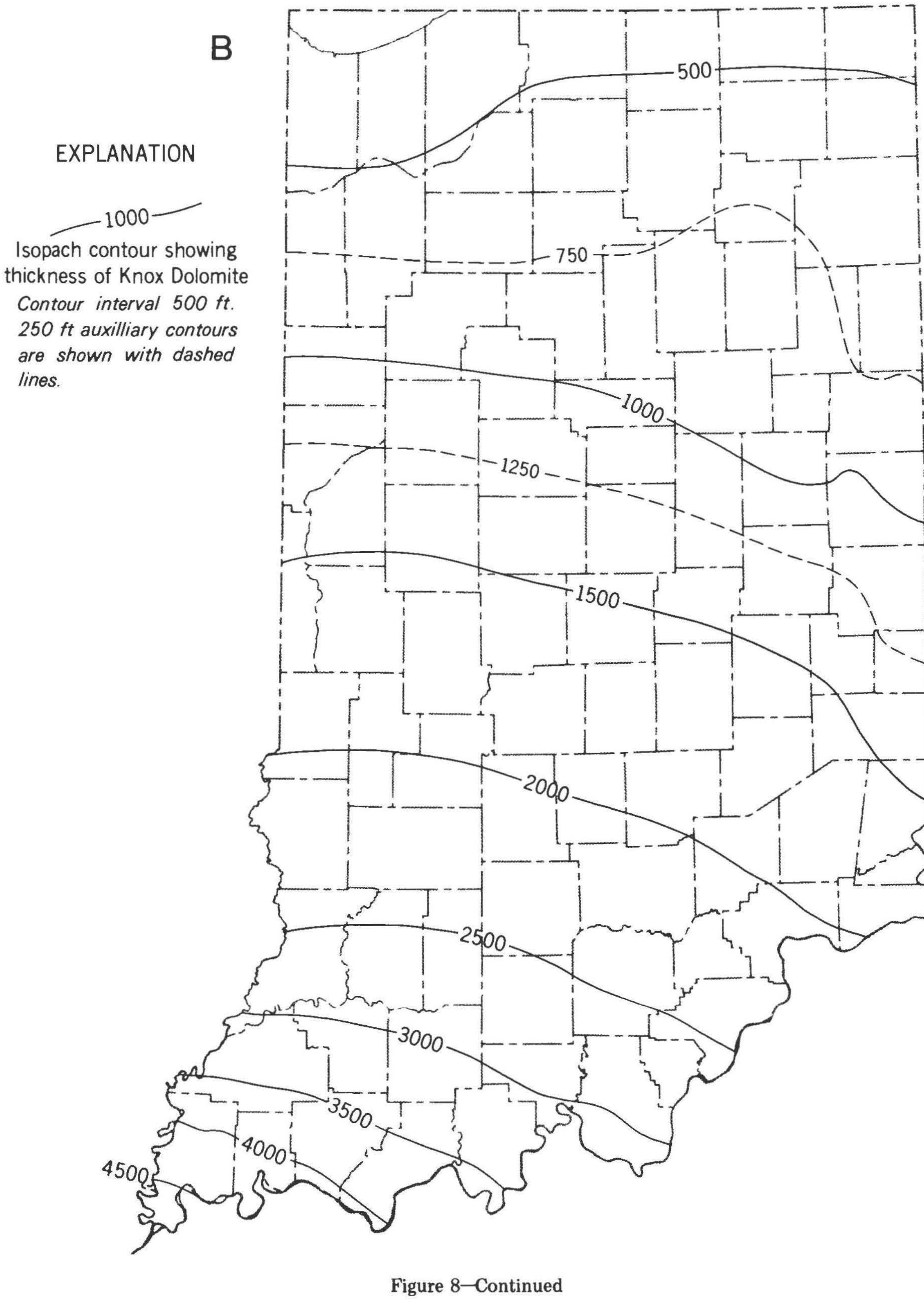


Figure 8. Maps of Indiana showing structure contours on top of the Knox Dolomite (modified from Bond and others, 1971) (*A*) and thickness of the Knox Dolomite in Indiana (from Bond and others, 1971; Dawson, 1960; and Gutstadt, 1958) (*B*).



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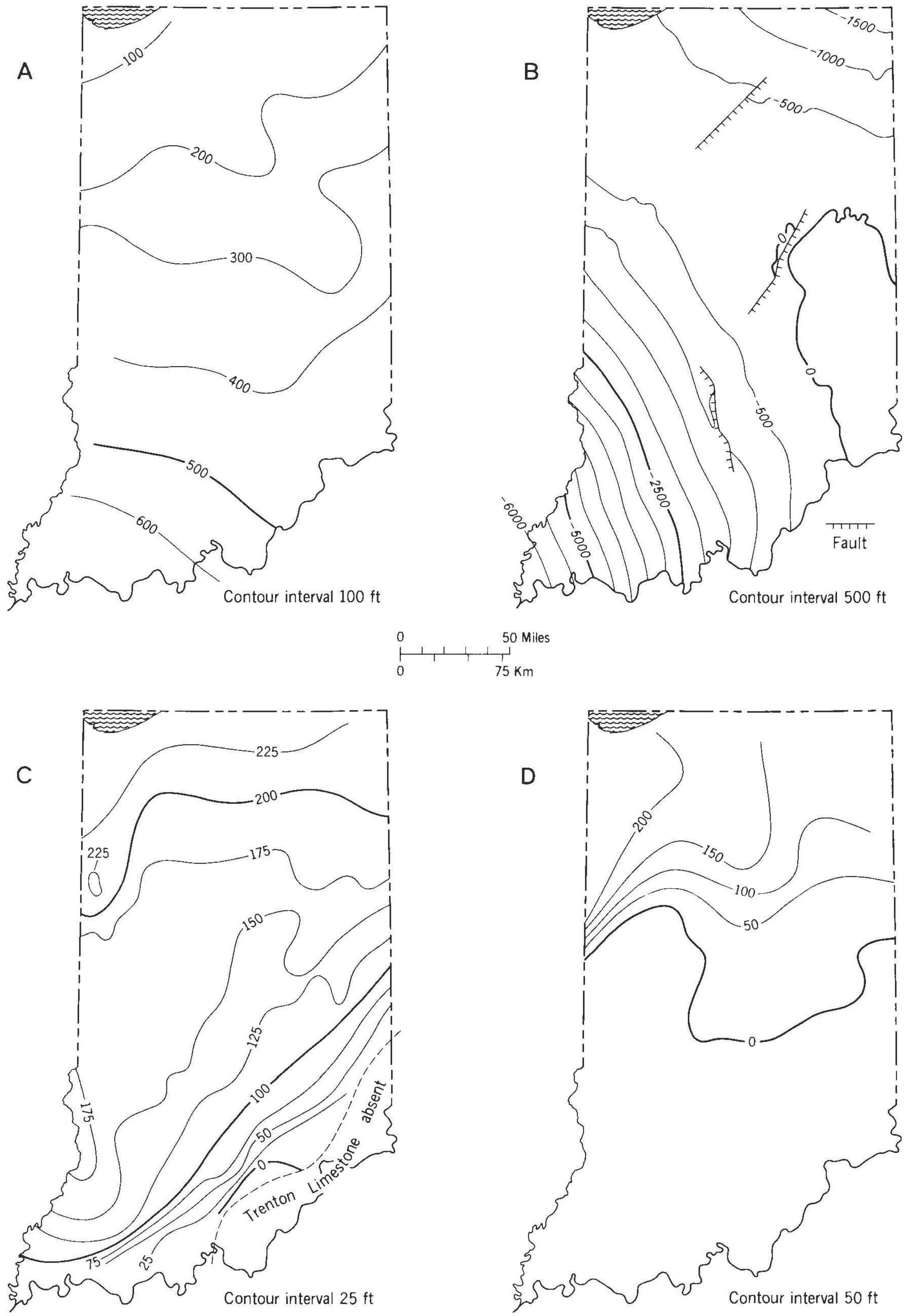
A
100
200
300
400
500
600
Contour interval 100 ft
B
1500
1000
500
0
500
2500
5000
6000
Fault
Contour interval 500 ft
0 50 Miles
0 75 Km
C
225
200
225
175
150
125
175
100
50
0
75
25
Trenton Limestone absent
Contour interval 25 ft
D
200
150
100
50
0
Contour interval 50 ft

The Muscatatuck Group (Shaver, 1974b) contains Middle Devonian carbonate rocks that are assigned to the Jeffersonville Limestone and the overlying North Vernon Limestone in areas southwest of the Cincinnati Arch or to the Detroit River Formation and the Traverse Formation in the area north of the arch. Becker (1974) has described Devonian rocks southwest of the arch; Doheny and others (1975) have reported on the Detroit River, and Droste and Shaver (1975) and Lazor (1971) have studied the Traverse Formation of northern Indiana.

The basal Devonian rocks in central Indiana are assigned to the Geneva Dolomite Member of the Jeffersonville Limestone. The Geneva ranges from 0 to 60 feet in thickness in central Indiana but does not occur everywhere in the state. It consists of buff to brown granular dolomite that commonly contains vugs, carbonaceous laminae, crystalline calcite, and, in west-central Indiana, rounded frosted quartz. This member has potential as an ore host but is rather thin.

South of the Cincinnati Arch the Jeffersonville Limestone overlies Lower Devonian carbonate rocks or Silurian rocks. It thickens southwestward from 25 to about 150 feet. The Detroit River makes up the lower part of the Muscatatuck Group and overlaps various Silurian units in the area north of the arch. The Jeffersonville is made up of fine- to medium-grained light-brownish limestones that are sandy, dolomitic, or cherty in places. It thickens southwestward from 25 feet on the outcrop to 150 feet in southwestern Indiana. The Detroit River Formation contains dolomites and evaporites of sabkha origin, porous replacement-type dolomite, and lithographic limestones (Doheny and others, 1975). It thickens northward from the arch from 0 to 160 feet. These units correlate with the Grand Tower Limestone of Illinois.

The North Vernon Limestone, which contains 1 to 80 feet of variable carbonate rocks in southwestern Indiana, and the Traverse Formation, which consists of 0 to more than 100 feet of fine to coarse limestones and dolomitic limestones in the north, complete the Muscatatuck Group.

Rocks of the Muscatatuck Group have fair potential for mineralization, especially in the north where breccias are noted in the Traverse Formation or where solution of evaporites in the Detroit River Formation might produce open spaces or breccias and in the south where the vuggy dolomitic Geneva Dolomite Member of the Jeffersonville Limestone is present.

The top of the Devonian section is represented by black organic-rich shales of the New Albany Shale. The upper part of the New Albany is Early Mississippian in age. It is separated from a thick sequence of shales and siltstones of the overlying Borden Group (Mississippian) by the thin Rockford Limestone. None of these units are likely to be suitable hosts, although local syngenetic metal enrichment could occur in sulfide-rich parts of the New Albany Shale, which might also contribute metals or sulfur.

Figure 9 (*on facing page*). Maps of Indiana showing thickness of the Black River Limestone (from Gutstadt, 1958) (*A*); structure contours on top of the Trenton Limestone (from Carpenter and others, 1975; Dawson, 1971) (*B*); thickness of the Trenton Limestone (from Gutstadt, 1958) (*C*); and thickness of the dolomite facies of the Trenton Limestone (from Gutstadt, 1958) (*D*).

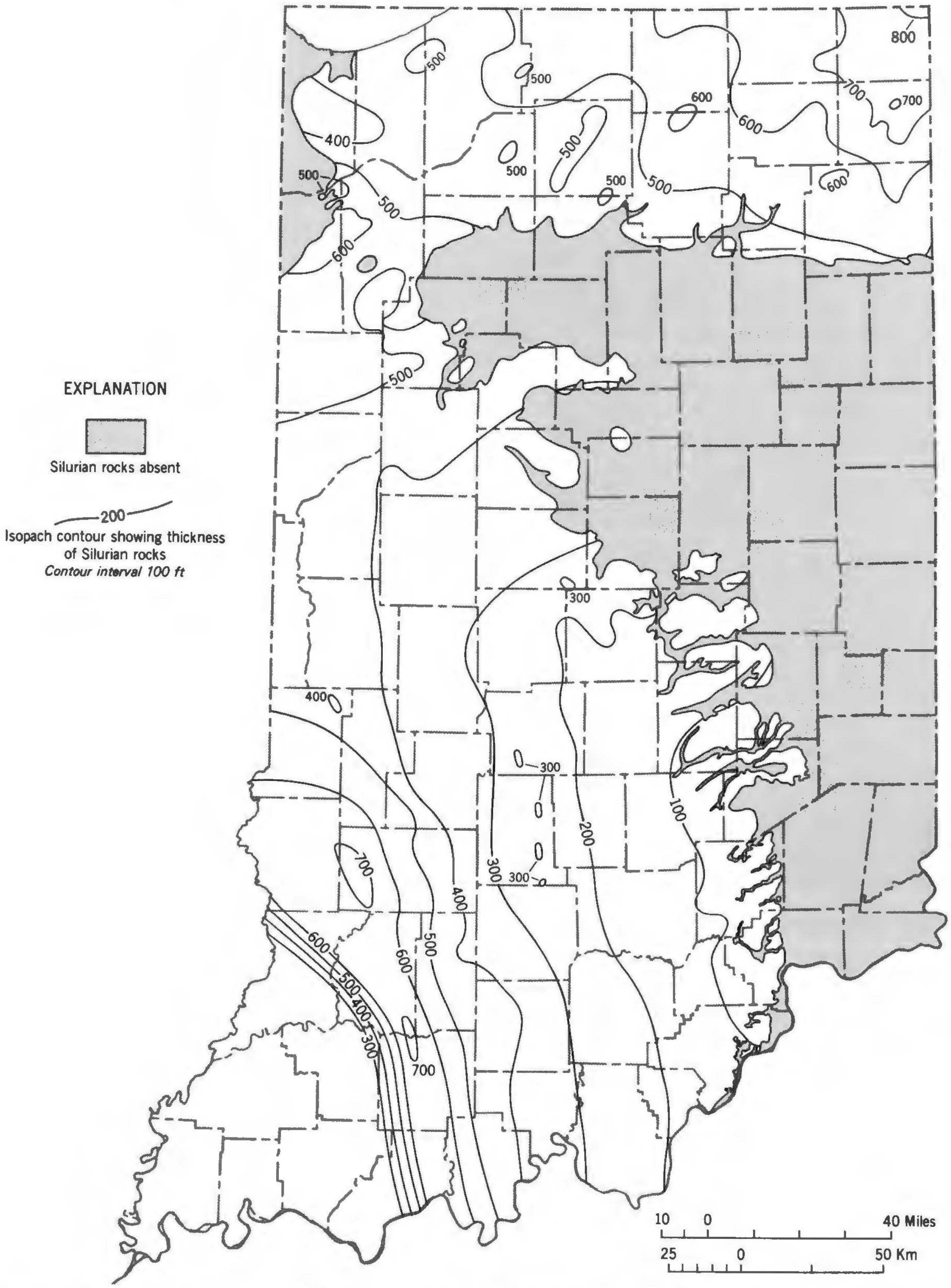

Figure 10. Map of Indiana showing thickness and outcrop of Silurian rocks. Modified from Becker (1974).

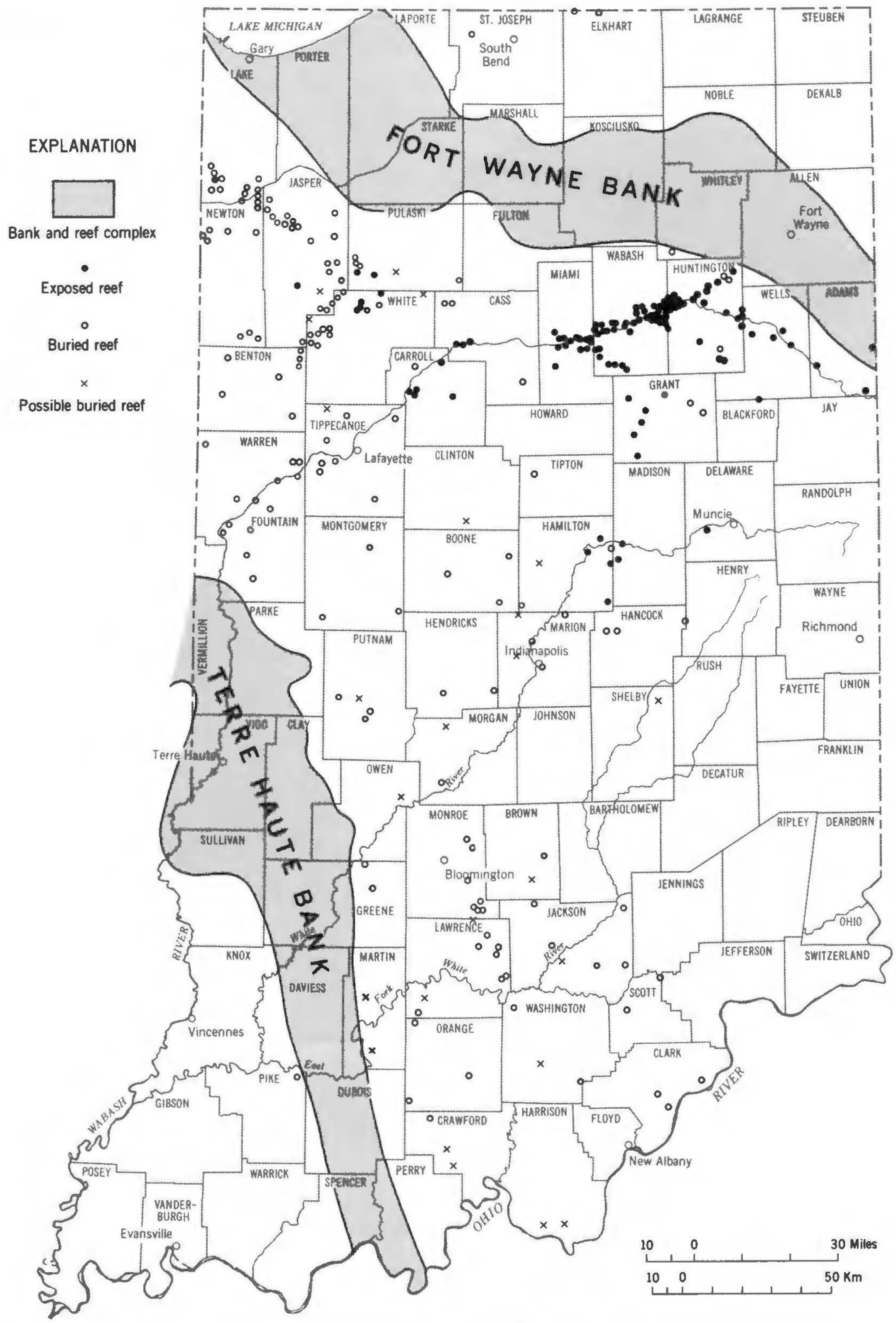

Figure 11. Map of Indiana showing locations of reefs. Modified from Ault and others (1976).

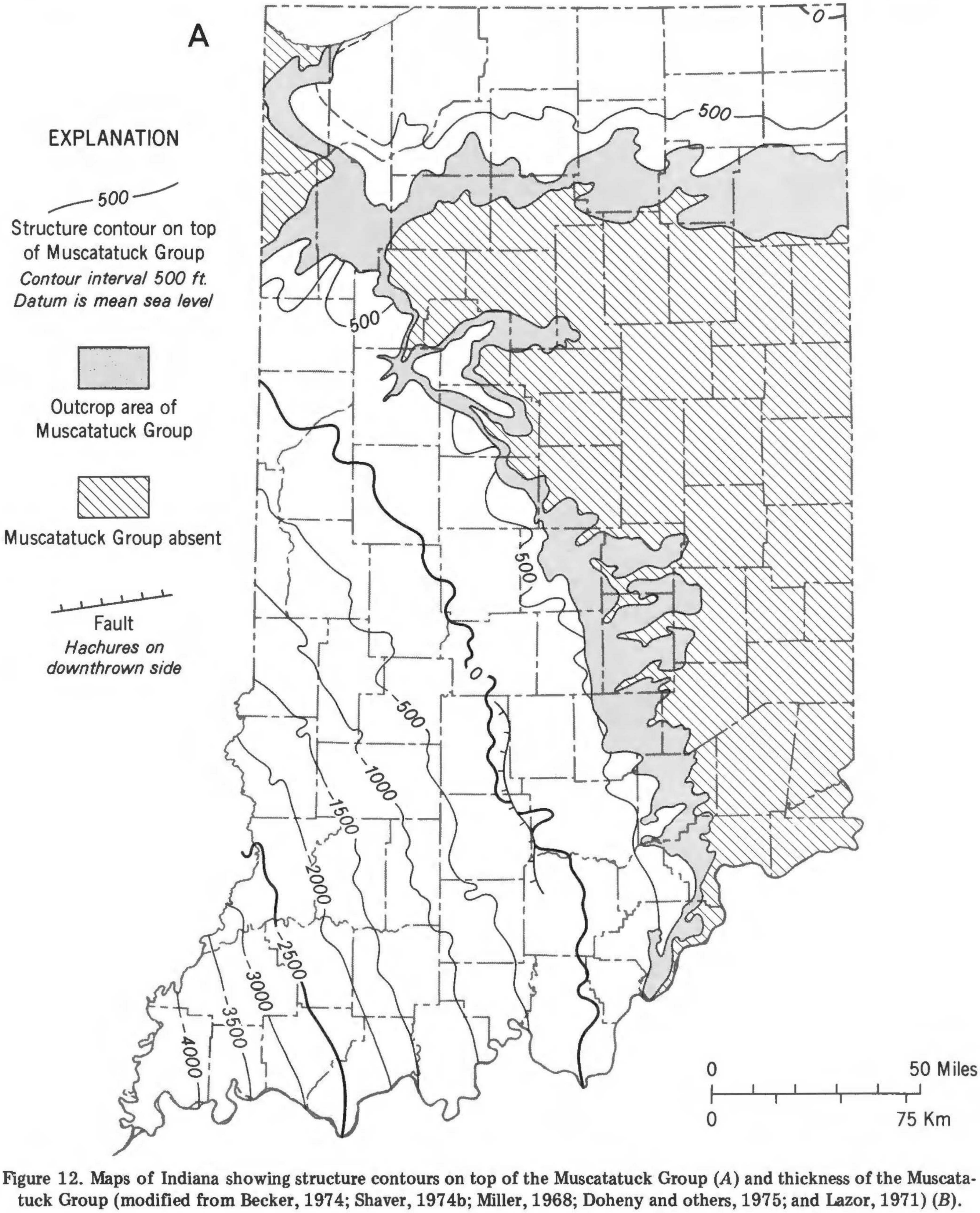

Figure 12. Maps of Indiana showing structure contours on top of the Muscatatuck Group (*A*) and thickness of the Muscatatuck Group (modified from Becker, 1974; Shaver, 1974b; Miller, 1968; Doheny and others, 1975; and Lazor, 1971) (*B*).

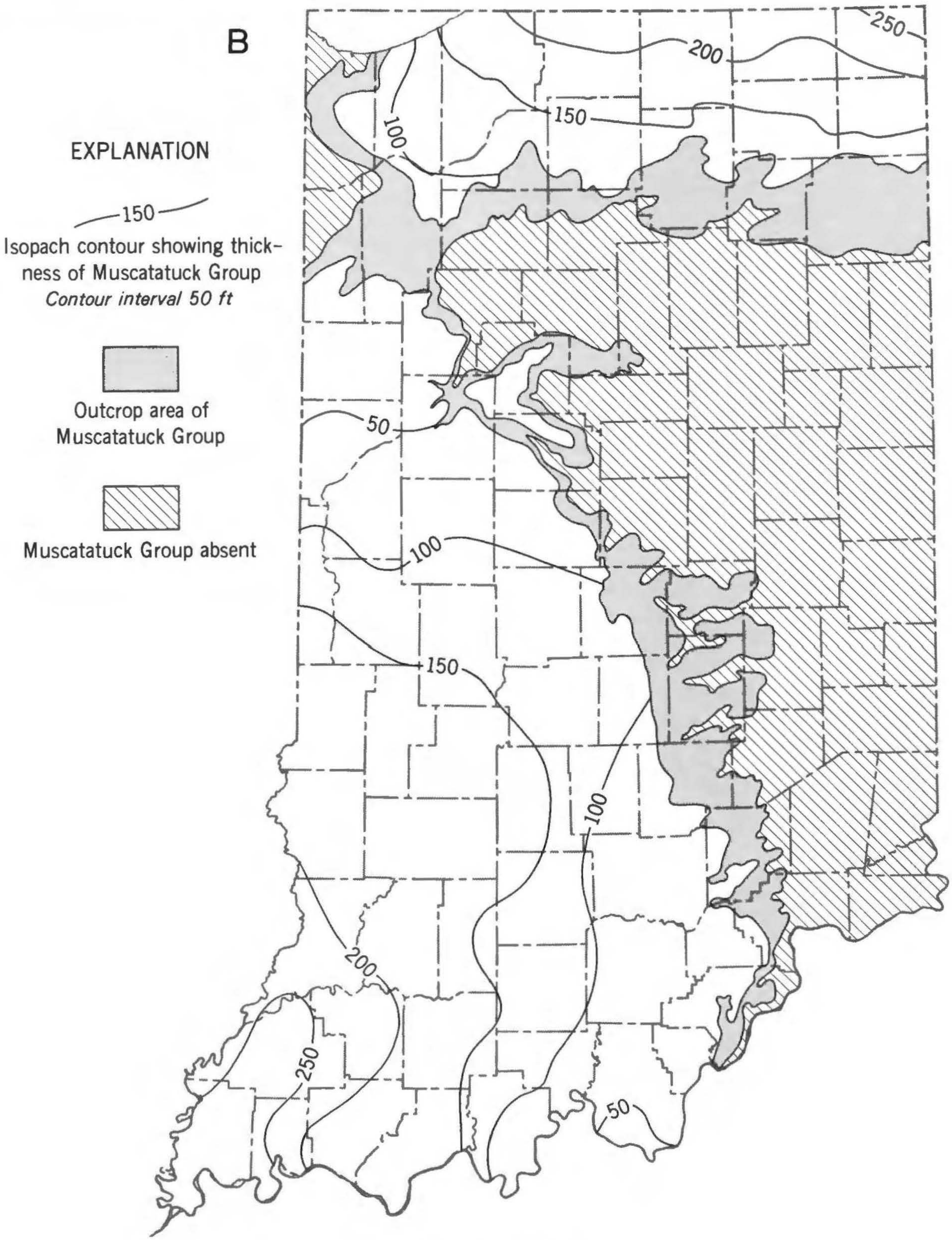

Figure 12—Continued

MISSISSIPPIAN

Mississippian limestones of the Sanders and Blue River Groups that overlie the Borden Group contain 80 to 480 feet and 60 to 400 feet respectively of possible ore host rocks. Pinsak (1957), Smith (1965), Perry and others (1954), and Nicoll and Rexroad (1975) have described these rocks. The Sanders Group is made up of the Ramp Creek Formation, composed of 17 to 28 feet of cherty argillaceous limestones, the Harrodsburg Limestone, composed of 30 to 120+ feet of light-brown coarse-grained biofragmental limestones with thin shale partings, and the Salem Limestone, which is mainly gray to tan well-sorted medium to coarse calcarenite but may also contain fine-grained argillaceous dolomitic limestone. It produces oil and natural gas and contains laminae of carbonaceous material. The Salem and Harrodsburg are possible hosts for ore deposition, especially in places where faulting may have formed breccias or where solution has formed karst areas.

Rocks of the overlying Blue River Group consist of the St. Louis, Ste. Genevieve, and Paoli Limestones. The St. Louis is brown or tan to gray thin-bedded microcrystalline dolomitic limestone that is 80 to 400 feet thick. It contains many black, gray, or greenish shales throughout and brittle blue-gray chert in the upper part. Large deposits of gypsum and anhydrite (fig. 13) occur in the lower St. Louis (McGregor, 1954; French and Rooney, 1969). Thick (10- to 40-foot) lenses of breccia also are found in this lower part. The St. Louis is overlain by 60 to 170 feet of the Ste. Genevieve Limestone, which is composed mainly of micritic, pellet, and lump limestone with considerable skeletal and oolitic limestone and minor amounts of dolomite, shale, chert, and sandstone. Prominent oolite beds occur in the Ste. Genevieve (Carr, 1973), and breccias are also present. The Ste. Genevieve has produced petroleum as has the overlying Paoli Limestone, which consists of 3 to 65 feet of gray oolitic limestone, greenish-gray or dark-gray calcareous shale, dense lithographic limestone, and calcareous sandstone. The Paoli and the upper part of the Ste. Genevieve are equivalent to the Renault Formation of the subsurface. These rocks are correlative with those of the same names in Illinois, where some host ore in the southern Illinois district. Rocks of the Blue River Group have fair potential as possible ore hosts, especially in places where beds are brecciated.

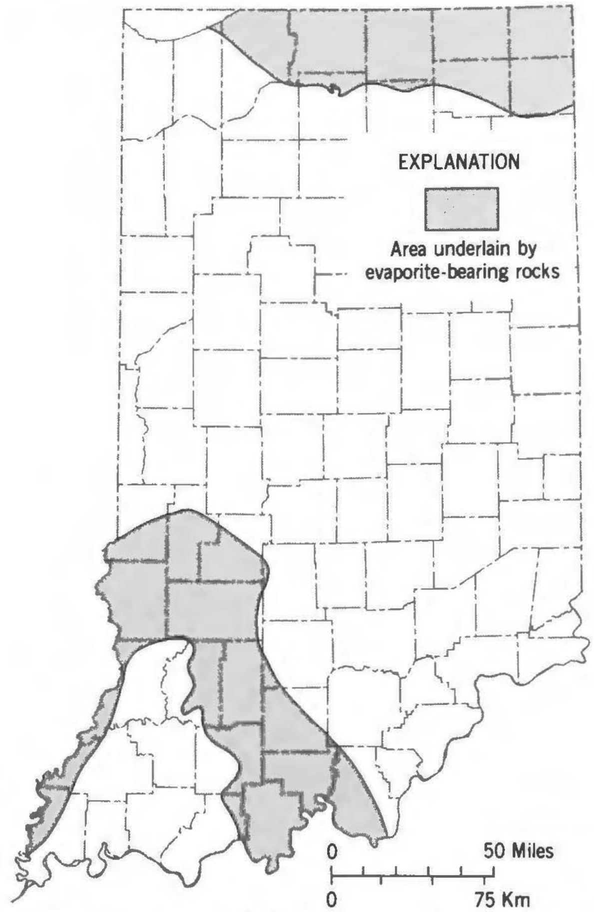

Figure 13. Map of Indiana showing distribution of gypsum and anhydrite. Evaporites occur in the Detroit River Formation (Middle Devonian) in northern Indiana and in the St. Louis Limestone (Middle Mississippian) in southwestern Indiana. From French and Rooney (1969).

Mississippian rocks lying above those of the Blue River Group include 100 to 200 feet of varicolored shales, sandstones, and impure limestones of the West Baden Group (Sullivan, 1972); 130 to 160 feet of gray limestones, shales, and sandstones of the Stephensport Group; and 0 to 350 feet of shales, sandstones, and micritic limestones of the Buffalo Wallow Group (Gray, 1978). No rocks above the Paoli have good potential for being mineralized, except as noted below.

Table 1. General stratigraphy of Indiana showing approximate thickness of rock units mentioned in the text, petroleum and mineral shows, and ore potential

Unit	Lithology[1]	Approximate thickness (ft)	Oil production	Mineral shows	Ore potential
Pennsylvanian					
McLeansboro Group	Sh, ss, c, ls	340- 770	–	–	–
Carbondale Group	Sh, ss, c, ls	260- 470	x	x	–
Raccoon Creek Group	Sh, ss, c, ls	400- 900	x	x	–
Mississippian					
Buffalo Wallow Group	Ss, ls, sh	0- 350	x	–	–
Stephensport Group	Ls, sh, ss	130- 160	x	–	–
West Baden Group	Sh, ss, ls	100- 260	x	–	–
Blue River Group					
Paoli Limestone	Ls, sh	3- 65	x	–	Fair
Ste. Genevieve Limestone	Ls	60- 170	x	x	Good
St. Louis Limestone	Ls, sh, ev	80- 400	–	x	Good
Sanders Group					
Salem Limestone	Ls	50- 360	x	x	Good
Harrodsburg Limestone	Ls	30- 120	x	x	Fair
Ramp Creek Formation	Ls, dol, slt, sh	16- 33	x	x	Fair
Borden Group	Sh, slt	480- 800	x	x	–
Rockford Limestone	Ls	2- 22	–	x	–
Devonian					
New Albany Shale	Carb sh	65- 300+	–	x	–
Muscatatuck Group					
Traverse Formation North Vernon Limestone	Ls	0- 100+	x	x	Good
Detroit River Formation Jeffersonville Limestone	Ls, dol, ev	0- 140	x	x	Good
Silurian					
Wabash Formation	Dol reefs, ls, dol, arg dol	100- 300	–	x	Good
Louisville Limestone	Arg ls, dol	50- 85	–	–	Poor
Waldron Shale (Formation)	Sh, ls, dol	10- 30	–	–	–
Salamonie Dolomite	Dol	90- 200	–	x	Fair
Ordovician					
Maquoketa Group	Sh, ls	200-1,000	–	x	Poor
Trenton Limestone	Ls, dol	0- 225+	x	x	Excellent
Black River Limestone	Ls, dol	100- 600	x	x	Fair
Joachim Dolomite	Dol	0- 70	–	–	–
St. Peter Sandstone	Ss	0- 135	–	–	–

Table 1. General stratigraphy of Indiana showing approximate thickness of rock units mentioned in the text, petroleum and mineral shows, and ore potential—Continued

Unit	Lithology[1]	Approximate thickness (ft)	Oil production	Mineral shows	Ore potential
Cambrian					
Knox Dolomite	Dol, ss	500-1,500	x	x	Fair
Eau Claire Formation	Gla, ss, sh	500- 700	--	--	--
Mount Simon Sandstone	Fld, ss	200-2,000	--	--	--
Precambrian					
	Gn, bs, mt		--	--	--

[1] Sh = Shale
Ss = Sandstone
C = Coal
Ls = Limestone
Dol = Dolomite
Ev = Evaporites
Slt = Siltstone
Carb = Carbonaceous
Arg = Argillaceous
Gla = Glauconitic
Fld = Feldspathic
Gn = Granite
Bs = Basalt
Mt = Metasediment

PENNSYLVANIAN

A major unconformity occurs between Mississippian and Pennsylvanian strata. The Pennsylvanian System consists of three groups: the Raccoon Creek, Carbondale, and McLeansboro Groups. Rocks in this system are mainly clastics and show cyclic sedimentation patterns. Major commercial coalbeds are in the Pennsylvanian. Some coals in the Illinois Basin contain appreciable amounts of sphalerite (Hatch and others, 1976). In Indiana sphalerite has been reported in the Seelyville Coal Member (III) of the Staunton Formation (Boctor and others, 1976) and in the Hymera Coal Member (VI) of the Dugger Formation (Dove, 1921). Although coal seams may contain enough sphalerite to be exploited, no attempt was made in this study to explore this possibility.

SUMMARY

Several stratigraphic units seem to bear gross similarities to rocks that host ore elsewhere in the Midwest. The Knox, Trenton, Salamonie, Wabash (Huntington Lithofacies), Muscatatuck, Sanders, and Blue River rock units may be suitable for developing and hosting ores (table 1).

Previously Reported Mineral Occurrences

The occurrence of sphalerite was noted as early as 1839 when David Dale Owen found sphalerite-bearing concretions in Pennsylvanian rocks of western Indiana. Other early reports mentioning sphalerite were reviewed by Erd (1954). These included occurrences in the coal-bearing rocks of Knox, Vermillion, Pike, Fountain, and Warren Counties; sphalerite-bearing geodes in Harrodsburg and Borden outcrops in Lawrence, Brown, Morgan, and Washington Counties; sphalerite specimens collected by Gorby (about 1886) from unspecified rocks in Harrison, Miami, and Tippecanoe Counties; and minor open-space sphalerite fillings in carbonate rocks in Delaware, Henry, Huntington, Miami, and Wabash Counties of northern Indiana. Many early reports of fluorite and barite and a few occurrences of galena in drift are also known.

Table 2. Previously reported occurrences of sphalerite, barite, and fluorite in Indiana

County	Sec.		T.	R.
	Sphalerite occurrences			
Bartholomew	NE¼	6	8 N	7 E
Clay	NE¼NE¼	25	13 N	7 W
Harrison	SE¼	10	2 S	2 E
Howard	NW¼NE¼	3	23 N	3 E
Huntington	SW¼SE¼	12	28 N	9 E
Jackson	SE¼SE¼	29	5 N	3 E
	SW¼SE¼	29	5 N	3 E
Jasper	SE¼SE¼	30	29 N	6 W
Jennings	NE¼	34	7 N	8 E
Knox	Donation	142	4 N	8 W
Lawrence	SE¼NE¼	25	6 N	1 E
	SE¼SE¼	29	6 N	2 W
	NE¼NW¼	23	4 N	1 E
Madison	NE¼	28	19 N	6 E
Miami	NE¼SW¼	29	26 N	4 E
Monroe	NW¼SW¼	10	9 N	1 E
	NE¼NW¼	4	9 N	1 W
	SW¼SW¼	21	9 N	1 W
		25	9 N	1 W
	SW¼NW¼	27	9 N	1 W
	SE¼NW¼	34	9 N	1 W
	NE¼SW¼	27	9 N	1 W
	SW¼NW¼	28	9 N	1 W
	NE¼SW¼	33	9 N	1 W
	SW¼NE¼	6	7 N	1 W
	SW¼NW¼	32	7 N	1 W
Montgomery	NW¼NW¼	32	17 N	4 W
	SE¼SW¼	34	17 N	6 W
Owen	NE¼NE¼	29	11 N	2 W
	NE¼SW¼	32	11 N	2 W
	SE¼SE¼	24	10 N	3 W
	NE¼	22	10 N	3 W
Parke	NE¼	7	17 N	6 W
	SE¼NW¼	9	16 N	8 W
Putnam	NW¼SE¼	8	16 N	5 W
	SE¼	28	16 N	5 W
		20	14 N	4 W
		32	14 N	4 W
	NW¼SW¼	17	13 N	4 W
Scott	SE¼	20	3 N	8 E
Spencer	SE¼SW¼	9	6 S	4 W
Warren	SW¼NE¼	29	23 N	8 W
	SW¼SW¼	2	20 N	9 W
	Sphalerite occurrences—Continued			
Washington	SE¼	24	2 N	4 E
	NW¼NE¼	32	2 N	4 E
	SW¼SE¼	13	2 N	3 E
	NE¼	24	2 N	3 E
	NW¼SE¼	2	1 N	4 E
	SW¼SE¼	22	1 N	4 E
	SW¼SE¼	21	1 N	4 E
Wayne	NE¼SW¼	11	13 N	1 W
Wells	SW¼NE¼	29	27 N	11 E
	Barite occurrences			
Benton	NE¼	1	26 N	7 W
	NW¼SW¼	24	25 N	7 W
Decatur	SW¼SW¼	8	10 N	11 E
Jackson	SE¼SE¼	29	5 N	3 E
	SW¼SE¼	29	5 N	3 E
Jefferson	NE¼SW¼	34	4 N	10 E
Jennings	NE¼	34	7 N	8 E
Lawrence	SE¼NE¼	25	6 N	1 E
	NW¼	20	6 N	2 W
	SW¼NE¼	31	6 N	2 W
	SE¼NE¼	17	5 N	2 E
	SW¼SE¼	5	5 N	1 E
	NE¼NW¼	23	4 N	1 E
	SE¼SW¼	6	4 N	2 W
	SE¼NE¼	12	3 N	2 W
Monroe	NE¼SE¼	21	10 N	1 W
	NW¼SW¼	10	9 N	1 E
	NE¼NW¼	4	9 N	1 W
	NW¼SW¼	21	9 N	1 W
	NW¼SW¼	25	9 N	1 W
	SW¼NW¼	28	9 N	1 W
	SW¼NE¼	4	8 N	1 W
	SW¼NW¼	28	8 N	1 W
	SW¼NW¼	11	7 N	1 W
	NW¼SE¼	20	7 N	1 W
	SE¼NE¼	29	7 N	1 W
Montgomery	NE¼NE¼	2	17 N	3 W
	SE¼SW¼	34	17 N	6 W
Morgan	NE¼NE¼	35	13 N	1 E
Orange	SW¼SE¼	24	3 N	1 W

Table 2. Previously reported occurrences of sphalerite, barite, and fluorite in Indiana—Continued

County	Sec.		T.	R.
Barite occurrences—Continued				
Owen	SE¼SE¼	24	10 N	3 W
Parke	NE¼	7	17 N	6 W
Perry	NW¼SE¼	32	5 S	1 W
Putnam	NW¼SE¼	8	16 N	5 W
			14 N	4 W
	NW¼SE¼	34	13 N	5 W
Ripley	NE¼NW¼	8	6 N	12 E
Switzerland	NE¼NW¼	9	5 N	12 E
Warren	SW¼NE¼	29	23 N	8 W
Washington	SW¼SW¼	4	3 N	4 E
	NW¼NE¼	32	2 N	4 E
	SW¼SE¼	22	1 N	4 E
Wayne	NE¼SW¼	11	13 N	1 W
	NE¼SW¼	22	13 N	1 W
Fluorite occurrences				
Bartholomew	NE¼	6	8 N	7 E
Harrison	SE¼	10	2 S	2 E
	SW¼NE¼	20	3 S	3 E
	NE¼SW¼	20	3 S	3 E
	SE¼SE¼	25	3 S	3 E
Monroe	SE¼NW¼	34	9 N	1 W
Shelby	NE¼NW¼	32	11 N	7 E
Washington	SW¼SE¼	22	1 N	4 E

More recently Fix (1939) described veins of sphalerite in the Harrodsburg Limestone in Monroe County, and Henderson (1974) noted small crystals of sphalerite in the Rockford Limestone. Erd (1954) and Erd and Greenberg (1960) listed surface occurrences of many minerals in Indiana that included sphalerite, galena, fluorite, and barite (table 2).

Worl and others (1974) mapped several occurrences of fluorite in Indiana, and Heyl (1968 and 1974) published maps showing occurrences of sphalerite, barite, and fluorite in Indiana and surrounding areas.

Heyl (1968) compiled and mapped many reported occurrences of sphalerite, galena, fluorite, and barite scattered throughout the Midwest and suggested that some groupings of occurrences, including one in Indiana, might have significance for mineral exploration. Worl and others (1974) included minor occurrences of fluorite in Indiana on their map of fluorite resources of the United States, and Shawe (1976) included southern Indiana in his map showing the distribution of fluorine-bearing minerals.

Besides many studies of specific deposits in neighboring states, a few reports about outlying mineral occurrences have been made. Bradbury (1957) detailed minor occurrences of fluorite, sphalerite, and galena in Illinois. Miller (1905), Robinson (1931), Beck (1949), and Plummer (1971) discussed sparsely mineralized rocks of central Kentucky, and Jewell (1947) reported on surface veins of barite, fluorite, galena, and sphalerite in middle Tennessee. Occurrences of sphalerite in well cuttings from Tennessee were also listed by the Tennessee Geological Survey long before the zinc discoveries in Smith County, Tenn. Evans (1948, 1962) noted subsurface occurrences of sphalerite in Kansas.

Less information on mineral occurrences in Ohio and Michigan is available and, except for the references noted below consists of popular accounts. Heyl and Brock (1962) reported sphalerite mineralization from the Serpent Mound cryptoexplosion structure of southwestern Ohio, and Reidel (1975) expanded their observations. Botoman (1975) and Strogonoff (1966) noted several occurrences of sphalerite, galena, and fluorite in the Silurian rocks of northwestern Ohio, and Botoman and Stieglitz (1978) characterized some sulfide and associated mineral occurrences in Ohio as Mississippi Valley type. Guillet (1967) reported on lead-zinc mineralization in the Middle Silurian rocks of the Bruce Peninsula of Ontario, and Sangster and Liberty (1971) noted other occurrences there. Worl and others (1974) cited a paper by Fitzgerald and Thomas (1932) reporting fluorite in well cuttings from Michigan.

Heinrich (1976) reported on minerals of Michigan, including sulfides, and Shaw (1976) noted that sulfides accompanied secondary dolomitization in the Albion-Scipio oilfield. Stieglitz (1975) mentioned a similar occurrence in the Trenton of northwestern Ohio. Thus small showings of Mississippi Valley-type ore minerals in Indiana and surrounding states are known.

Sample Collecting and Study

Part of the vast literature concerning Mississippi Valley-type deposits was searched to determine what geologic features of Indiana could be considered favorable for hosting ore. The references at the end of this report should help anyone wanting basic knowledge of the subject. After determining that Indiana had suitable geology, I examined outcrops, collected and measured samples, and attempted to assess the results.

A major part of this project involved field checking exposures and microscopically examining available samples for shows of mineralization. Sample sets of more than 10,500 wells are in files of the Indiana Geological Survey. Sample sets consist of washed rock chips obtained during rotary or cable-tool drilling of various types of wells. About 20 to 50 grams of sample were taken from every 5- to 10-foot interval in most wells, but longer sample intervals were used in some older wells. Sample quality except for that of samples from older wells was generally good. A small part of each sample was mounted on cardboard strips to form lithologic strip logs, and the remaining part was retained in paper envelopes. (See fig. 14.) Nearly all strips were examined with a binocular microscope (10 to 30 power) equipped with normal and ultraviolet light. When mineralization was noted on a strip, the larger envelope sample was consulted. For several areas where numerous mineral shows occurred, unmounted envelope samples from nearby wells were also examined. Small traces of mineralization were found in many of these envelope samples, even when mineralization did not show on the strip log. There may be other small unreported shows of mineralization in these samples.

Figure 14. Lithologic strip logs that allowed a rapid survey of samples. Larger samples are in envelopes.

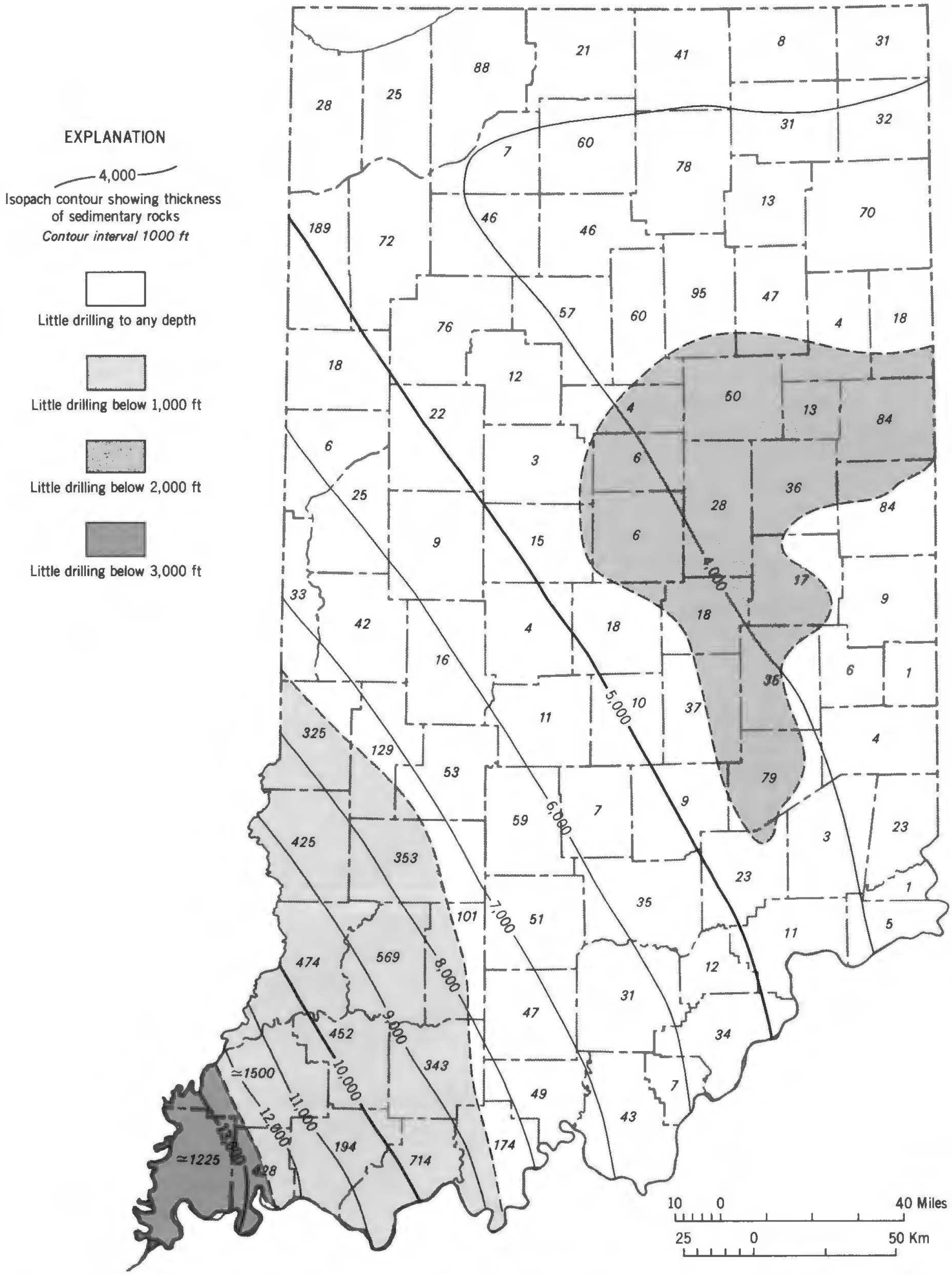

Figure 15. Map of Indiana showing extent of drilling and thickness of sedimentary rocks. Numbers indicate number of sample sets from each county that were on file at the Indiana Geological Survey during this study.

Minerals were identified mainly by appearance, especially color, luster, cleavage, and zoning, and by physical properties, such as hardness. Gross lithologic characters of surrounding rocks were also noted. Small samples of sphalerite and galena were removed from most occurrences. These were chemically analyzed by emission spectrometry to check the microscopic identification and to provide information on trace-element content. Fluid inclusions in doubly polished ½-mm-thick plates of sphalerite were observed with a polarizing microscope fitted with a heating stage to determine their temperatures of homogenization. Fluid-inclusion temperatures were also measured by Edwin Roedder of the U.S. Geological Survey. Lead isotopes in one galena sample were analyzed spectrographically by Mark Haden and Gunter Faure of The Ohio State University.

The chip samples are mainly ditch samples, and as such they represent only a small fraction of the rock penetrated. Not only are small samples obtained, but also the large difference in specific gravity of ore minerals relative to host rocks and the easy cleavability of sphalerite, galena, and fluorite could easily lead to biasing of samples. Material from higher positions in the hole may cave in, which would contaminate deeper samples, and lag times needed for bottom-hole samples to return to the surface may vary. Thus the samples may be biased with too much or too little mineralization, and intervals reported may not represent precise depths. Because the rocks are broken, little can be seen about relationships of minerals to surrounding rock, and structures, such as breccias, fractures, and vugs, are obliterated. Most mineral fragments are also crushed to a fairly fine size and so are not useful for some tests, such as determination of fluid-inclusion temperature.

Although many sample sets are available, they do not cover the area well geographically or stratigraphically (fig. 15). Many wells have been drilled to relatively shallow depths; some have not even reached below Pennsylvanian rocks. This is especially true of those wells in the deeper part of the Illinois Basin in southwestern Indiana where there is a fairly good geographic distribution. Only about 250 wells penetrate the Knox Dolomite, and these are not well distributed. Many wells tend to be clustered in small areas where oil pools or underground storage structures are located. A similar problem with surface-sample distribution exists. Much of Indiana is covered by glacial materials (see fig. 3) that obscure the bedrock. Thus the reported occurrences of minerals are not a completely fair representation of their actual distribution but are limited to available exposures and well sites. No wells were drilled especially for this study; untested areas abound. We should keep these limitations in mind as we examine known mineral occurrences.

Mineral Locations

SPHALERITE AND GALENA

More than 50 sample sets contained shows of sphalerite or galena, and 20 surface shows (table 3; fig. 16) were added to about 50 previously known occurrences (table 2). The amount of mineralization in occurrences varied greatly, ranging from crystalline sphalerite masses weighing more than 50 pounds to traces in surface samples. The amount in well cuttings ranged from a few cleavage fragments in many samples to an estimated 10 to 15 percent in one sample. Because of the limitations of the samples mentioned previously, no information on the amount of mineralization is given. Most surface samples were coarsely crystalline (fig. 17), and the samples from wells were cleavage fragments.

Of the several patterns of mineralization that can be seen (fig. 16), perhaps the most prominent is a trend of occurrences in Mississippian limestones that roughly parallels the Mt. Carmel Fault in south-central Indiana. This pattern is similar to the distribution of fluorite and barite occurrences (fig. 18). Heyl (1974) called attention to this trend as a possible area for mineral exploration because of the concurrence of the fault and mineralization. But caution must be used in interpreting this trend because many occurrences noted were in surface geodes. Geodes bearing ore minerals occur in the central Kentucky district (Jolly and Heyl, 1964) and in southeastern Iowa (Van Tuyl, 1925) considerably south of the upper Mississippi Valley district, but they can also be found in barren areas.

Table 3. Sphalerite and galena occurrences in subsurface samples and surface exposures in Indiana

County	Sec.		T.	R.	Stratigraphic unit	Lithology[1]	Survey file No.	Depth (ft)	Sample No.
					Subsurface samples				
Allen	NW¼SE¼	17	30 N	14 E	Trenton	Dol	9229	1,625-1,640	Z1
	SW¼SE¼	11	31 N	12 E	Wabash	Dol	7126	430- 440	Z2
	NW¼	2	31 N	13 E	Trenton	Dol	9287	1,640-1,645	Z3
	SW¼SW¼	11	31 N	13 E	Trenton	Dol	7274	1,704-1,714	Z4
Boone	SE¼SE¼	28	19 N	1 W	Wabash	Dol	5012	539- 553	Z5
Brown	SW¼	36	9 N	3 E	Muscatatuck	Ls	6490	530- 575	
	SE¼	33	10 N	3 E	Salamonie	Dol	4734	755- 761	Z6
Daviess	NE¼NW¼	1	3 N	7 W	Blue River	Ls	10438	1,055-1,065	Z52
Fulton	SW¼SW¼	29	29 N	1 E	Salamonie	Ls	7835	405- 415	
	NW¼NE¼	14	31 N	1 E	Trenton	Dol	6723	1,120-1,160	Z7 and Z53
Greene	SW¼	19	6 N	4 W	Muscatatuck	Dol	9965	1,710-1,725	Z10
	SW¼SW¼	30	6 N	5 W	Blue River	Ls	10052	655- 660	Z9
	NW¼SE¼	34	6 N	7 W	Wabash?	Ls	3637	2,380-2,395	Z8
	SW¼SW¼	32	7 N	6 W	Sanders	Ls	10234	915- 920	
Hancock	NW¼	18	16 N	8 E	Trenton	Dol	7770	1,016 (circulation)	Z12
Harrison	SW¼SW¼	32	3 S	4 E	Sanders	Ls	521	215- 245	Z13
Howard	SW¼NW¼	32	24 N	5 E	Wabash	Silty dol	589	309- 320	
Jackson	SW¼SE¼	21	5 N	4 E	Salamonie?	Ls	6456	635- 660	Z14
Jasper	NE¼NW¼	29	28 N	5 W	Muscatatuck	Dol	8742	15- 20	Z15
Knox	NW¼NW¼	10	4 N	8 W	Blue River	Ls	9889	1,270-1,370	Z33
Lagrange	SW¼NE¼	8	36 N	11 E	Muscatatuck	Ls	8104	860- 900, 920-930	Z16
	SW¼SW¼	2	37 N	9 E	Salamonie	Dol	5649	1,225-1,470	Z17 and Z18
LaPorte	NE¼NE¼	22	33 N	4 W	Trenton	Dol	4936	1,105-1,134	
Lake	SW¼	27	32 N	8 W	Muscatatuck	Dol	8575	70- 85	Z21
	NE¼SW¼	16	34 N	7 W	Trenton	Dol	7752	1,220-1,230	Z25
	SE¼SW¼	29	37 N	8 W	Trenton	Dol	8033	890- 960	Z20A and 20B
	SE¼SW¼	8	37 N	9 W	Trenton	Dol	5063	919- 970	
		14	37 N	9 W	Trenton	Dol	8719	880- 900, 930-950, traces 1,000	Z22
	SE¼NE¼	32	37 N	9 W	Trenton	Dol	1720	800- 805, 835-840	Z23
Lawrence	NE¼NE¼	27	5 N	2 E	Sanders	Ls	9940	40- 50	
Marshall	SW¼NW¼	17	32 N	2 E	Salamonie	Dol	8295	800- 850	Z19
Miami		8	27 N	4 E	Maquoketa	Shaly ls	2569	470- 500	Z28

Table 3. Sphalerite and galena occurrences in subsurface samples and surface exposures in Indiana—Continued

County	Sec.		T.	R.	Stratigraphic unit	Lithology[1]	Survey file No.	Depth (ft)	Sample No.
					Subsurface samples--Continued				
Monroe	SW¼SW¼	9	9 N	1 E	Muscatatuck	Dol	6970	832- 848	Z39
	NE¼SE¼	20	9 N	1 E	Muscatatuck	Dol	5376	895- 935	Z29
	NE¼SE¼	10	9 N	2 W	Sanders	Ls	5103	155- 165	Z30
Morgan	NW¼NW¼	15	11 N	1 W	Muscatatuck	Dol	5314	675- 690	Z32
Parke	NW¼NW¼	20	14 N	8 W	Sanders	Ls	579	665- 681	Z31
Perry	SW¼NW¼	7	7 S	2 W	Blue River	Ls	1575	539- 563	
Porter	SE¼SW¼	16	35 N	5 W	Trenton	Dol	9110	1,315-1,400	Z34A and 34B
	SW¼	29	37 N	6 W	Trenton	Silty dol	8865	1,140-1,150	Z38
Pulaski	SE¼NW¼	18	29 N	2 W	Wabash	Dol	8374	185- 195	Z35
Randolph	NE¼SE¼	16	19 N	13 E	Knox	Dol	8632	2,095-2,145	Z36
	SW¼SE¼	9	19 N	13 E	Knox	Dol	8143	1,540-1,545	Z37
Sullivan	NW¼NE¼	30	9 N	8 W	Muscatatuck	Dol	10411	1,952-1,958	
Tippecanoe	NW¼SW¼	8	23 N	5 W	Black River	Dol	6604	1,590-1,600	Z41
Tipton	NE¼SW¼	36	23 N	3 E	Trenton	Dol	7702	1,115-1,120	Z42
Vigo	SE¼SE¼	7	10 N	8 W	Blue River	Ls	10061	960- 990	Z45
	SE¼NW¼	26	10 N	11 W	Blue River	Ls	5763	1,245-1,270	Z43
	SW¼	14	11 N	8 W	Sanders	Ls	6807	875- 890	Z44
	SE¼NE¼	32	13 N	7 W	Sanders	Ls	10435	640- 680	Z46
Wabash	SE¼SW¼	25	29 N	6 E	Trenton	Dol	8032	1,205-1,250	Z47
Wells	SW¼SE¼	25	25 N	10 E	Knox	Dol	9112	1,410-1,441	Z49
White	SW¼SE¼	10	26 N	6 W	Muscatatuck	Ls	1018	105- 142	Z48A and 48B
	SW¼SW¼	11	26 N	6 W	Muscatatuck	Ls	9099	100- 110	
	SW¼	8	27 N	5 W	Wabash	Dol	10038	210- 220	Z50
	NE¼NE¼	13	27 N	6 W	Muscatatuck	Ls	10040	80- 110	
	SE¼NE¼	35	27 N	6 W	Wabash	Dol	9756	310- 340	Z51
					Surface exposures				
Allen	NW¼NE¼	29	30 N	12 E	Muscatatuck	Ls			Z79
Carroll	SE¼SE¼	19	25 N	2 W	Wabash	Dol			Z55, 56, 57, 68, 69
Cass	NE¼	27	27 N	2 E	Wabash	Ls			Z76
Clay	SW¼SE¼	17	11 N	6 W	Raccoon Creek	Sh			Z83
		5	11 N	6 W	Raccoon Creek	Sh			

Table 3. Sphalerite and galena occurrences in subsurface samples and surface exposures in Indiana—Continued

County	Sec.		T.	R.	Stratigraphic unit	Lithology[1]	Survey file No.	Depth (ft)	Sample No.
					Surface exposures—Continued				
Howard	NW¼NE¼	3	23 N	3 E	Wabash	Ls			Z77
Jasper	SE¼SE¼	27	29 N	6 W	Muscatatuck	Ls			
Jennings		27	7 N	8 E	Muscatatuck	Dol			Z74
Lawrence	SW¼NW¼	12	3 N	2 W	Blue River	Ls			Z81
Madison	NW¼NE¼	28	19 N	6 E	Muscatatuck	Dol			Z80
	NW¼NE¼	10	18 N	7 E	Muscatatuck	Ls			Z73
Monroe	SW¼	29	7 N	1 W	Sanders	Ls			Z70
	SW¼NE¼	8	9 N	1 E	Sanders	Ls			Z71
Newton	NW¼NE¼	25	27 N	9 W	Trenton?	Dol			Z84
Putnam	SW¼SW¼	32	14 N	5 W	Raccoon Creek	Slt			Z78
Shelby	NE¼SW¼	32	11 N	7 E	Muscatatuck	Dol			
Wells	SE¼NW¼	28	27 N	12 E	Wabash	Dol			Z75

[1] Dol = Dolomite
Ls = Limestone
Sh = Shale
Slt = Siltstone

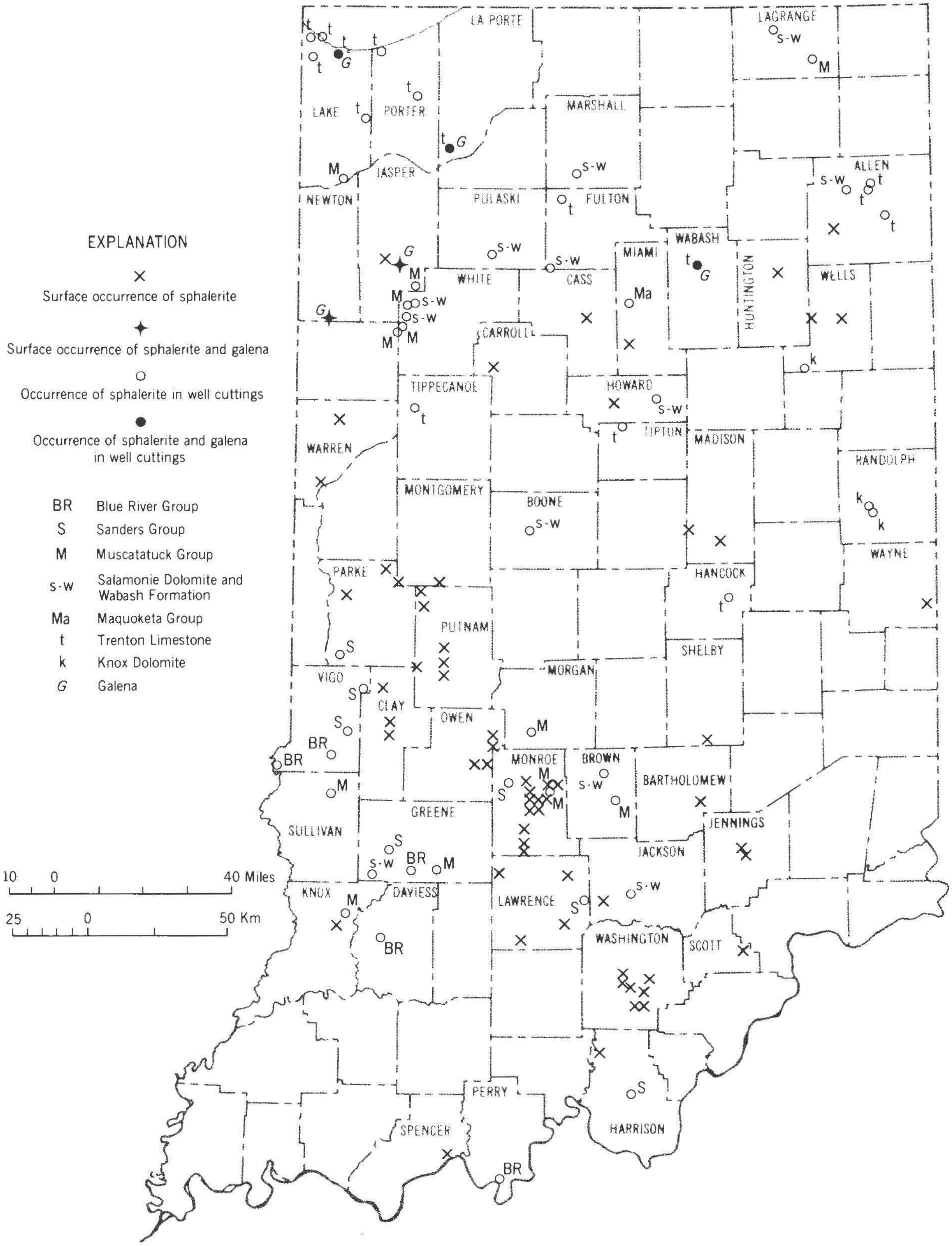

Figure 16. Map of Indiana showing locations and stratigraphic distribution of sphalerite and galena occurrences.

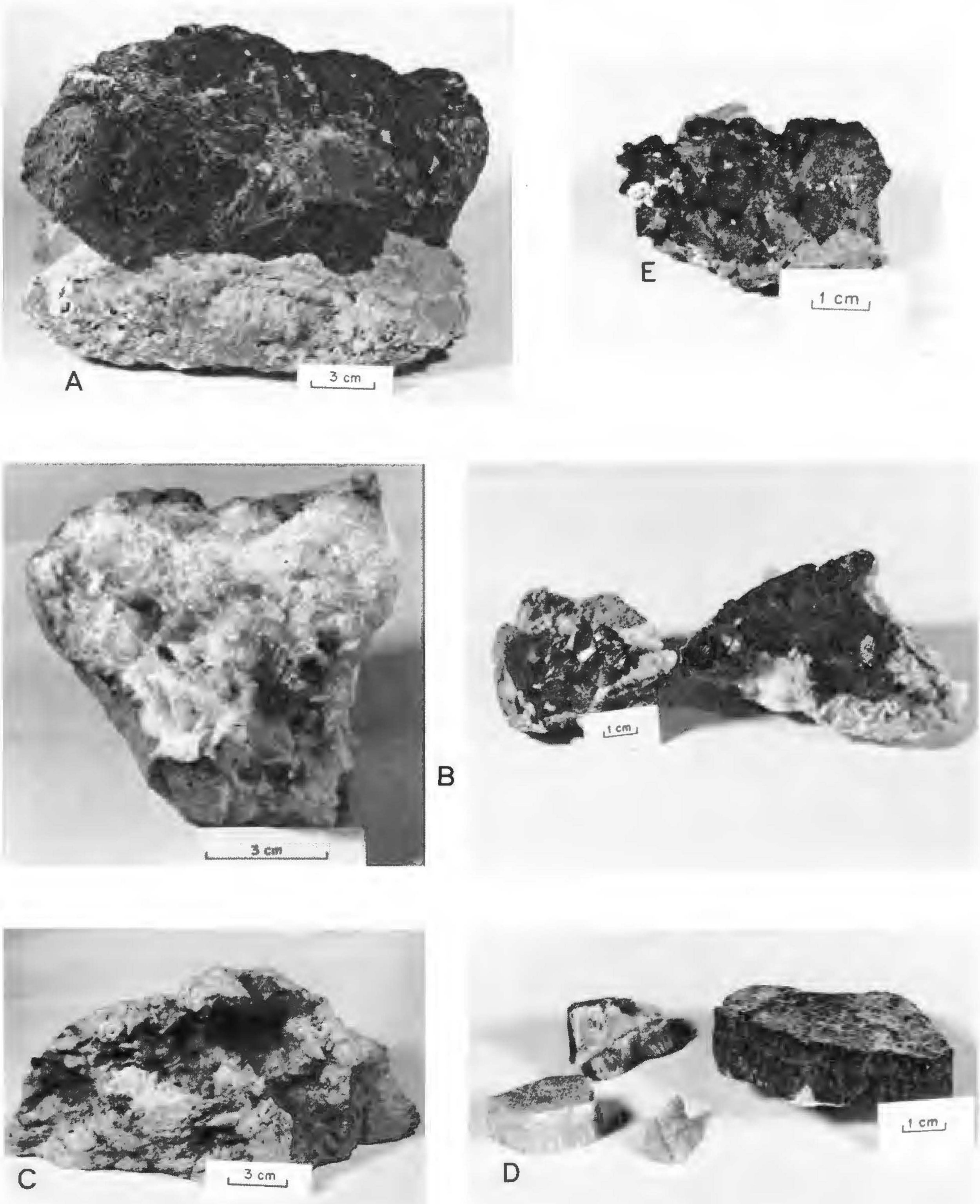

Figure 17. Examples of surface occurrences of sphalerite, fluorite, and barite. Sphalerite from a Carroll County reef (*A*); geodes with sphalerite (right) and barite (left) from the Sanders Group in Monroe County (*B*); fluorite crystals from Allen County (*C*); fibrous fluorite (right) and barite (left) from the Blue River Group in southern Indiana (*D*); sphalerite from the Geneva Dolomite Member of the Jeffersonville Limestone (*E*).

The Mt. Carmel Fault area has been better explored than much of Indiana because it was not glaciated and it lies near Bloomington, home of the Indiana Geological Survey and the Indiana University Department of Geology. On the other hand, some shows occur in the subsurface. Fluid-inclusion measurements of sphalerite from a geode indicated that sphalerite had been formed from brines at moderate temperatures, and mineralization was apparent in shales cut by the Mt. Carmel Fault (Erd, 1954).

Less well-defined concentrations of sphalerite and galena occur in the Trenton Limestone of northern and especially northwestern Indiana. The Trenton has been extensively dolomitized in this area and in some places contains shows of orange, black, or yellow sphalerite; it rarely also contains shows of galena. In many places the minerals are associated with coarse sparry white to pinkish dolomite. The thickest section of mineralization thus far observed in Indiana was in a well in sec. 14, T. 37 N., R. 9 W., in Lake County. It contained sphalerite shows for 70 feet and was underlain by another 60 feet of the Trenton containing traces of galena. Nearby wells had small shows. Sphalerite shows also occurred in 80 feet of Trenton cuttings from a well in Porter County. Quarry exposures of Trenton rocks at the Kentland cryptoexplosion structure also yielded traces of galena (Henry H. Gray, oral communication) and traces of sphalerite in float. Other shows in the dolomitized part of the Trenton of northern Indiana occurred in Lake (5),[1] LaPorte (1), Wabash (1), Fulton (1), and Allen (3) Counties, and a single sphalerite show in Tippecanoe County occurred in Black River rocks. No minerals were found in the Trenton of southern Indiana, where it has not been dolomitized, but a single show in Hancock County was found in partly dolomitized Trenton rocks.

Certainly not a trend, but of considerable interest, are shows of sphalerite in the Knox Dolomite in east-central Indiana. Three wells contained shows of sphalerite in coarse white or tan dolomite in Randolph and Wells Counties. Some sphalerite was associated with a brown clay-rich bed. These shows are of interest because the Knox is mineralized elsewhere in the Midwest, and the occurrences are near a high area on the Knox surface (fig. 8).

Many shows were in surface exposures of Silurian rocks along the northern flank of the Cincinnati Arch. Most were confined to reef rocks of the Huntington Lithofacies, but rare occurrences in interreef rock were noted. This material is black to brown sphalerite that occurs as open-space fillings of solution features; minor fluorite was also seen. Sphalerite in the Silurian is not restricted to the near surface; it has been observed in subsurface samples from 12 counties. Potential host rocks abound in the great bands of reef material fringing the Michigan Basin in northern Indiana and in the northern and eastern parts of the Illinois Basin in western and southwestern Indiana. Small but thus far uneconomic amounts of sphalerite and galena in Upper Silurian rocks are widespread; these occurrences have been reported from Ohio (Botoman, 1975), New York (Cannon, 1955), and southern Ontario, Canada (Guillet, 1967; Sangster and Liberty, 1971).

Devonian rocks of the Muscatatuck Group contain sphalerite in some places. Fine-grained sphalerite and galena were found in oil-saturated Silurian and Devonian rocks at one place in Jasper County. And a group of subsurface occurrences of sphalerite was noted nearby in White County. Cuttings from the wells in White County had the highest percentage of sphalerite of any cuttings examined in this study. In one well, in sec. 10, T. 26 N., R. 6 W., sphalerite was an estimated 10 to 15 percent of a sample of Muscatatuck rocks. Many other shows of sphalerite in Devonian rocks of northwestern Indiana were in White (5), Jasper (2), Lake (1) and Pulaski (1) Counties. A lone Devonian occurrence of sphalerite was in northeastern Indiana in Lagrange County.

Farther south, sphalerite, and occasionally fluorite, is found in vugs or along joints in the Geneva Dolomite Member (Jeffersonville Limestone). Fluorite has also been reported in insoluble residues of the Geneva. Westward from the outcrop small amounts of sphalerite or fluorite were noted in cuttings.

[1]Number of locations with shows are in parentheses.

Occurrences in Mississippian rocks of western Indiana may be of interest. Most of these are minor and are in limestones or associated with chert, anhydrite, or gypsum. The evaporite-associated minerals may be syngenetic. Except for some places in extreme southwestern Indiana little major faulting is known to have disrupted Mississippian carbonate rocks, but solution of evaporites or karstification along the major unconformity at the top of the Mississippian section might offer suitable sites for ore deposition.

In summary, most sphalerite occurrences have been in (1) Mississippian limestones in a belt along, but more extensive than, the Mt. Carmel Fault and in an area of Vigo, Sullivan, Greene, and Knox Counties; (2) Middle Ordovician dolomites in northern Indiana; (3) Silurian rocks in exposures of dolomitized reefs in many places in northern Indiana; (4) Devonian rocks of the Muscatatuck Group throughout much of Indiana; and (5) Knox Dolomite of Cambro-Ordovician age in eastern Indiana.

Shows of galena were rarer than those of sphalerite; five were in northern Indiana, and all appeared to be minor. All but one occurrence, which was in Wabash County, were in northwestern Indiana, and at only one location was galena in rocks other than the Trenton Limestone. A minor show in oil-saturated Silurian and Devonian rocks from a quarry in Jasper County and an unconfirmed report of galena-bearing geodes in Silurian rocks in Tippecanoe County represent the only in-place surface occurrences. Galena has been reported in glacial materials, but how far such material has been transported is uncertain. Most shows were in subsurface samples of Trenton rock, but one specimen was obtained from an exposure of the Trenton Limestone in the Kentland cryptoexplosion feature. The strongest show included more than 60 feet of minor galena in Trenton rocks from a well in Lake County. Nearby LaPorte County had a well containing nearly 30 feet of minor shows.

FLUORITE AND BARITE

Shows of fluorite and barite, which are generally less abundant than sulfides, have been mostly in southern Indiana (table 4; fig. 18). The locations of most surface occurrences are from Erd (1954) and Erd and Greenberg (1960).

Several trends in the distribution of fluorite and barite can be seen. The most pronounced is a broad strip through south-central Indiana that roughly follows the Mt. Carmel Fault. A similar trend in sphalerite shows has been observed. Smaller areas with mineral shows are in Bartholomew, Brown, Greene, Crawford, and Harrison Counties. Most shows have been in Mississippian limestones of the Sanders and Blue River Groups. Exceptions to this general observation are: fluorite in Devonian (Muscatatuck) rocks in Bartholomew (1), Brown (4), Greene (2), Jennings (1), Lawrence (1), and Shelby (1) Counties; fluorite in Devonian (Muscatatuck) and Silurian (Wabash) rocks in Allen (2) County; barite in Ordovician (Maquoketa) rocks in Decatur (1), Jefferson (1), Ripley (1), and Switzerland (1) Counties. Minor shows have also appeared in Upper Mississippian and in Pennsylvanian rocks.

Many shows of barite in the Sanders Group have been in geodes. Fluorite is rare in geodes, but it is associated with gypsum or anhydrite in many shows. These occurrences, along with those in geodes, may be minor because they probably formed syngenetically or from ground water. Fluorite in extreme southern Indiana is associated with coarse pink dolomite in many places; some fluorite seems to have formed at moderately warm temperatures (101° to 104°C). These occurrences may indicate possible ore-forming fluids. The isolated shows in northeastern Indiana may represent an extension of the fluorite-bearing region that Shawe (1976) noted in northwestern Ohio. The apparent concentration of occurrences in Greene County may partly result from the rather high well density in that area, but the occurrences in Brown, Crawford, and Harrison Counties were in sparsely drilled areas.

The amount of mineralization of barite or fluorite is low in all occurrences. But the largest surface shows have been in Harrison and Allen Counties, and the best subsurface shows have been in Brown and Greene Counties. Fluorite has occurred with evaporites, chert, or secondary dolomite in many shows, but most occurrences have been in limestone host rock.

Table 4. Fluorite occurrences in subsurface samples and surface exposures in Indiana

County	Sec.		T.	R.	Stratigraphic unit	Lithology[1]	Survey file No.	Depth (ft)
					Subsurface samples			
Brown	SW¼SE¼	28	8 N	3 E	Muscatatuck	Ls	678	440- 495
	SE¼SW¼	6	9 N	3 E	Muscatatuck	Ls	7975	560- 565
	SW¼	36	9 N	3 E	Muscatatuck	Ls	6490	500- 510
	SE¼	33	10 N	3 E	Muscatatuck	Ls	4734	540- 560
Crawford	SE¼SE¼	17	2 S	2 W	Blue River	Ls	9144	510- 530
	NE¼NE¼	20	2 S	2 W	Blue River	Ls	7819	784- 787
	NE¼NE¼	21	2 S	2 W	Blue River	Ls	1571	540- 560
	SW¼NE¼	21	2 S	2 W	Blue River	Ls	5319	678- 683
Greene	NW¼SE¼	5	6 N	5 W	Blue River	Ls	9120	555- 585
	NW¼NE¼	24	6 N	5 W	Muscatatuck	Ls	9782	1,685-1,700
	SW¼SE¼	35	6 N	5 W	Blue River	Ls	4484	577- 592
	NE¼	6	6 N	6 W	Muscatatuck	Dol	10005	1,850-1,875
	SW¼NE¼	31	6 N	6 W	Blue River	Ls	10071	845- 860
	SW¼NE¼	5	7 N	5 W	Blue River	Ls	7845	667- 673
	SW¼NW¼	25	7 N	5 W	Blue River	Ls	9177	350- 392
	SE¼NW¼	29	7 N	5 W	Blue River	Ls	9178	560- 580
Harrison	SW¼NE¼	30	3 S	3 E	Blue River	Ls	8854	224- 228
	SW¼SE¼	14	4 S	2 E	Blue River	Ls	8403	180- 190
Martin	NW¼SE¼	3	2 N	4 W	Blue River	Dol	1824	457- 468
	SW¼SE¼	24	3 N	3 W	Blue River	Ls	7030	490- 507
	SW¼SW¼	23	3 N	4 W	Blue River	Ls	4147	410- 420
Orange	NE¼SW¼	24	1 N	2 W	Blue River	Ls	7238	430- 480
	NE¼NW¼	32	3 N	1 W	Muscatatuck	Dol	3576	1,245-1,251
	SE¼SE¼	15	1 S	1 E	Blue River	Ls	8402	225
Perry	SW¼NW¼	7	7 S	2 W	Blue River	Ls	1575	563- 575
					Surface exposures			
Allen	NW¼NE¼	29	30 N	12 E	Muscatatuck and Wabash	Dol		
	Center	36	30 N	11 E	Muscatatuck and Wabash	Dol		
Crawford	SE¼SE¼	25	4 S	1 E	Blue River	Ls		
Harrison	SW¼NE¼	13	4 S	3 E	Blue River	Ls		
	NE¼SW¼	13	4 S	3 E	Blue River	Ls		
Lawrence	NW¼SW¼	15	5 N	1 W	Sanders	Ls		

[1] Dol = Dolomite
Ls = Limestone

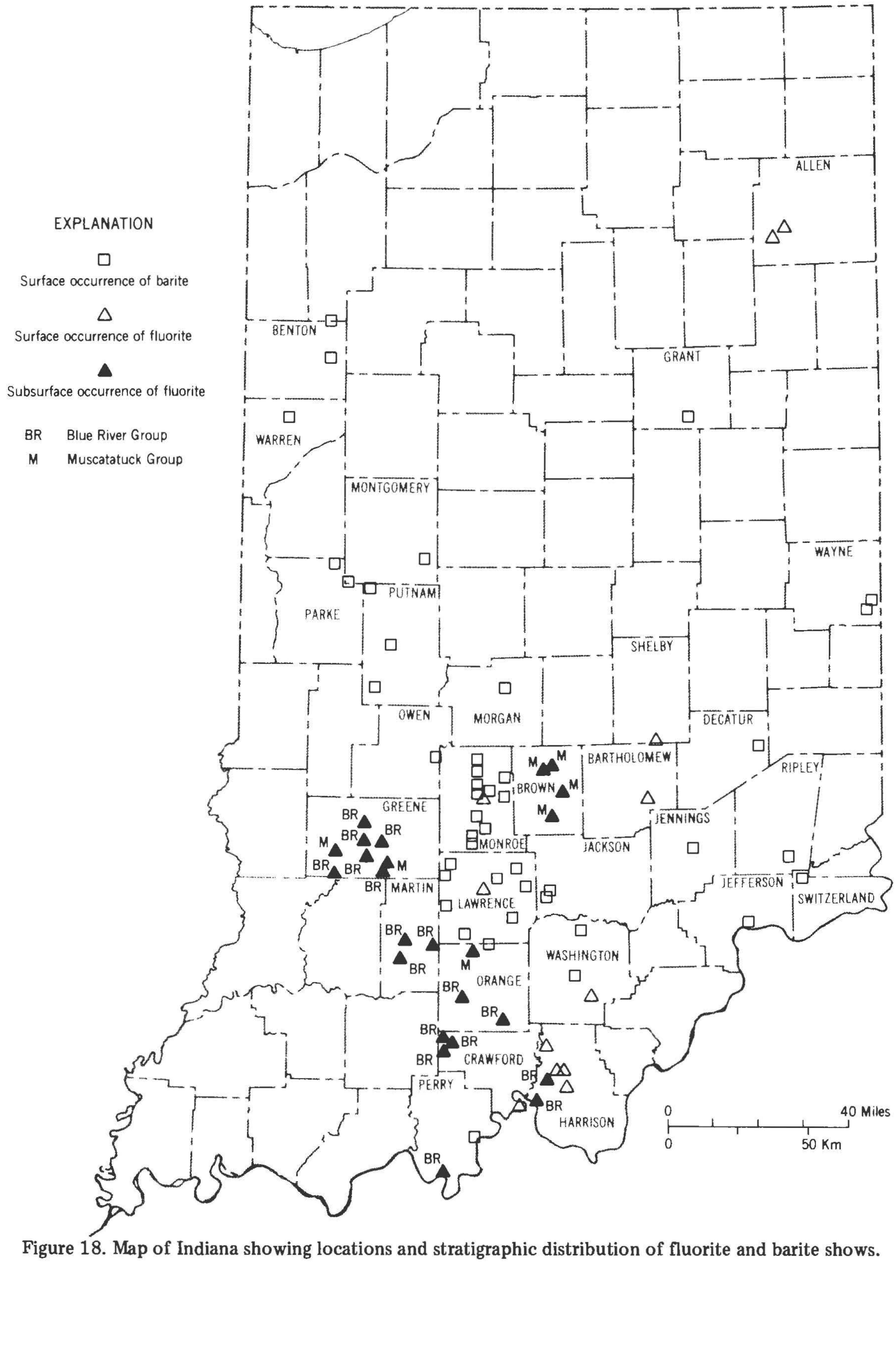

Figure 18. Map of Indiana showing locations and stratigraphic distribution of fluorite and barite shows.

Table 5. Distribution of subsurface shows in Indiana and sample density

County	Number of wells in Survey file	Number of wells with shows	Approximate percentage of wells with shows
Allen	70	4	6
Boone	15	1	7
Brown	7	4	57
Crawford	49	4	8
Fulton	46	2	4
Greene	353	12	3
Hancock	18	1	6
Harrison	43	2	5
Howard	4	1	25
Jackson	35	1	3
Jasper	72	1	1
Knox	474	1	<1
Lagrange	8	2	25
Lake	28	6	21
LaPorte	88	1	1
Lawrence	51	1	2
Marshall	60	1	2
Martin	101	3	3
Miami	60	1	2
Monroe	59	3	5
Morgan	11	1	9
Orange	47	3	6
Parke	42	1	2
Perry	174	1	1
Porter	25	2	8
Pulaski	46	1	2
Sullivan	425	1	<1
Tippecanoe	22	1	4
Tipton	6	1	17
Vigo	325	4	1
Wabash	95	1	1
Wells	46	1	2
White	76	5	7

ANALYSIS

Account must be taken of the distribution of rocks available for examination either in outcrop or as cuttings. About five-sixths of Indiana is covered with glacial materials. Outcrops in glaciated regions are rare, but most of these that exist are manmade exposures in quarries, mines, or road cuts. Although most of these shows are small, a surprising number of exposures (see tables 3 and 4) have some mineral occurrence.

To determine the significance of shows in cuttings, the number of samples available has been compared with the number that actually contains mineralization (table 5). Table 5 does not consider that some samples contain only short intervals or have missing sections. In addition, samples are not evenly spaced, but many of them are clustered into small areas of a county. Despite these limitations, table 5 is a general guide.

Brown County, which has four shows and only seven sample sets, probably has more promise for commercial mineralization than Greene County, which has more shows (12) but many times more sample material (more than 300 sets). Counties with respectable numbers of shows for the number of sample sets on file, say about 5 percent, are Brown, Howard, Lagrange, Lake, Morgan, Tipton, and White. Those counties that have smaller percentages but are still above average are Allen, Boone, Fulton, Harrison, Monroe, Orange, Porter, and Tippecanoe. Areas in northern Indiana, especially Lake, Porter, White, Fulton, and Allen Counties, and a few areas in south-central Indiana, especially Brown, Morgan, Monroe, Orange, and Harrison Counties, seem to have more shows per sample than other areas.

No clear-cut relationship between mineral occurrences and lineaments, as seen on aerial photography or satellite imagery, has been noted. In southwestern Indiana where lineaments have been mapped (Wier and others, 1974), only 11 occurrences out of nearly 30 have shown even a remote relationship to lineaments. Occurrences at the Kentland feature and in Carroll County have been near prominent linear features, however, and some strong shows have occurred near the Galena Lineament proposed by Snyder (1970).

A few mineral occurrences are associated with geophysical anamolies. Several sphalerite shows in Allen County lie on the flank of an aeromagnetic high, as do those in White and LaPorte Counties; fluorite occurrences are common on the west flank of a marked magnetic high in Harrison County. But numerous fluorite shows in Greene County and a sphalerite show in Randolph County are near magnetic lows. Gravity information for Indiana is less extensive, but shows near gravity lows occur in Fulton and Harrison Counties and near gravity highs in Allen and White Counties. Thus there seems to be no consistent relation between mineral occurrences and geophysical anomalies.

Occurrences near known faults are found in south-central Indiana. In northwestern Indiana a few shows are along the Royal Center Fault and near the Kentland cryptoexplosion feature. A basement structural high (Henderson and Zeitz, 1958) occurs in the Allen County area where several interesting shows have been seen. But many occurrences cannot be readily related to known structures. From information at hand there is little clear-cut evidence that mineralization is related to any structural features except possibly the Mt. Carmel Fault. This lack of positive correlation raises questions about the evidence that can be found to help explain these occurrences and help evaluate their significance.

Information from Samples

Fluid inclusions in samples from four locations (table 6) were examined by Edwin Roedder of the U.S. Geological Survey. Other measurements made during this study (table 6) generally confirmed his data. All samples were collected near the surface, but they showed relatively high temperatures of homogenization and fairly high salinity. Inclusions in sphalerite from a large Silurian reef at Delphi, Carroll County, showed temperatures that generally ranged from 80° to 88°C; temperature extremes were 69° to 119°C, and salinity ranged from 15.5 to 22 percent. Sphalerite in a Mississippian geode from south-central Indiana contained inclusions that indicated high salinity (15.5 percent) and a temperature of 120°C. This temperature was probably too high because it was obtained from an inclusion that was "necked down," but a relatively warm temperature of 83°C was also obtained from an inclusion in associated quartz. A sample of fluorite associated with coarse pink dolomite in Mississippian rocks of extreme southern Indiana had inclusions that showed temperatures of 101° to 104°C and salinity of about 14.5 percent. A barite sample from Mississippian rocks in western Indiana showed temperatures of 97° to 99°C and only about 7 percent salinity. The latter value is suspect because barite recrystallizes easily (Roedder, written communication).

Temperatures and salinity reported thus far cast doubt on ground water as a depositing medium for most of the minerals. Ground water may account for minor occurrences of sulfides and fluorite in some carbonate rocks, but it cannot account for all occurrences. Fluid inclusions indicate that temperatures and salinity are higher than those found for contemporaneous brines contained in even the deepest rocks in Indiana (Walker, 1959) and are similar to those found in ore deposits.

Table 6. Fluid-inclusion measurements on sphalerite, fluorite, barite, and quartz from Indiana

County	Mineral	Stratigraphic unit	Homogenization temperature (°C)	Freezing temperature (°C)	Salinity[1] (pct)
Carroll	Sphalerite	Wabash	82- 82 (6)[2]	–14.1	19
	Sphalerite	Wabash	86 (4)	–14.1	19
	Sphalerite	Wabash	84- 88 (15)	12.3 to –12.4	16.5
	Sphalerite	Wabash	97 (1)	–15.5	21
	Sphalerite	Wabash	119	–16.6	22
	Sphalerite	Wabash	102-108 (11)	–14.1	19
	Sphalerite	Wabash	69 (2)	–14.1	19
	Sphalerite	Wabash	109	–15.1	20
	Sphalerite	Wabash	113-118 (4)	([3])	
Cass	Sphalerite	Wabash?	60- 64 (2)	([3])	
Harrison	Fluorite	Blue River	101-104	–10.9	14.5
Madison	Sphalerite	Muscatatuck	72- 74 (3)	([3])	
Monroe	Sphalerite	Sanders	120	–11.7	15.5
	Quartz	Sanders	83	–10.1	13
Parke	Barite	Sanders	97- 99	– 5.6 to –5.7	7

[1] Salinity obtained from freezing temperature and phase diagram for NaCl-H_2O mixtures in Roedder (1962).

[2] Numbers in parentheses are number of inclusions tested.

[3] Measurement made at Indiana University by the author. Freezing temperatures were not determined.

Unfortunately, little information for either diagenetic mineralization or mineralization induced by ground water is available. Roedder (1967) reported salinity of about 24 percent from sphalerite and fluorite at Clay Center, Ohio. Erd and others (1957) found temperatures of 25° to 40°C in smythite-bearing calcite from Indiana geodes. Temperatures of 25° to 150°C and high salinity were determined for fluid inclusions in samples from several diagenetic environments by Roedder (1976). But his samples included Mississippi Valley-type deposits. The normal temperature range for such deposits is generally given as 70° to 150°C, but temperatures can be as high as 200°C or as low as 50°C. The temperatures and salinity of a few sphalerite and fluorite samples from Indiana fall within this range. Sphalerite from coal in the Illinois Basin showed fluid-inclusion temperatures of 82° to 102°C and salinity approaching 100,000 μg/g (Cobb and others, 1978), but much of this material came from northwestern Illinois, where it could have been affected by ore fluids from the upper Mississippi Valley district. It cannot be conclusively stated that ore-forming fluids caused the observed minor mineralization, but fluids similar to those trapped in ore minerals of Mississippi Valley-type deposits are indicated.

Most samples had black or dark-brown zones, probably rich in petroleum, in an amber or orange matrix. A black gummy amorphous residue was left after one sphalerite sample was dissolved. The sphalerite was light yellow to red in small fragments but appeared black or dark brown in large pieces.

Sphalerite samples analyzed thus far have shown relatively low iron content and have contained appreciable amounts of cadmium and trace amounts of germanium and gallium. Similar results have been obtained for many ore minerals from Mississippi Valley-type deposits (Mercer, 1976). Table 7 lists the minor elements in many Indiana sphalerite samples as determined by emission spectrograph. In general, sphalerites from Mississippi Valley-type ore deposits contain relatively high amounts of cadmium (0.2 to 2.0 percent), copper, and germanium and low amounts of iron (generally $<$0.5 percent) when compared with sphalerite of diagenetic origin. Samples Z78 and Z83 were almost certainly diagenetic in origin and showed low

Table 7. Minor elements in sphalerite samples from Indiana

Sample[1]	Ga (pct)	Fe (pct)	Cd (pct)	Cu (pct)	Ge (pct)	Mn (pct)	Sample[1]	Ga (pct)	Fe (pct)	Cd (pct)	Cu (pct)	Ge (pct)	Mn (pct)
Z1	.05	.33	.47	.02	.08		Z28	.01	.37	.09	.03	nd	
	.01	.28	.70	.005	nd[2]		Z29	.016	.11	.40	.03	nd	
Z2	.005	.30	1.18	.03	.37			nd	.03	.21	< .0001	nd	
Z3	.006	.33	.03	.0064	nd	.006	Z39	.02	.02	.20	.0067	nd	
Z4	.006	.11	.22	.09	.03		Z30	.0042	.19	.39	< .0001	nd	
Z5	.02	.04	.23	.007	.01		Z31						
Z6	.03	.17	.01	.06	.07		Z32	.0016	.05	.29	.05	.02	
Z7	.01	.13	1.36	nd	nd		Z33	.0067	.06	.78	.0018	nd	
Z8	.0024	.05	.24	.0049	.001		Z34A	.03	.12	.37	.01	nd	
Z9	nd	.07	6.9	.003	nd		Z34B	.014	.037	.17	.051	.27	
Z10	.019	.01	.55	.04	.01		Z38	.004	.004	.24	.024	nd	
Z12	.14	.20	.30	.03	.02		Z35	.03	.20	.14	.01	nd	
Z13	.005	.20	.08	.01	.002	.002	Z36	.005	.16	.31	.004	.004	
Z14	.008	.40	.14	.01	nd		Z37	.007	.0098	.38	.0014	nd	
	.0004	.11	.09	.0099	nd		Z41	.01	.18	.12	.0017	.0098	
Z15	.0038	.17	1.8	.03	3.1		Z42						
Z16	.01	.0058	.27	.0004	.006		Z43	.0075	.13	.85	< .0001	nd	
Z17	.01	.02	.16	.03	.03		Z44	nd	.09	.63	< .0001	nd	
Z18	.009	.05	.31	.02	.004		Z45	.01	.11	1.3	.0048	nd	
Z19	.03	.04	.08	.01	.007		Z46	.006	.14	1.7	< .0001	nd	
	.0005	.05	.10	.003	.006		Z47	.01	.12	.33	.003	nd	
	nd	.03	nd	nd	.01		Z49	nd	.22	.38	nd	nd	
Z20A	.02	.003	.20	.55	.06		Z48A	.02	.13	.16	.01	.02	
	.01	.13	.30	.01	nd	.0003		.01	.10	.18	.01	.01	
	nd	.03	.47	.02	nd		Z48B	.01	.13	.20	.009	.02	
Z20B	.03	.11	.34	.08	.05		Z50	.0047	.008	.24	.005	nd	.0005
	.02	.023	.67	.01	nd		Z51	.0075	.09	.23	.0018	nd	
	nd	.11	.67	.032	nd		Z52	.007	.08	.93	.0022	nd	
Z21	.0014	.61	.05	.0015	.02	.0005	Z53	.04	.08	.42	.02	.04	
Z22	.01	.04	.16	< .0001	nd		Z55	.020	.044	.53	.0043	.0062	.0003
Z23	.03	.06	1.0	.01	nd		Z56	.026	.048	.57	.0055	.0011	.0002
Z25	.02	.07	.40	.03	nd		Z57	.019	.032	.23	.0065	.015	.0004
	.0086	.29	1.57	.01	nd		Z68	.0007	.47	3.5	.042	nd	

Table 7. Minor elements in sphalerite samples from Indiana—Continued

Sample[1]	Ga (pct)	Fe (pct)	Cd (pct)	Cu (pct)	Ge (pct)	Mn (pct)
Z69	.12	.053	3.4	.037	.0048	
Z70	.003	.05	1.5	.02	.0013	
Z71	.02	.07	2.02	.006	.0018	
Z73	.006	.14	.96	.0096	.005	
Z74	.019	.038	.26		.032	
Z75	.009	.03	.25	nd	.14	
Z76	.0018	.049	.20	.011	.0080	
Z77	.013	.026	.50	.0015	.0026	
Z78	.0068	.08	.06	.0056	.00093	.0005
Z79	.01	.3	.1	.012	.002	
Z80	.0022	.040	.10		nd	
Z81	.03	.06	1.03	.01	.0081	
Z83	.0086	.18	.12	.0078	nd	.0014
Z84	.01	.05	.83		.0013	

[1] Locations and stratigraphic information for samples are in table 3.

[2] nd = not detected

Cd and high Fe content. Many other samples contained minor elements in amounts similar to concentrations in sphalerites from ore deposits. Galena from Indiana did not contain detectable silver, but a sample from Silurian rocks of northwestern Ohio did contain traces. Fluorite and barite samples were not chemically analyzed. Preliminary data indicate that lead isotopes in galena from northern Indiana are similar to anomalous (J-type) isotopes from the southeastern Illinois district (Heyl and others, 1974). Present chemical data are not very helpful in proving if samples formed under conditions suitable for ore deposition, but they do not preclude that event.

In summary, information gained to date indicates that some mineral samples from Indiana are similar in gross chemistry and fluid-inclusion homogenization temperatures to minerals from known ore districts. This observation, along with generally favorable geologic conditions, argues well for the possible occurrence of Mississippi Valley-type deposits in Indiana.

Conclusions

Indiana may contain undiscovered Mississippi Valley-type ore deposits. It has a structurally high area, the Cincinnati and Kankakee Arches, and a thick section of Paleozoic carbonate rocks. It lies in a lead-zinc province and contains rocks whose stratigraphic equivalents are mineralized elsewhere and structures with potential to trap ore fluids.

Many small but interesting shows of mineralization have been noted in Ordovician limestone of the Trenton in northern and northwestern Indiana; Silurian reefal carbonate rocks in northern Indiana; Devonian carbonate rocks of the Muscatatuck Group statewide; and Mississippian limestones of the Sanders and Blue River Groups in south-central and southwestern Indiana.

Fluid-inclusion data indicate that mineral samples from Indiana formed from fluids similar to those from which ore deposits formed. Thus it appears that ore-forming brines were present in Indiana. This is not surprising because the generation of these brines is probably common in the development of sedimentary basins. A complete range from scattered uneconomic mineralization to the formation of large ore bodies from brines probably exists in nature. The mineral occurrences in Indiana may represent the lower part of that range or possibly the first indication of larger hidden deposits.

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