Regional Potential of Selected Paleozoic Carbonate Units in the Northern Midcontinent for Undiscovered Mississippi Valley–Type Deposits

Prepared in cooperation with the Geological Surveys of Arkansas, Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, Oklahoma, and Wisconsin

U.S. GEOLOGICAL SURVEY BULLETIN 1989–G

Chapter G

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Prepared in cooperation with the Geological Surveys of
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STRATEGIC AND CRITICAL MINERALS IN THE MIDCONTINENT REGION, UNITED STATES

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PREFACE

At this writing, the base-metal mining industry in the United States is struggling to keep alive, both because of domestic environmental constraints and because of cheaper sources of metals abroad. In the midcontinent region the zinc and lead mines of the Upper Mississippi Valley district and the Kansas-Missouri-Oklahoma Tri-State district have been shut down for some years because of environmental problems, even though ore reserves remain; and attempts to open new mines along extensions of the Viburnum Trend in southeastern Missouri have met with increasing public opposition. In the light of these problems, the present report may seem to be a classic exercise in futility, and I am not so naive as to think that it will inspire a surge of exploration in the Midcontinent. However, foreign mineral sources, though relatively cheap at present, are no less finite than our own. Eventually they will be mined out, and in the meantime changes in international trade relations could interrupt such supplies at any time. Yet I believe that we will continue to need these metals for generations to come. (Various synthetic materials are increasingly being substituted for metals in many products; but there are some things that synthetics simply cannot do, and even so synthetics also are made from raw materials—in large part derived from hydrocarbons, which have potentially serious supply problems of their own.) Eventually we will need to know what metal resources are still available domestically, and by then surely we will have learned the lessons of multiple use and successful land reclamation that are already being practiced in many parts of the world. Thus my intent in this report is to provide objective geologic data that will be helpful in future assessments of this region's mineral resources—in keeping with the 1879 enabling legislation of the U.S. Geological Survey (the Organic Act), the Mining and Minerals Policy Act of 1970 (30 U.S.C. 21a), the National Materials and Minerals Policy, the Research and Development Act of 1980 (30 U.S.C. 1602), and the stated objectives of the Midcontinent Strategic and Critical Minerals Project.

Regional Potential of Selected Paleozoic Carbonate Units in the Northern Midcontinent for Undiscovered Mississippi Valley–Type Deposits

By Walden P. Pratt

Abstract

World-class Mississippi Valley–type (MVT) deposits—stratabound, carbonate-hosted deposits of predominantly zinc and lead sulfides—occur in the midcontinent of the United States in Upper Cambrian rocks (Southeast Missouri district), in Middle and Upper Ordovician rocks (Upper Mississippi Valley district), and in Mississippian rocks (Tri-State district). The initial discoveries in all three districts were made at or near the surface. Therefore the same formations in the subsurface elsewhere in the region may have potential for undiscovered MVT deposits. This report attempts to identify areas where the geologic conditions for such deposits are favorable.

The currently favored model for the origin of MVT deposits is that they are deposited by laterally migrating basin brines, which, because they are under relatively higher hydrostatic head, will move upsection wherever they are unconfined. MVT deposits are hosted in dolomitic rocks that are close to a limestone interface and are (or once were) capped by impermeable shales. New map compilations showing the thickness and limestone-dolostone ratios of the three principal Paleozoic carbonate packages in the northern midcontinent make it possible to identify potentially favorable carbonate terranes, using the concept of a favorable limestone-dolostone "interface zone" 5 mi on each side of the 1:4 limestone-dolostone isopleth. Other new compilations showing the extent of the principal Paleozoic shale units indicate areas where the favorable carbonate terranes are accessible to underlying aquifers but are covered by shale caprocks. Combining these maps thus makes it possible to identify areas that fulfill the lithologic and physical conditions of the model and should therefore be potentially favorable sites for accumulation of MVT deposits.

Among numerous areas thus identified, those that seem to be the most intriguing for further investigation are (1) in the Upper Cambrian carbonates, areas in Ralls County, Mo., and west-central Iowa; (2) in the Middle and Upper Ordovician carbonates, possible south and southwest extensions of the Upper Mississippi Valley district, an area in Marion and Mahaska Counties in south-central Iowa, and a zone extending irregularly across north-central Illinois; and (3) in the Mississippian carbonates, an area in Carroll County, Mo.

INTRODUCTION

The midcontinent of the United States is the location of three world-class mining districts (Southeast Missouri, Tri-State, and Upper Mississippi Valley) and several lesser mining districts that contain ores of the Mississippi Valley type (MVT)—simply defined as stratabound deposits of base-metal sulfides, mostly zinc and lead, hosted in shallow-water platform carbonates (fig. G1). These districts were originally discovered through exposures of the ore minerals at or near the surface. Yet the same or similar sedimentary host formations continue throughout much of the region in the subsurface; hence it seems reasonable that a potential for undiscovered deposits in these formations may exist elsewhere in the midcontinent region, where they are buried under younger sediments.

Figure G1. Index map of central United States showing area of Midcontinent Strategic and Critical Minerals Project and principal known Mississippi Valley–type (MVT) districts. 1, Upper Mississippi Valley zinc-lead district; 2, Southeast Missouri lead-zinc-barite-copper-silver district; 3, Tri-State zinc-lead district; 4, Central Missouri barite district; 5, Northern Arkansas zinc district; 6, Illinois-Kentucky fluorspar-lead-zinc-barite district.

The northern midcontinent MVT deposits have been the subject of much recent discussion in the literature (for example, see Snyder, 1968; Economic Geology, 1977; Heyl, 1983; Kisvarsanyi and others, 1983; Sangster, 1983; Leach and Rowan, 1986; Ohle, 1990; Pratt and Goldhaber, 1990; Viets and Leach, 1990; Clendenin, 1991; Goldhaber and Eidel, 1992). Many details of their origin are still matters of debate, especially questions regarding the source and mode of transportation of the sulfur and the physical and chemical processes of sulfide precipitation. Nevertheless, all these districts have three simple **physical** geologic elements in common: (1) they are hosted in carbonate rocks, relatively close to regional or local transitions from limestone to dolostone (Snyder, 1968, p. 278; Pratt and Wandrey, in press); (2) they are in contact with or accessible to underlying aquifers that could have served as conduits for mineralizing brines—either directly or through windows in intervening impermeable shales—and (3) in most cases they are, or were in the past, overlain by impermeable shale caprocks.

The role of an "impermeable shale caprock" is more complex than it may seem. The classic concept was that an overlying shale was necessary to prevent the mineralizing fluids from escaping upward without depositing their minerals. Thus in a simple model the fluids would be confined under the shale cap and would spread out laterally, undergoing whatever reactions were necessary with the host rock (or with other fluids) to precipitate the ore minerals. But what then? Given the enormous volumes of brine that would have to **pass through** the host rock to produce such huge ore deposits, we must assume that the brine eventually escapes, whether vertically or laterally. A regionally extensive unbroken shale caprock would tend to retard such escape and thus might inhibit mineral deposition rather than promote it. However, a local breaching or discontinuation of the shale cap—whether caused by erosion, nondeposition, facies change, or faulting—would focus resumed upward movement of the brine, and in the right physical setting would produce a funneling effect, permitting the continuous flow necessary to produce a large ore deposit; in short, the system has to be dynamic rather than static. Thus the concept of a shale caprock inherently includes the paradox that the caprock must be breached or at least disturbed, somewhere in the vicinity of the ore deposit. Where the ensuing discussions refer to a shale caprock, this concept will be implicit.

In summary, apart from more subtle factors, three fundamental conditions must be met for the genesis of an MVT deposit: (1) the presence of a carbonate host rock; (2) access to an aquifer that could have transported a mineralizing fluid; and (3) some lithologic or structural mechanism for focusing or retaining that fluid in the host rock long enough for it to deposit its load of mineral components before escaping laterally or upward. The premise of this report is that if we can identify areas in the midcontinent where these three conditions coexist, then we will have identified terranes that have the **basic lithologic and physical elements** that are requisite for the formation of MVT deposits, and this information could be used as a first step in prospecting for such deposits. Hence this report attempts to apply two factors to identify areas that are potentially favorable for MVT mineralization: (1) the potential host rocks are lithologically favorable, because of a perceived favorable limestone-to-dolostone ratio; and (2) these lithologically favorable host rocks are in a physically favorable situation to have received and temporarily retained upwelling mineralizing fluids—that is, situated above a window (or a fracture zone) in any underlying shale beds and overlain by a continuous shale caprock.

Regional data on several of these geologic elements common to midcontinent MVT deposits have recently been compiled as part of the Midcontinent Strategic and Critical Minerals Project, a cooperative effort between the U.S. Geological Survey and the northern midcontinent state geological surveys (Pratt, 1985a,b; Pratt and

Sims, 1987). Those compilations form the data base for the present report. Building on those compilations, in this report I will use the following empirical, descriptive model that incorporates and amplifies the three elements described above.

Acknowledgments.—Most of the concepts on which this paper is based have grown out of discussions with numerous colleagues in the Midcontinent Strategic and Critical Minerals Project of the U.S. Geological Survey and cooperating state geological surveys: in particular I thank Ralph Erickson, Marty Goldhaber, Tim Hayes, Allen Heyl, and John Viets of the USGS; Ken Anderson, Jim Martin, Ira Satterfield, and Heyward Wharton of the Missouri Geological Survey; Jim Baxter and Jim Eidel of the Illinois Geological Survey; Bob McKay and Brian Witzke of the Iowa Geological Survey Bureau; and Ernie Ohle, formerly of the M.A. Hanna Mining Company. The two sets of regional maps used in preparing this report, showing areal extent of selected shales, and thicknesses and limestone-dolostone ratios of selected carbonates, were prepared from state maps compiled by many people whose efforts have been acknowledged in those publications. The report benefitted greatly from critical reviews by Marty Goldhaber and John Viets, particularly with regard to the concept of the shale caprock.

DESCRIPTIVE MODEL FOR MIDCONTINENT MVT DEPOSITS

Source of Mineralizing Fluids

The working model for the genesis of MVT deposits that is currently accepted by USGS mineral assessment teams involves upward movement of metal-bearing brines from an underlying aquifer to a site in the carbonate section where the metals are precipitated as sulfides. The fluids are widely considered to originate as deep basin brines and to migrate laterally by gravity-driven flow systems (see, for example, Leach and Rowan, 1986; Palmer and Hayes, 1989; Bethke and Marshak, 1990; Viets and Leach, 1990; Viets and others, 1992; Garven and others, 1993). Possible source basins for such brines in this region would include the Arkoma, Anadarko, Black Warrior, Illinois, Salina, and Forest City Basins, and perhaps even the Williston Basin. The existence of the several MVT districts in this region attests to the likelihood that there could have been several different ultimate fluid sources at one time or another. Beyond those generalizations, I do not consider in this report the source of the metals or sulfur, or the processes responsible for precipitating the metals as sulfides.

Permeable Formation(s) to Serve as Aquifer(s) for Lateral Transmission of the Mineralizing Fluids from the Originating Basin or Other Ultimate Source

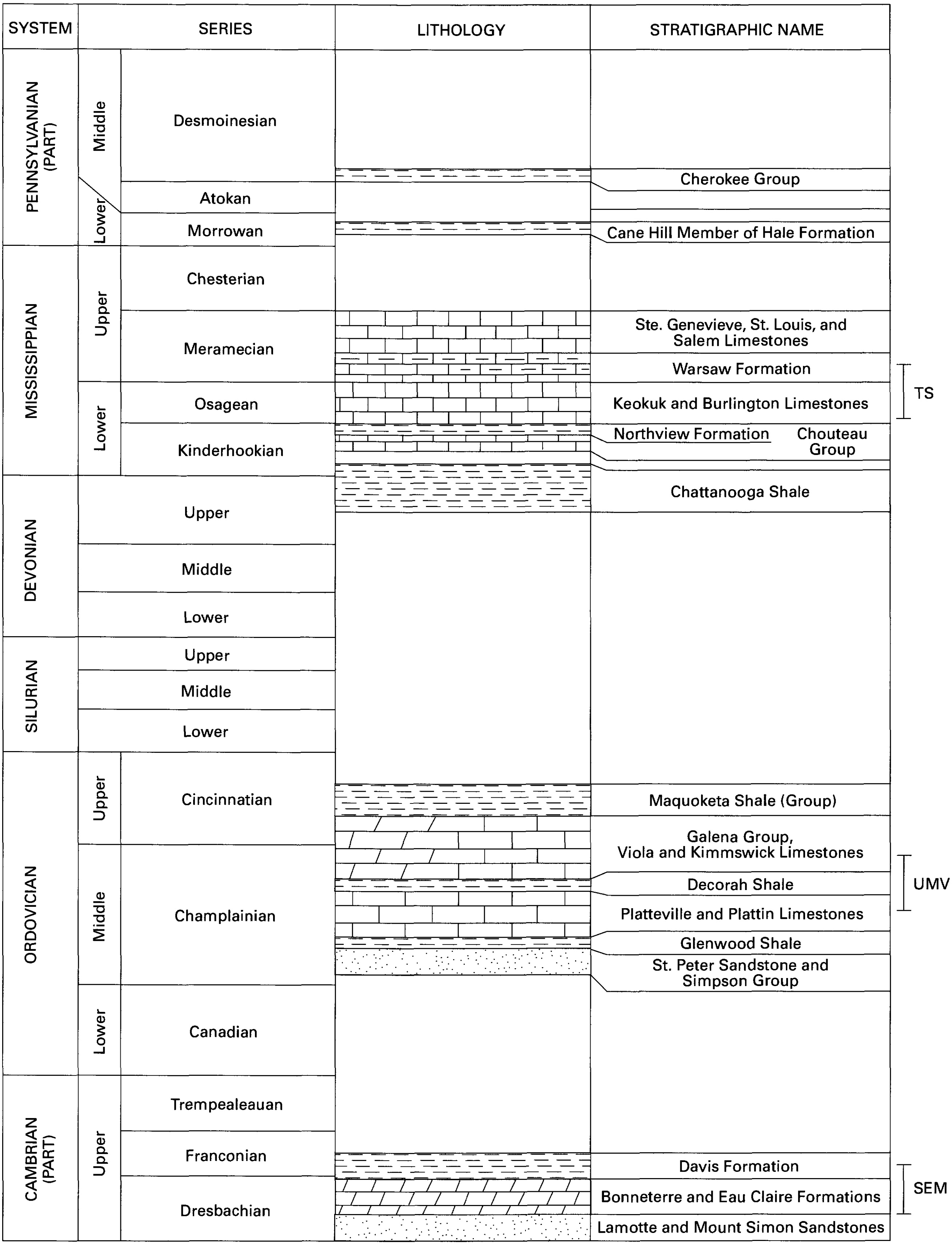
The two principal regional sandstone units pertinent to this model are the Lamotte and Mount Simon Sandstones (lower Upper Cambrian) and the St. Peter Sandstone and sandstones of the Simpson Group (Middle Ordovician) (see fig. G2). We have not made specific compilations of the areal extent of these sandstone units, but examination of the regional Phanerozoic cross sections prepared for this project (Mugel and Pratt, 1992) shows that the lower Upper Cambrian sandstones extend through most of the area except the northwestern part of the area and central and northeastern Kansas, and that the Middle Ordovician sandstones are absent mainly from the northwestern and northeastern parts of the area and from the Ozark region in southern Missouri and adjacent parts of Kansas and Oklahoma.

For the Mississippian host rocks the postulated aquifer is the Cambrian-Ordovician regional aquifer, which consists primarily of carbonates; this will be discussed more fully under the Mississippian model.

Permeable Formations or Zones to Provide Conduits for Vertical Transmission of the Mineralizing Fluids from the Lateral Aquifer into the Host Rock

In the lowermost of the three models considered here, the Upper Cambrian carbonates, the host formation directly overlies the assumed mineralizing aquifer (the Lamotte and Mount Simon Sandstones) and a distinct or separate formation forming a vertical conduit is not a consideration. In the models involving host formations higher in the section—the Ordovician and Mississippian—the principal requirement of this model is not a specifically defined permeable zone, but rather the absence of an impermeable zone—in other words, a window or edge in the next underlying shale, to focus upward migration of the mineralizing fluids into the potential host rocks. For this report, the extents of the principal Paleozoic shale units, in thicknesses of 5 ft or more (considered by consensus to be a minimum thickness to serve as an effective aquitard), were obtained from the compilations by Pratt (1993).

A zone of structural weakness, if present, would enhance vertical fluid migration; data on regional Phanerozoic structures have been compiled by Anderson (1988), and data on regional Precambrian structures by Sims (1990).


SYSTEM
SERIES
LITHOLOGY
STRATIGRAPHIC NAME
PENNSYLVANIAN (PART)
Middle
Desmoinesian
Lower
Atokan
Morrowan
Cherokee Group
Cane Hill Member of Hale Formation
MISSISSIPPIAN
Upper
Chesterian
Meramecian
Lower
Osagean
Kinderhookian
Ste. Genevieve, St. Louis, and Salem Limestones
Warsaw Formation
Keokuk and Burlington Limestones
Northview Formation
Chouteau Group
Chattanooga Shale
TS
DEVONIAN
Upper
Middle
Lower
SILURIAN
Upper
Middle
Lower
ORDOVICIAN
Upper
Cincinnatian
Middle
Champlainian
Lower
Canadian
Maquoketa Shale (Group)
Galena Group,
Viola and Kimmswick Limestones
Decorah Shale
Platteville and Plattin Limestones
Glenwood Shale
St. Peter Sandstone and Simpson Group
UMV
CAMBRIAN (PART)
Upper
Trempealeauan
Franconian
Dresbachian
Davis Formation
Bonneterre and Eau Claire Formations
Lamotte and Mount Simon Sandstones
SEM

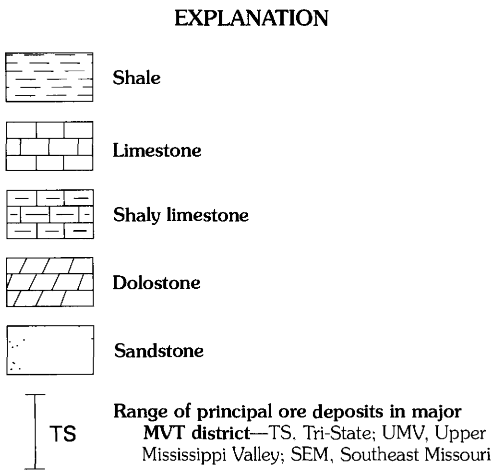


Figure G2 (facing page). Stratigraphic relationship of principal carbonate units in the northern midcontinent region having potential as Mississippi Valley–type (MVT) host rocks, and their relation to selected shales and sandstone aquifers. Blank sections represent either gaps in the stratigraphic section or formations not pertinent to this report. Names are in current usage by participating state geological surveys. Modified from Adler (1987).

A Carbonate Host Rock

With minor exceptions, the principal host rocks in all the midcontinent MVT deposits are sedimentary carbonates, and in most cases they are dolostones. (The two minor exceptions to the rule of carbonate host rocks are in the Southeast Missouri district: the galena deposits in Lamotte Sandstone at the Indian Creek Mine at the north end of the Viburnum Trend and similar deposits in Lamotte Sandstone in the Mine LaMotte area of the Old Lead Belt near Fredericktown, Mo. In both areas these deposits are subjacent to typical MVT deposits in dolomite of the overlying Bonneterre Formation, and for this reason they are not considered as a separate deposit type.)

Moreover, Snyder, in a review of the midcontinent MVT districts, stated "The favored locus for ore occurrence is at or near the limestone-dolomite interface. Mineralization in undolomitized limestone in the major midcontinent districts is rare. Ore is almost as rare well within the dolomitized area." (Snyder, 1968, p. 278). The importance of the limestone-dolostone transition in all the districts is further discussed by Pratt and Wandrey (in press).

The Midcontinent Strategic and Critical Minerals Project team decided to focus on the three Paleozoic carbonate assemblages that are known to host MVT deposits in various parts of the region. The compilations by Pratt and Wandrey (in press) show both the thickness and the limestone-dolostone ratios of these three principal Paleozoic carbonate "packages" (so called because some of them are too complex in regional stratigraphy to be referred to simply as "units"). These are the Upper Cambrian package, comprising the Bonneterre and Eau Claire Formations and equivalents; the Middle and Upper Ordovician package, comprising the Galena Group and equivalents; and the Mississippian package, consisting of carbonates of the Kinderhookian, Osagean, and Meramecian Series (see fig. G2).

A Shale Caprock

For most workers, an overlying impermeable unit, to confine the mineralizing fluid within the potential host rocks long enough to deposit the ore minerals, is a final critical element of the model. Again, information on the distribution of shales was obtained from the compilation by Pratt (1993).

PROCEDURE

The procedure used in this study was basically simple: overlaying the various carbonate and shale maps to locate places where a limestone-dolostone interface is overlain but not underlain by shale—fulfilling the model conditions of a shale edge or window underneath and a shape caprock above. The principal problem was defining the limestone-dolostone interface. Ideally this interface would be represented by the 1:1 isopleth, with pure limestone on one side and pure dolostone on the other. However, the range of isopleths from 1:4 to 4 (that is, 20 percent to 80 percent limestone) indicates that the situation is not that simple. In the Southeast Missouri district, for example, the interface is an intertonguing zone several miles wide and, pragmatically, the 1:16 isopleth is the effective "interface" for exploration purposes because it most accurately delineates the ore trends throughout the district (Erickson and others, 1978; Thacker and Anderson, 1979). But in the regional compilation (Pratt and Wandrey, in press) we are dealing with isopleths that have been interpolated between points with simple numerical values, each value representing the relative amounts of limestone and dolostone in a total section of carbonate rock from tens to hundreds of feet thick. So the concept of the interface is very scale dependent, and we must use it accordingly in this analysis. Thus the thicker the carbonate package, the more broadly the isopleths have to be interpreted.

Furthermore, we must also consider the mechanistic reason for emphasizing this interface, in addition to its empirical validity as an ore guide. Most regional platform dolostones originate as limestones, with a tendency, after some diagenesis, toward retarding fluid flow. The fact that they have been dolomitized indicates that they have transmitted fluids (the dolomitizing fluids) and therefore are aquifers, not aquitards. What we are looking for in this synthesis is the edge of the limestone aquitard, and the consensus of carbonate sedimentologists on the project team was to select the 1:4 isopleth, representing 20 percent limestone, as the minimum cutoff. However, considering that in most places these isopleths are interpolated and hence approximate, and also in order to broaden the parameters for the purpose of this study, I am here defining the potentially favorable lithology as an interface zone no more than 10 mi wide, centered on the 1:4 isopleth; on the dolostone side the zone extends out 5 mi from the 1:4 isopleth, and on the limestone side, 5 mi or to the 1:1 isopleth, whichever is less. Also, in most places the transition is considered an interface zone only where the distance between the 1:4 and 1:1 isopleths is narrow enough (10 mi wide or less) to indicate that the transition is relatively abrupt.

Using this concept of the limestone-dolostone interface, I overlaid the originals of the respective carbonate and shale maps, all at a scale of 1:1,000,000, to determine areas where the requisite conditions are met: a window or edge in the underlying shale, a limestone-dolostone interface zone in the carbonate, and a shale caprock above. The areas thus delineated have been copied onto plates G1–G3 at 1:2,000,000 for convenient inclusion in this report, but anyone interested in pursuing this matter further should use the original maps as published at 1:1,000,000. Thicknesses and depths of the carbonate units were estimated from regional cross sections (Mugel and Pratt, 1992) or, in a few places, from drill-hole data.

Finally, three other sources were consulted for additional pertinent data. Two of these are the companion maps of Phanerozoic structures compiled by Anderson (1988) and the Precambrian map of Sims (1990). The third is a set of maps of the individual states showing locations of visible sulfides in subsurface samples, as reported in drillers' logs; these maps, at 1:500,000 scale, were prepared by the state geological surveys for this project but were never published and have now been returned to the respective states, where presumably they are available for inspection.

I will consider all three carbonate packages as potential host rocks, with selected combinations of mineralizing aquifers, underlying shale windows, and overlying shale caprocks. Specifically, these are an Upper Cambrian model; two Ordovician models, one with a St. Peter aquifer and the other with a Lamotte–Mount Simon aquifer; and a single Mississippian model using the Upper Cambrian and Lower Ordovician aquifer. A generalized view of the regional Paleozoic stratigraphy and nomenclature pertinent to this report is given in figure G2.

This report is based on compilations made at 1:1,000,000 scale. It is not intended to supersede the larger-scale (1:250,000) mineral-resource assessments of five 1° × 2° quadrangles within the project area that have been done recently under the Conterminous United States Mineral Assessment Program (CUSMAP). Specifically (and chronologically), these are the Rolla, Springfield, Joplin, Harrison, and Paducah quadrangles (Pratt and others, 1984; Erickson and Chazin, 1991; Goldhaber and Eidel, 1992; Pratt and others, 1993a,b). That the present study does not identify all the areas assigned a high MVT potential in the CUSMAP assessments is partly a result of scale, but largely a result of the use of other kinds of data, such as geochemical anomalies, in the CUSMAP studies.

An earlier publication in this series (Pratt, 1987) made a somewhat similar attempt to define permissive lithologies for MVT deposits for the entire Sauk sequence—rocks of Cambrian and Early Ordovician age—by mapping the distribution of the limestone:dolostone and carbonate:clastic ratios. That attempt failed as a regional prospecting guide because of the great preponderance of dolostone over limestone when the Sauk sequence is taken in its entirety. However, it was that failure that led us to the present effort using smaller stratigraphic units.

UPPER CAMBRIAN MODEL

Lamotte Aquifer

Bonneterre Formation and Equivalents Capped by Shale of Davis Formation

This discussion will **not** address several areas where the limestone-dolostone interface zone is relatively narrow (about 10 mi wide or less) but is far removed from overlying Davis Formation—such as in east-central and southern Illinois. Numbers in the list below are keyed to plate G1.

1. The validation of this model is the identification of the famous Viburnum Trend mining district in Crawford, Washington, Dent, Reynolds, and Shannon Counties, Mo. This method was successful in "predicting" the occurrence of this major district. The complete limestone-dolostone transition from 1:4 to 4 occurs within about 3 mi laterally in Bonneterre Formation averaging about 300 ft thick, all under a continuous Davis cap. A similarly tight interface trends east-west in northeast Oregon and southwest Carter Counties, also under a Davis cap.

2. A possible northeasterly extension of the Viburnum Trend occurs in Washington, Jefferson, and southern Franklin Counties, Mo., where separate interface zones are under separate Davis caps. Anderson (1988) showed several northwesterly trending normal faults in this area, and the Missouri subsurface mineralization map shows numerous drill holes that reveal visible lead, zinc, and copper sulfides and barite in Lower Ordovician and Upper Cambrian formations.
3. Farther west in Missouri the interface zone is 7–10 mi wide and extends northwest and west from Howell County through Douglas, Wright, and Laclede Counties, mostly under the Davis cap, and continues north into Miller County, where it makes an abrupt northeast kink under a Davis cap. The structure through all this area (from Wright County north into Miller County) is characterized by numerous northwest-striking normal faults (Anderson, 1988; Middendorf and others, 1991). The Bonneterre Formation is about 200–300 ft thick and is an estimated 1,000–2,000 ft below the surface. The southernmost part of this segment of the interface zone, in Douglas and Howell Counties, is of special interest because it is in the same area described by Erickson and others (1981) as having potential for MVT deposits, not in the Bonneterre but in post-Bonneterre Cambrian carbonates.
4. In Cole County, Mo., just north of Jefferson City, the interface zone forms a narrow band about 15 mi long under the Davis cap; the Bonneterre is about 200 ft thick and is at a maximum depth of about 1,500 ft. The interface zone is cut by a short north-northwest-trending normal fault (Anderson, 1988).
5. In Ralls County, Mo., a northwest-trending oval area about 25 mi long is defined by an interface zone only 1–2 mi wide in Bonneterre Formation about 300 ft thick and at a maximum estimated depth of 2,000–2,500 ft. An overlying Davis cap is nearly coincident with the limestone-rich area. The area is on the crest of the northwest-trending Lincoln Fold (Anderson, 1988). The Missouri subsurface mineralization map shows zinc sulfide in four holes in the vicinity, in Ordovician (Champlainian), Devonian, and Mississippian (Kinderhookian) formations.
6. In Howard and Boone Counties, Mo., northwest and west of the city of Columbia, the east-trending interface zone is partly covered by an east-west-elongate Davis cap about 35 mi long and 8 mi across; the Bonneterre is about 200–300 ft thick and a maximum of about 2,300 ft deep.
7. In west-central Iowa, in an area west and south of Des Moines, I have made an exception to the rule of considering an interface zone only where the transition from 1:4 to 1 is less than 10 mi wide, because this large island of limestone-rich rock in the regional expanse of dolostone appears to be anomalous and should not be ignored. In this area the interface zone indicates a well defined northwest-trending dolomitized oval area about 85 mi long, centered on Dallas County. The Bonneterre is 110–180 ft thick and a maximum of about 2,500–3,200 ft deep; the northeast side of the area is delimited by a facies transition to siliciclastics. The Davis cap is widespread. The Thurman-Redfield structural zone cuts northeast across the middle of the area, paralleled by a northeast-trending syncline (Anderson, 1988). No subsurface sulfide mineralization is reported, but one drill log reported sparry dolomite.

ORDOVICIAN MODELS

St. Peter Aquifer

Windows in Glenwood and Decorah Shales—Maquoketa Shale (Group) Cap Overlying Galena Group

Numbers in this list are keyed to plate G2.

1. The test of this model is the Upper Mississippi Valley district, which is approximately centered on the intersection of two significant lines: the limestone-dolostone 1:4 isopleth, which approximately bisects the district from north-northwest to south-southeast, and the edge of the Decorah Shale, which crosses the district sinuously from north-northeast to south-southwest. Thus at least two elements of the model are fulfilled, although the influence of the limestone-dolostone interface is more subtle here, because the district extends as much as 50 mi out from the interface rather than being narrowly restricted along it as the Viburnum Trend is. Nevertheless, these elements of the model successfully identify the host area for this district.

   The third element, the cap of Maquoketa Shale (Group), is more problematical. The present erosional edge of the Maquoketa extends from near Decorah, Iowa, southeasterly into Livingston County, Ill., and then northward to beyond Fond du Lac, Wisc. (Pratt, 1993, map D); the Maquoketa has been eroded from across the Wisconsin Arch. Thus the required cap is conspicuously absent from the district, the southwest edge of the district being nearly coincident with the present erosional edge of the Maquoketa. The Maquoketa almost certainly was originally present across the entire district, because several outliers remain within the district, in southwestern Wisconsin and northern Iowa (Heyl and others, 1959, p. 6; B.J. Witzke, Iowa Geological Survey Bureau, oral commun., 1994). The question is whether this Maquoketa cap was present at the time of mineralization—which probably was at least as late as Pennsylvanian (Heyl, 1983, p. 41) or Permian (about 270 m.y., according to Rb-Sr dating of sphalerite by Brannon and others, 1992). Witzke believes that the Maquoketa cover remained intact at least into the Pennsylvanian, but unfortunately the record has been largely removed and there is no definitive evidence as to the extent of the Maquoketa in either the Pennsylvanian or the Permian. (If one fully accepts the shale cap requirement of the model, one could argue that the presence of the mineralized district is in itself evidence of the extent of the Maquoketa; in the present context, however, that argument would be unacceptably circular.)

Heyl and others (1959, p. 170) stated quite emphatically, "A Maquoketa shale cover has no bearing on the presence of mineralization in the underlying beds." However, Heyl has subsequently explained that his intention in that statement was only to rule out the idea that the Maquoketa had a ponding effect on postulated downward-percolating mineralizing solutions—the older theory of ore genesis in this district (A.V. Heyl, oral commun., 1993).

2. The map (pl. G2) shows apparently favorable ground—a broad interface zone beneath Maquoketa Shale—immediately south and southwest of the Upper Mississippi Valley district, mainly in Dubuque and Jackson Counties, Iowa, and Jo Daviess and Carroll Counties, Ill. This lends support to the suggestion of Heyl and West (1982) that prospecting in that direction might find potentially productive extensions of the district. The Galena here is at depths of somewhat less than 1,000 ft, as it is in the two following areas.
3. The interface zone overlies an irregular Glenwood Shale window about 10 mi square in Cedar and Clinton Counties, Iowa, centered on the crest of a northwest-trending anticline on the southwest flank of the East Central Iowa Basin.
4. In southern Linn County, Iowa, potentially favorable ground is outlined by two small windows between edges of the Glenwood and Decorah Shales, along a southwest extension of the Plum River Fault Zone (Anderson, 1988; Sims, 1990).
5. Similarly, in Marion and Mahaska Counties, Iowa, two small adjacent favorable areas of the interface zone are outlined by small windows between the edges of the Glenwood and Decorah Shales. These areas are within the Ancestral Iowa Basin (Anderson, 1988) and approximately centered on the major northwest-trending Des Moines River structural zone (Sims, 1990). Estimated depth of the Galena is 1,000–1,500 ft.
6. The interface zone is present at several places in central and northern Illinois. The longest continuous run, hereafter referred to as the trans-Illinois zone, is a narrow band that extends east and southeast from Hancock County to Menard County, then northeast to McLean County, and then irregularly north and eastward to the edge of the map area in Kankakee County. The somewhat angular areal pattern of the zone reflects the three regional structures that it crosses: the north-northeast-trending Mississippi River Arch in Hancock and Henderson Counties; the north flank of the Illinois Basin; and the north-northwest-trending Lasalle Anticlinal Belt through Lasalle and Livingston Counties. Limestone-dolostone transitions occur at three other places in northern Illinois—a circular area in Bureau, Marshall, and Stark Counties; another circular area in Kane and Kendall Counties; and an irregular oval area in Grundy and Will Counties that merges with the trans-Illinois zone.

Most of these interface zones should have potential for MVT mineralization. The Galena strata are approximately 200–500 ft thick through this area and are buried at depths ranging from about 900 to 3,000 ft. As plate G2 shows, in most of the areas described the interface zones are clear of underlying Glenwood or Decorah Shales and (except across the Lasalle Anticline) are overlain by Maquoketa Shale. Smaller structures that might influence mineralization are several east-northeast folds in McDonough and Fulton Counties; paired north-trending folds in west-central McLean County; north-northwest folds in southwest Grundy County; and a northwest fault in western Will County (Anderson, 1988). Sparry dolomite was noted at two places along the trans-Illinois zone—one in McLean County, about 10 mi north-northeast of Bloomington, and the other in southeast Grundy County. The Illinois subsurface mineralization map (unpublished) shows a few sulfide occurrences along the western part of this zone, as far east as Menard County (due south of the city of Peoria), and several more occurrences near the east end in Grundy, Kankakee, Will, and Kane Counties, but nothing in the intervening area.

7. A westerly extension of the trans-Illinois interface zone, along the west side of Hancock County, Ill., is technically eliminated from consideration because it is just outside the west edge of the Maquoketa cap. If the Maquoketa previously extended as little as 10 mi farther west, as is probable (Willman and Buschbach, 1975, p. 82, 84–86), then this area would fit the criteria of the model. This is noteworthy because Erickson and others (1987, p. 22), in their report on subsurface geochemical anomalies, cited this general area as one meriting further study for potential MVT deposits not only in the Ordovician rocks but also in the overlying Devonian:

   > *** The Maquoketa Shale window in Illinois may have played the same role [as the Chattanooga Shale window in the Tri-State district]—i.e., concentrating and funneling metal-bearing fluids from carbonates of the Ottawa Megagroup *** into a relatively thin middle Devonian carbonate ***. Although the pilot study data points are sparse, findings suggest that the Devonian carbonates and the Platteville through Galena interval would seem to be favorable prospecting ground in this part of Illinois.

   The Galena strata here are at an approximate depth of 1,000–1,200 ft. The same band in the interface zone extends westward across northern Missouri. Tight kinks in this zone in Shelby, Knox, and Lewis Counties, Mo., are located on the crest of the Lincoln anticline; the carbonate is 40–80 ft thick. Although this area lacks a present cap of Maquoketa Shale, it is relatively close to the present erosional edge of the Maquoketa, like the area in Hancock County, Ill., just described, and may therefore have some potential.

8. A small dolomitized island of carbonate rock in western Ford County, Ill., is not dolomitized to the extent required by this model—the limestone-dolostone ratio is <2 but >1—but sparry dolomite was noted in a drill hole in this area.

9. A very small area of the interface zone, about 2–3 sq mi, in southeastern Buchanan and northeastern Platte Counties, Mo., above a Decorah edge and capped by Maquoketa, is on the southeast flank of the Forest City Basin but has no other apparent structures and no reported subsurface mineralization. The Galena is about 200–300 ft thick and about 1,000–1,500 ft deep.

10. In eastern Kansas, a trapezoid-shaped exposure of the interface zone 10 mi wide, just west of Lawrence, is on the southeast flank of the North Kansas Basin but has no other apparent structures and no reported subsurface mineralization; the Galena is about 100 ft thick and about 2,800 ft deep. A few miles northwest of this area, and northwest of Topeka, is another exposure of the interface zone about 20 mi long. Both of these areas are defined by a window in the Decorah Shale.

11. In west-central Coffey County, Kans., a short section of the interface zone, in a thin (15–20 ft) sequence of carbonates about 2,000–2,300 ft deep, is underlain by a small reentrant in the generally northeast-trending erosional edge of the Decorah Shale. The area is many miles from the edges of the shales of the Davis and Glenwood Formations. The present edge of the Maquoketa Shale is some 30 mi to the northwest, but as with the areas described under 6., above, restitution of possibly eroded Maquoketa could provide the necessary overlying cap. Structurally, the area is where the northwest-trending Bourbon Arch crosses a northeast-trending arm of the Cherokee Basin.

12. In southern Smith County, Kans., the edge of the Decorah and the Maquoketa cap define a favorable area 3–4 mi wide in a carbonate section 140–200 ft thick and about 1,000–1,400 ft deep. The area is on an indistinct boundary between the North Kansas Basin and the Salina Basin, and lies between a north-northwest-trending paired syncline and anticline.

13. Hatch and others (1983) described an area in southeast Wapello County, Iowa, as having some potential for MVT deposits in the Upper Cambrian St. Lawrence Formation, the Lower Ordovician Oneota Dolomite and Shakopee Dolomite, and the Middle Ordovician Platteville Formation, on the basis of anomalously high amounts of the MVT base-metal suite in chip samples of these rocks from deep water wells and anomalously high metal contents in overlying Pennsylvanian coals. To the extent that windows in the underlying shales are necessary to this model, the present study appears to cast some doubt on that potential, because southeast Wapello County is well within the area underlain by Davis Formation and several miles from the nearest known opening in the underlying Glenwood Shale. However, the map of the

Galena Group dolomites does show that the area in question is close to a tight stricture and bend in the interface zone.

Lamotte–Mount Simon Aquifer

Windows in Davis Formation and Glenwood and Decorah Shales—Maquoketa Shale (Group) Cap Overlying Galena Group

A second model for MVT mineralization in the Ordovician carbonates assumes the basal sandstones of the Upper Cambrian Lamotte Sandstone and the stratigraphically equivalent Mount Simon Sandstone as aquifers, and thus requires windows in the Upper Cambrian Davis Formation as well as the younger Glenwood and Decorah Shales. However, this has only minor effect on the Ordovician models already discussed because of the relatively limited extent of the Davis. The Upper Mississippi Valley district remains virtually unaffected, except for about 10 mi of the southwesternmost part of the suggested extension of the district to the southwest in Jackson County, Iowa. The Davis or equivalents do underlie all of central Iowa and this eliminates areas 3, 4, 5, and 13 described above. The remainder of the Davis Formation in the map area is confined largely to southern Missouri, so the other Ordovician areas delineated on the basis of a St. Peter Sandstone aquifer are also viable for a Lamotte–Mount Simon aquifer.

MISSISSIPPIAN MODEL

Upper Cambrian and Lower Ordovician Aquifer

Windows in Glenwood, Decorah, Maquoketa, and Chattanooga Shales—Northview Formation Cap over Sandstones of the Chouteau Group; Warsaw Formation Cap over Burlington Limestone

This model is based on the MVT deposits of the Tri-State district of Kansas, Missouri, and Oklahoma. The numbers in the list below are keyed to plate G3.

Viets and others (1992) proposed that the "post-Bonneterre Cambrian-Ordovician regional aquifer"—consisting primarily of carbonates—was the primary aquifer for the Tri-State district and several minor districts in the Ozark region. However, the Middle and Upper Ordovician strata are not present in the Tri-State area (McKnight and Fischer, 1970, p. 15–18); hence the principal aquifer in this model, at least in its type locality, consists only of the Upper Cambrian and Lower Ordovician carbonates.

1. Confirming the validity of the model, the Tri-State district is located far from the nearest edges of the Glenwood, Decorah, and Maquoketa, but above a window defined by the northern edge of the Chattanooga Shale and the southern erosional limit of the Northview Formation (Brockie and others, 1968, fig. 1). The Mississippian carbonates here are 300–400 ft thick and are partly capped by shale of the Cherokee Group. (A more detailed and larger-scale analysis of the application of this model in the Tri-State district is given in the mineral-potential assessment of the Joplin 1° × 2° quadrangle (Pratt and others, 1993a).)

   The Tri-State district apparently fails the model's parameter of a limestone-dolostone interface—the Mississippian package here is well over 80 percent limestone. The dolostone is not developed regionally, but rather occurs within the host limestone beds as cores or islands of coarse-grained, massive, gray spar as much as several hundred feet across (McKnight and Fischer, 1970); the ores surround these dolostone cores and are in fractured jasperoid zones at the limestone-dolostone contacts (Brockie and others, 1968, p. 417). However, the dolostone cores are not thick enough to reduce the Mississippian limestone-dolostone ratio below a value of 4, and therefore the interface zone used in the previous models is of no use here. Consequently, plate G3 includes all the limestone-dolostone isopleths in the broad region where the underlying Chattanooga and other shales are absent, to be used as described below.

2. A broad area of Mississippian carbonates extends north-northeast from the Tri-State district across north-central Missouri (see pl. G3). The Warsaw Formation is absent from most of this area, but the Cherokee is widespread and provides the necessary cap.

   If we follow the Tri-State model in a broad sense and simply disregard a low limestone-dolostone ratio (that is, an interface defined by limestone:dolostone = 1:4) as a criterion for MVT potential, then this entire area has to be considered potentially favorable; in fact, the Missouri subsurface mineralization map (unpublished) shows numerous wells that penetrated sphalerite occurrences through most of this area. However, this is not realistic for our objective, which is to narrow down the area to smaller targets—especially considering that the Mississippian is either exposed or buried only shallowly through much of this area and therefore has been widely sampled either by surface prospecting or by drilling. An alternative approach would be to use the carbonate ratio in the Tri-State district to define a new model specific to the Mississippian, focusing only on areas where the limestone-dolostone ratio is greater than 4. This, however, is clearly contrary to our underlying premise. Instead I suggest that we should still attempt to incorporate as (relatively) low a limestone-dolostone ratio as possible. If we compromise on a maximum limestone-dolostone ratio of 1:1 rather than 1:4, then we narrow down this broad belt to three small areas:

2a. An irregular area just north of Nevada, Mo., is capped by Cherokee Group and includes a circular 15-mi-wide area within the 1:2 isopleth. The larger area is astride the northwest-trending Bolivar-Mansfield tectonic zone, which defines the northeast side of a graben in both the basement and the Phanerozoic rocks; the Bolivar-Mansfield tectonic zone is flanked by two northwest-trending anticlines in the Phanerozoic rocks (Anderson, 1988; Sims, 1990).

2b. A small area in northwest Carroll County, Mo., is close to a north-northwest-trending anticline in the Phanerozoic rocks (Anderson, 1988).

2c. A small area in northwest Howard County and southern Rudolph County, Mo., cuts across a northwest-trending syncline in the Phanerozoic rocks.

3. Finally, dolostone makes up 50 percent or more of the Mississippian package in southeastern Phillips, southwestern Smith, and northwestern Osborne Counties, Kans.; a reentrant in the Decorah Shale and a cap of Cherokee Group shale provide a stratigraphically favorable locus for mineralization. Moreover, the area is on the southwest flank of the Salina Basin. However, the small thickness of the carbonates—20 ft or less—reduces the potential for significant MVT deposits.

Elsewhere in much of the study region the MVT potential of the Mississippian limestones under this model is eliminated because of the widespread presence of the underlying Chattanooga Shale. In much of Nebraska the Mississippian carbonates are widespread and the Chattanooga is absent, but there is no overlying impermeable cap of Mississippian age to complete the model.

A second Mississippian model using the St. Peter Sandstone as an aquifer is theoretically possible but would be subject to the same constraints as the model just described because of the Chattanooga Shale.

CONCLUSIONS

1. Among the numerous areas identified above as meeting the favorable criteria for possible MVT deposits, the following strike me (personally and subjectively) as the most intriguing for further investigation:

   - In the Upper Cambrian carbonates (pl. G1), the areas in Ralls County, Mo. (area 4) and west-central Iowa (area 6)
   - In the Middle and Upper Ordovician carbonates (pl. G2), the possible south and southwest extensions of the Upper Mississippi Valley district (areas 2 and 3), the area in Marion and Mahaska Counties in south-central Iowa (area 5), and the trans-Illinois zone (areas 6 and 7)
   - In the Mississippian carbonates (pl. G3), the area in Carroll County, Mo. (area 5)

   "Further investigation" as suggested here would include the following:

   - Literature study of the area of interest, including inspection of well records available from the respective state geological surveys
   - Examination of drill samples for visible sulfides; pink or white, coarsely crystalline vuggy dolomite; jasperoid; or other indicators of possible MVT mineralization (see Pratt, 1982)
   - If possible, analysis of HCl-insoluble residues of drill samples, especially those containing visible pyrite or marcasite; such analysis has been found to be particularly useful and informative for indicating the passage of metal-bearing fluids and outlining broad areas of potentially favorable ground for mineral discovery (see Erickson and others, 1978, 1981, 1983)
   - Physical exploration, if warranted

2. For more detailed follow-up study of other areas, a finer tuning (larger scale) of the limestone-dolostone interface might be more productive, but this would require reexamination of the original drill logs.

3. There may be other, or thinner, or areally less extensive Phanerozoic carbonate units than the ones discussed here that could serve as MVT hosts. One example might be the Devonian carbonate in Walworth County, S. Dak.—just barely within the northwest boundary of this project. As described by Redden (1975, p. 94):

   > The Williston basin has thick lower and middle Paleozoic carbonate rocks. Ordinarily these rocks change from limestone in the center of the basin to dolomite on the edges. Furthermore, there is a change to shallow reef conditions. *** Unfortunately, the amount of deep exploratory drilling by oil companies on the southern edge of the basin in South Dakota has been small. Yet drill cuttings from one well in Walworth County have small amounts of galena and sphalerite in Devonian carbonate rocks.

   Another example of possible MVT mineralization has long been known in deeply buried carbonates of the Ordovician part of the Arbuckle Group in west-central Kansas, 325 mi west-northwest of the Tri-State district (Evans, 1962).
4. As noted in the discussion of the Upper Mississippi Valley district, the Maquoketa Shale is inferred to have extended across the district at the time of mineralization but has subsequently been eroded back to the southwest, leaving the initial impression that the Maquoketa cap required by the model was not present. Thus other areas that fit this model for potential mineralization but apparently lack a shale cap should be examined carefully for possible post-mineralization erosion of overlying shales. Obviously this applies to any models of this type, not just those including the Maquoketa.
5. This study was limited to the area of the Midcontinent Project, but the same principles are applicable to other areas of the midcontinent.

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