# Geology and Mineral-Resource Assessment of the Springfield 1° × 2° Quadrangle, Missouri, As Appraised in September 1985

U.S. GEOLOGICAL SURVEY BULLETIN 1942

# Geology and Mineral-Resource Assessment of the Springfield 1° × 2° Quadrangle, Missouri, As Appraised in September 1985

Edited by JAMES A. MARTIN and WALDEN P. PRATT

Prepared in cooperation with the Missouri Department of
Natural Resources, Division of Geology and Land Survey

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# PREFACE

This report brings together under one cover the principal results of a 5-year Federal-State cooperative study of the geology and mineral-resource potential of the Springfield 1°×2° quadrangle in southwestern Missouri. All the authors of papers in this volume are associated either with the Missouri Department of Natural Resources, Division of Geology and Land Survey, Rolla, Missouri, or with the U.S. Geological Survey, Denver, Colorado. We express here our appreciation not only to the authors, as members of the Springfield Conterminous United States Mineral Assessment Program (CUSMAP) "team," but also to many other individuals who contributed to the preparation of this volume: at the Missouri Geological Survey, Susan Dunn and Billy Ross for preparing illustrations, Tami Allison and Rita Brasure for typing, and Robert Hansman for preliminary editing; and at the U.S. Geological Survey, Rich Schoenfeld and Helen Whitney for help in preparing illustrations and Margaret Clemensen and Pat Drouillard for invaluable aid in preparation of the manuscript.

James A. Martin
Missouri Geological Survey

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# Introduction

*By* Walden P. Pratt

## BACKGROUND OF THE PROJECT

This report represents the culmination of a 5-year cooperative project between the U.S. Geological Survey and the Missouri Department of Natural Resources, Division of Geology and Land Survey. The project was administered under the Conterminous United States Mineral Assessment Program (CUSMAP) of the U.S. Geological Survey. Its purpose was to integrate data on the field geology, stratigraphy and sedimentology, igneous petrology, geochemistry, and geophysics of the Springfield quadrangle in order to provide the basis for a multidisciplinary analysis of the mineral-resource potential of the area.

The Springfield quadrangle was selected for this study as a logical followup to the assessment of the adjoining Rolla 1°×2° quadrangle (Pratt, 1981; Pratt and others, 1984). The quadrangle is midway between the Southeast Missouri mining district, where the principal host rocks of the Mississippi Valley–type (MVT) ores are dolomites of the Upper Cambrian Bonneterre Formation, and the Tri-State district of Missouri-Oklahoma-Kansas, where MVT ores are hosted by Mississippian limestones. The Bonneterre Formation has long been known to extend westward, deeply buried in the subsurface, to the Tri-State district, and it was reasonable to suspect that the Bonneterre might contain undiscovered MVT deposits somewhere between the two major districts. The Rolla project established a method for assessing the mineral-resource potential of large areas of carbonate terranes, and subsequent work by Erickson and others (1981) indicates high potential for mineralization in and adjacent to the southeastern part of the Springfield quadrangle. Thus, the Springfield quadrangle provided the opportunity to apply the new method in an area where potential seemed high but few deposits were known, and where several other necessary features for such a project either existed or could be obtained: (1) a modern, detailed geologic map, (2) adequate subsurface samples, essential for both stratigraphic and geochemical studies, and (3) adequate gravity and aeromagnetic surveys.

Results of all of the Springfield CUSMAP project investigations, including geologic mapping, subsurface stratigraphic and lithofacies studies, geochemical analysis, and geophysical surveys, have now been released to the public, either as open-file reports of the Missouri Geological Survey or as formal map publications of the U.S. Geological Survey. A list of the principal maps and reports is given in appendix 1 of this report. A preliminary version of this report (Martin and Pratt, 1985) was released to coincide with a public meeting in Springfield on November 13, 1985, at which the same information was presented orally.

## CONTENT AND SCOPE OF REPORT

The 13 chapters of this volume discuss topics ranging from the surficial geology of the quadrangle to the mineral-resource potential of the deeply buried Precambrian basement rocks. They are arranged in two parts, the first dealing mainly with descriptive aspects of the geology and the second with both descriptive and interpretive aspects relating to the resource potential. Within each group the order of treatment of the topics is, broadly, from the surface down. Thus, the seven papers in the first part begin with a brief overview of the quadrangle and then discuss surficial geology, lithologic variations of the subsurface sedimentary rocks (and some examples of graphical data displays used to interpret them), geochemistry of the subsurface carbonate rocks and the basal sandstones, and finally Precambrian basement rocks as interpreted from aeromagnetic and gravity studies. The first two papers of the second part discuss known mineral resources, industrial and metallic, although both papers speculate to some extent on the potential for undiscovered resources. The third paper speculates on a possible source of ore fluids that deposited MVT lead-zinc ores throughout the U.S. Midcontinent, and the fourth discusses in more detail the potential for undiscovered MVT deposits in subsurface carbonate rocks, combining descriptive models of such deposits with the data base developed in the first part of the volume. Another speculative paper deals with the potential for red-bed–evaporite-associated stratabound copper deposits in the basal sandstones of a large area of the Midcontinent region. The final paper summarizes the direct physical evidence for the nature of the buried Precambrian basement rocks and speculates on a wide range of potential mineral deposits that might be associated with these rocks. The somewhat variable treatment of topics in these papers reflects not only the inclinations of the individual authors but also (inversely) the amount of detail in which some of this material has been published in other products of the Springfield CUSMAP project, as listed in appendix 1.

The final part of this volume, appendix 2, is a guide for a short field trip in the Springfield area designed to show the Lower Mississippian rock types and relationships, the nature of the Mississippian-Ordovician contact, and an exposure of the Chesapeake fault, one of the area's principal structural features.

## METHODOLOGY OF ASSESSMENT

The method used in this assessment of resource potential is essentially the same method used in the assessment of the Rolla quadrangle (Pratt, 1981). In simplest terms, the method attempts to answer the following questions. What kinds of rocks are present? What kinds of mineral deposits are normally associated with those kinds of rocks? What evidence exists that those kinds of mineral deposits do (or do not) in fact occur with these particular rocks in the Springfield quadrangle? (In this assessment, we considered undiscovered resources of conventional types of metallic and industrial minerals; we did not consider non-conventional or low-grade ("common rock") materials (U.S. Bureau of Mines and U.S. Geological Survey, 1980) or the resource potential for petroleum or natural gas.) In more formalized terms, the method ideally proceeds through the following logical steps.

1. Compilation of geologic, stratigraphic lithofacies, geochemical, and geophysical maps of the quadrangle to identify the known and inferred geologic environments.

2. Determination of types of mineral deposits that could be expected to be present in the quadrangle on the basis of (a) known worldwide associations of certain mineral-deposit types and geologic environments or terranes that are present in the quadrangle and (b) known mineral deposits and occurrences that actually exist in the quadrangle.

3. Development of conceptual, descriptive models of these mineral-deposit types.

4. From each descriptive model, derivation of "recognition criteria" for the occurrence or non-occurrence of that type of deposit.

5. Systematic examination of the available data for existence of the recognition criteria.

6. Evaluation of the areal distribution and relative importance of various recognition criteria to assess the probability of occurrence of each mineral-deposit type and also to indicate areas where data are insufficient for a knowledgeable appraisal.

Step 1 of the Springfield quadrangle assessment, in addition to compilation of existing data, required new 1:24,000-scale reconnaissance mapping and compilation of approximately 85 percent of the quadrangle; aeromagnetic surveying of approximately 50 percent of the quadrangle; drilling, at Federal government expense, of 6 basement core holes totalling more than 11,000 ft, in order to obtain essential lithologic and geochemical information; interpretation and integration of lithofacies and mineralogical data from logs of 39 drill holes; and spectrographic and chemical analyses of about 4,500 insoluble-residue samples from 34 drill holes. The assessment then proceeded systematically through the remaining five steps, although steps 3–6 tended to merge into a continuous process for most mineral-deposit types because both the models and the data were too sketchy to require (or to allow) a detailed step-by-step approach. This slight difference in treatment will be evident in the discussions of individual models. Nevertheless, we believe that the assessment presented here is as thorough as is possible using the data available as of September 1985. We stress that this assessment is time dependent and that it may be modified in the future as new data become available and new mineral-deposit models and theories of ore genesis are developed.

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PART I—THE GEOLOGIC DATA BASE

# Geologic and Structural Overview

*By* Mark A. Middendorf[1]

## LITHOLOGY

Sedimentary rocks are the dominant, almost the only, type of rock exposed in the Springfield 1°×2° quadrangle. These rocks are Late Cambrian to Early Pennsylvanian in age and are principally carbonate rocks, although sandstone and to a minor degree shale and siltstone are also present. Figure 1 shows a generalized geologic map of the quadrangle and figure 2 a generalized structural map; details are shown in Middendorf and others (1987). Lithology of the sedimentary units is summarized in table 1.

Aside from the exceptional exposure of Precambrian and Cambrian rocks in the Decaturville cryptoexplosion structure (Offield and Pohn, 1979), the only Cambrian unit exposed in the quadrangle is the Eminence Dolomite, which crops out in the Lake of the Ozarks area in the north-central part of the quadrangle. The Eminence Dolomite is a thick-bedded, coarsely crystalline dolomite containing some chert and quartz druse, and its surface exposure is the result of a regional Precambrian structural high and faulting.

The Lower Ordovician (Canadian) Series—Gasconade Dolomite, Roubidoux Formation, and Jefferson City and Cotter Dolomites—makes up the bedrock of approximately 60 percent of the quadrangle (the eastern one-third and the north-central area). For the most part, these formations are massive to thin-bedded, cherty dolomites that reflect a relatively narrow range of depositional conditions including subtidal to supratidal, shallow-platform environments. The thickness and similarity of rocks in these formations present a challenge to mapping stratigraphy and structure.

Mississippian rocks are present in the western one-third and in the south-central area of the quadrangle and are mostly cherty, fossiliferous limestone; some clastic units are in the Kinderhookian Series. The Lower Mississippian (Kinderhookian) Series—Bachelor Formation, Compton Limestone, and Sedalia and Northview Formations—is present throughout the Mississippian outcrop region of the quadrangle; however, the extent, thickness, and lithology of the individual formations vary over their outcrop area. The Lower Mississippian (Osagean) Series is represented by the Pierson Limestone, Reeds Spring and Elsey Formations, and Burlington and Keokuk Limestones. The Pierson Limestone is present throughout the Mississippian outcrop region, but the Reeds Spring and Elsey Formations pinch out depositionally northward in the vicinity of lat 37°30′ N. Because of this pinchout, the Burlington and Keokuk Limestones lie directly on the Elsey Formation in the southern half of the quadrangle and on the Pierson Limestone in the northern half. The Upper Mississippian (Meramecian) Series is represented by the Warsaw Formation, which crops out along the western edge of the quadrangle.

Sandstone, representing several different depositional environments, is the dominant lithology of the Pennsylvanian units. In the eastern 60 percent of the quadrangle, it generally is present as filled-sink deposits or as limited blanket deposits of obscure depositional origin. Pennsylvanian units in the western one-third of the quadrangle are deltaic channel deposits and clastic shallow-marine deposits. All Pennsylvanian units in the Springfield quadrangle are assigned to the Cherokee Group.

## STRUCTURE

The pattern of moderate faults in the Springfield quadrangle reflects its location in a stable cratonic region on the west flank of the Ozark uplift. High-angle normal faults dominantly striking northwesterly prevail, although several broad folds have also been mapped. In addition to the northwesterly striking faults, east-west faults are in the southwestern part of the quadrangle and north-south faults are in the northeastern part. Northeasterly striking faults are also present but are not prominent.

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[1]Missouri Geological Survey, P.O. Box 250, Rolla, Missouri 65401.

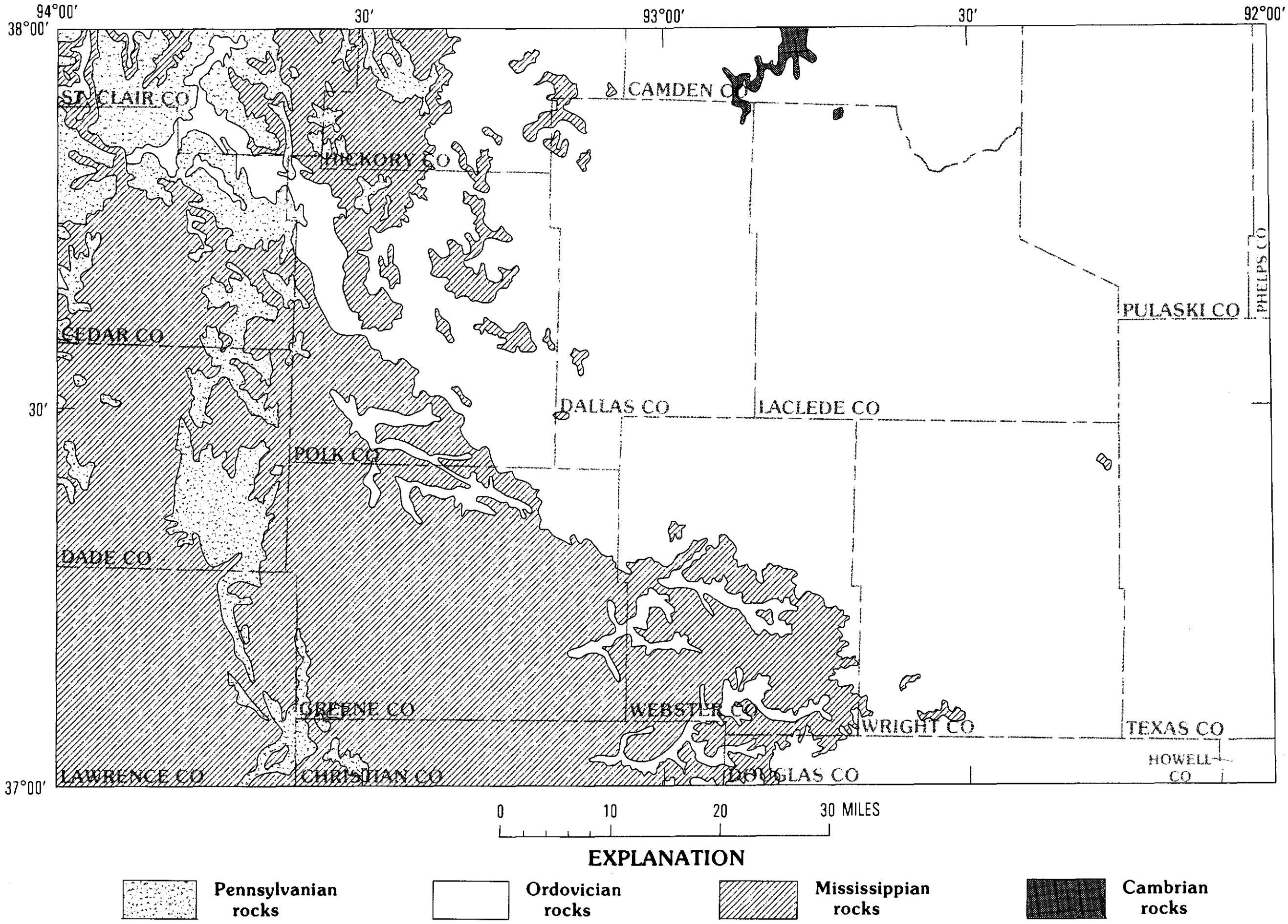


**Figure 1.** Generalized geology of the Springfield 1°×2° quadrangle.

The principal faults and fault systems are (1) the Bolivar-Mansfield fault system, (2) the Chesapeake fault, (3) the Red Arrow and County Line faults, (4) the Macks Creek-Smittle fault, and (5) the Jacksonville fault (fig. 2).

1. The Bolivar-Mansfield fault system comprises several long, northwest-striking en echelon faults and anticlines and numerous accompanying shorter faults. Displacement is generally down to the southwest.

2. The Chesapeake fault is a northwest-striking fault, down to the northeast. This fault reflects a basement magnetic trend and, like the faults of the Bolivar-Mansfield system, extends northwest and southeast beyond the quadrangle.

3. The northwest-striking Red Arrow and County Line faults in the northeastern part of the quadrangle are downthrown to the southwest and may represent a single fault except for a short segment where no evidence of faulting has been found. Sharp basement magnetic and gravity anomalies are aligned along the strike of these faults.

4. The Macks Creek-Smittle fault, shown as a single trace of northwesterly to east-west strike, may be two distinct faults. The downthrown side changes from the southwest along the northern segment of the fault to the northeast along the central and southern segments.

5. The Jacksonville fault strikes northwest and is downthrown to the northeast. It is one of the more clearly visible faults in the quadrangle.

Most of the larger faults have displacements of 100–200 ft. In the area of Ordovician outcrops, faults of lesser magnitude are difficult to discern because of similarity of lithology and thickness of formations; however, this type of faulting is probably as prevalent as that in Mississippian units, in which minor faulting can be recognized because the units are thinner and more distinct. The parallel horst-and-graben arrangement of many of the faults indicates dip-slip movement resulting from tensional forces. Normal faulting could have resulted from a wrench system, but there is no clear evidence to support such an origin from the structures that have been investigated. Geophysical studies (Cordell, this volume) suggest a connection between near-surface and basement structures.

**Table 1.** Lithologic description of sedimentary units exposed in the Springfield 1°×2° quadrangle

| | |
|---|---|
| | PENNSYLVANIAN SYSTEM |
| Cherokee Group | White to light-gray to red, fine- to medium-grained, medium to thickly bedded sandstone; associated gray to black, fissile shale and pebble to cobble chert conglomerate. Maximum exposed thickness about 100 ft. |
| | MISSISSIPPIAN SYSTEM |
| | Meramecian Series |
| Warsaw Formation | Light-gray to gray, coarsely to medium crystalline crinoidal limestone. Maximum exposed thickness about 80 ft. |
| | Osagean Series |
| Burlington and Keokuk Limestones | Light-gray to gray, coarsely to finely crystalline, massively bedded crinoidal limestone containing, in part, white to light-gray nodular chert. Maximum exposed thickness about 200 ft. |
| Elsey Formation | Light-gray, finely crystalline to micritic, dense limestone containing sparse crinoids. White to gray, nodular and elongate lenses of chert with irregular brown mottling make up 50 percent or more of the formation. Maximum exposed thickness about 80 ft. |
| Reeds Spring Formation | Alternating thin beds of gray to brown, finely crystalline limestone and irregular beds and nodules of dark-gray, blue, and brown chert having a distinctive light-gray border. Chert makes up 30-70 percent of the formation and is most abundant in the upper part. Maximum exposed thickness about 40 ft. |
| Pierson Limestone | Brown to tan, medium crystalline, thick- to thin-bedded limestone to dolomitic limestone. Maximum exposed thickness about 40 ft. |
| | Kinderhookian Series |
| Northview Formation | Green to gray shale and dolomitic shale containing at least two prominent siltstone to fine-grained sandstone burrowed units. Maximum exposed thickness about 80 ft. |
| Sedalia Formation | Gray to tan to buff, finely crystalline, argillaceous dolomitic limestone and gray to white nodular chert. Maximum exposed thickness about 40 ft. |
| Compton Limestone | Gray, medium to finely crystalline, thinly bedded limestone that exhibits poikilotopic "glint" reflection on many freshly broken surfaces. Maximum exposed thickness about 25 ft. |
| Bachelor Formation | Poorly sorted, pale-green, angular to subrounded quartz sandstone or conglomeratic sandstone overlain in some areas by a thin, green, sandy shale. Maximum exposed thickness about 2 ft. |
| | ORDOVICIAN SYSTEM |
| | Canadian (Ibexian) Series |
| Jefferson City and Cotter Dolomites | Buff to light-gray, finely to medium crystalline dolomite and argillaceous dolomite that typically contain banded nodular chert and thin seams of white to light-gray chert and some generally discontinuous lenses of fine- to medium-grained, poorly sorted, white to light-gray sandstone. Maximum exposed thickness about 500 ft. |
| Roubidoux Formation | Interbedded light-gray to light-brownish gray, medium to finely crystalline cherty dolomite, and fine- to medium-grained, light-gray to light-brown sandstone. Maximum exposed thickness about 220 ft. |
| Gasconade Dolomite | Light-gray, medium to coarsely crystalline, thinly to massively bedded dolomite; lower two-thirds of the formation commonly contains as much as 40 percent chert, whereas the upper one-third may have only trace amounts. Maximum exposed thickness about 300 ft. |
| | CAMBRIAN SYSTEM |
| | Upper Cambrian Series |
| Eminence Dolomite | Light-gray to gray, medium to coarsely crystalline, variably cherty dolomite and some quartz druse. Maximum exposed thickness about 200 ft. |

Several of the major faults and fault systems are aligned with gravity or magnetic trends and anomalies.

The age of the most recent faulting is known only to be post-Pennsylvanian. In some places Pennsylvanian rocks cover faulted Mississippian rocks but are not themselves deformed; whereas, in other places Pennsylvanian units are faulted. There is no evidence of faulting of the Quaternary to Cretaceous surficial deposits in the quadrangle.

Two small but interesting structural features, which are not included in the foregoing discussion of faults but have been studied in some detail in the past, are the Decaturville structure and the Weaubleau Creek structural complex. The Decaturville structure (Offield and Pohn, 1979) is a circular area of intense deformation of Cambrian and Ordovician rocks, in which a central uplift is surrounded by a structural depression that in turn is bounded

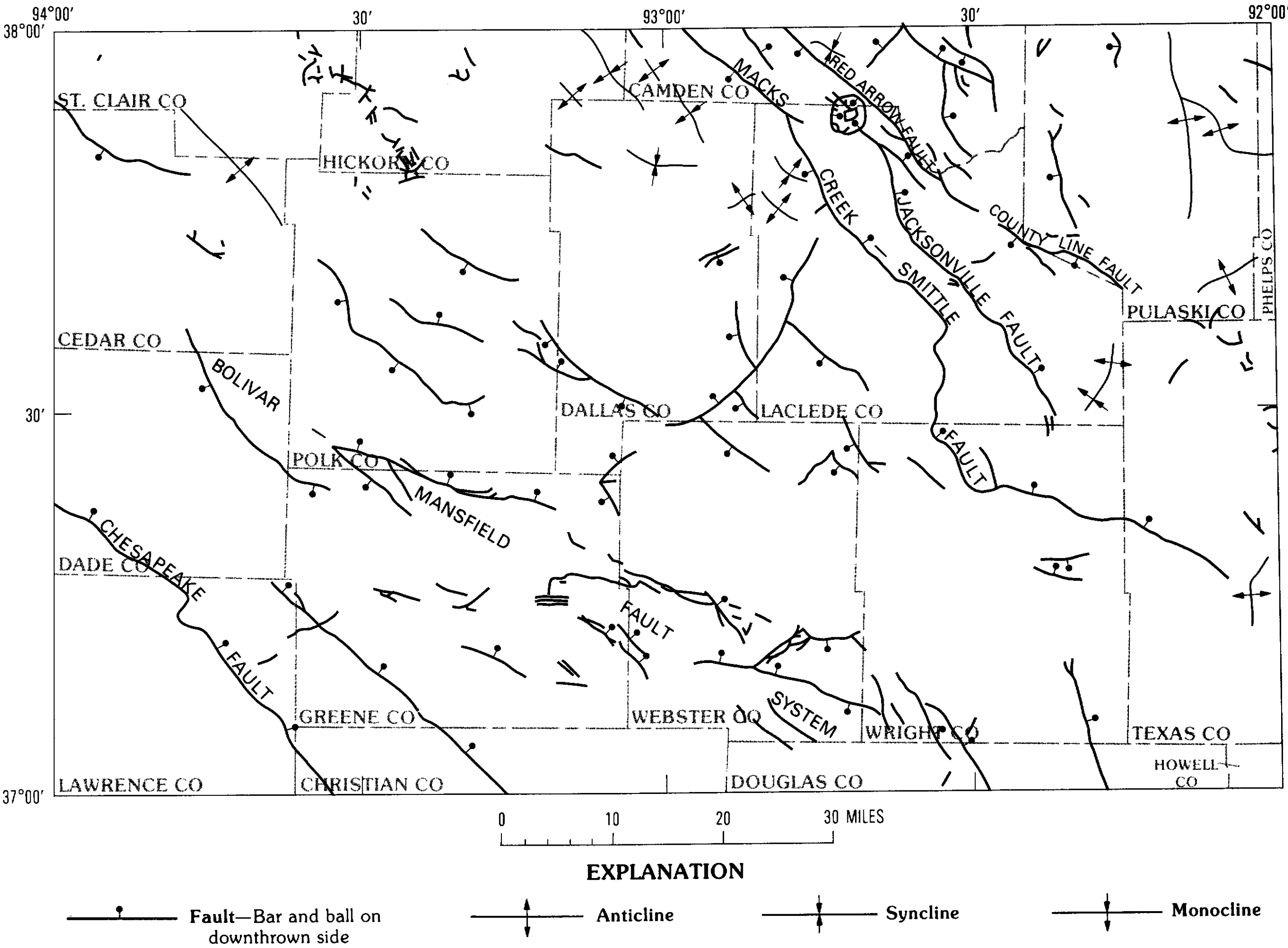


**Figure 2.** Generalized structure of the Springfield 1°×2° quadrangle.

by normal faults (see also Kisvarsanyi, this volume). Offield and Pohn mapped the area in detail and ascribed the structure to meteorite or comet impact. The Weaubleau Creek structural complex (Beveridge, 1951) involves both normal and thrust faulting of Ordovician and Mississippian rocks and was interpreted by Snyder and Gerdemann (1965) as a cryptovolcanic disturbance.

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# Surficial Geology

*By* John W. Whitfield[1]

All but a very small area in the northwestern corner of the Springfield quadrangle is in the Ozark Plateau Province. Landscapes of the eastern two-thirds of the quadrangle, in the Salem Plateau Subprovince, range from steep, wooded hills and narrow, stony valleys to broad, gently rolling uplands and wide, terraced river valleys. The Salem Plateau is underlain by hundreds of feet of Ordovician cherty dolomite and lesser amounts of sandstone. The western one-third of the quadrangle, in the Springfield Plateau Subprovince, consists primarily of gently to moderately rolling prairies underlain by Mississippian cherty limestone. A small area in the northwestern corner of the quadrangle, in the Osage Plains Province, consists of gently rolling to flat land surfaces. Bedrock comprises Pennsylvanian sandstone and shale and lesser amounts of limestone and coal.

Preserved on upland divides of the Salem Plateau are small, isolated remnants of Mississippian and Pennsylvanian sedimentary rocks that once covered the Ozarks but have been extensively removed by long periods of continuous erosion. Weathering of Ordovician cherty dolomite and sandstone that form the bedrock surface has produced a widespread, reddish, cherty residuum and colluvium. In places the residuum may be more than 100 ft thick and contain more than 70 percent chert and sandstone fragments. Weathering of the thick Mississippian cherty limestone underlying the Springfield Plateau has formed widespread cherty residuum and colluvium similar to those elsewhere in the Ozarks except that they are generally thinner. Cherty, reddish clay residuum is the dominant surficial material in the quadrangle; loess, colluvium, and alluvium are present in smaller amounts.

On the Osage Plains Province weathering of sandstone has produced a sandy residuum, generally only a few feet thick and commonly containing sandstone fragments. Where shale is predominant the residuum consists of sandy clay and clay, mostly less than 5 ft thick.

[1]Missouri Geological Survey, P.O. Box 250, Rolla, Missouri 65401.

In the Salem and Springfield Plateaus a typical upland profile of surficial material, from the surface down, comprises (1) a thin loess or pedisediment, (2) lag gravels, (3) illuviated residuum, and (4) residuum. Loess and lag gravels commonly have been eroded from ridgetops and mixed into stony colluvium on slopes.

Surficial material can be divided into mappable units on the basis of composition, genesis, and profile. For standardization, each surficial unit is given a geographic name from an area in which it is dominant, instead of a letter or number designation. As long as the unit criteria can be recognized the material will have the same name. By using this method a continuum is established so that each surficial unit is identified by the same name from map to map.

Seven surficial material units were identified in the Springfield quadrangle (Whitfield, 1986):

1. Buffalo residuum
2. St. Roberts residuum
3. Foose residuum
4. Springfield residuum
5. Northview Hill residuum
6. Cave Branch residuum
7. Billings residuum

Within each unit, colluvium and bedrock are present. The colluvium is on hillslopes and generally resembles the residuum from which it originated. Bedrock crops out in all surficial units but in much smaller areas than the dominant surficial materials. Principal areas of bedrock outcrop are steep slopes and bluffs bordering creeks and rivers. Smaller areas of bedrock outcrop are glades and knolls on hills.

Alluvium, consisting of intermixed and interbedded, light-brown to dark-gray clay, silt, sand, gravel, and cobbles, 5–60 ft thick, is present in the large river valleys. Floodplains in the large valleys are covered by finely textured silt and clay that become sandy and gravelly with depth.

In smaller creeks and streams the alluvium is generally 1–5 ft thick and comprises poorly sorted gravel and cobbles. In areas where the residuum is derived from Ordovician bedrock the alluvium consists of sand, gravel, and cobbles derived from weathering of Ordovician cherty dolomite.

In the western part of the map area, Mississippian-derived alluvium consists almost entirely of sand-free chert gravel and cobbles from Mississippian cherty limestone. Alluvium in the northwestern corner of the quadrangle contains finely textured sand, silt, and clay from Pennsylvanian sandstone and shale.

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# Distribution of Lithofacies and Inferred Depositional Environments in the Cambrian System

*By* James R. Palmer[1]

## INTRODUCTION

The Cambrian System in the Springfield quadrangle is composed of three major stratigraphic units: (1) the Lamotte Sandstone, (2) the Bonneterre Formation, and (3) the post-Bonneterre Cambrian (referred to herein as PBC), which includes the sequence from the Davis Formation through the Eminence Dolomite (fig. 5). These three sequences are composed of fourteen lithofacies assemblages—four in the Lamotte, eight in the lower part of the Bonneterre and PBC, and two in the upper part of the Bonneterre. This report emphasizes the distribution and characteristics of these lithofacies. In the Springfield quadrangle area, only the PBC has complex lithofacies relationships comparable with those of the ore-hosting Bonneterre Formation in southeastern Missouri.

Cambrian rocks in the Springfield quadrangle lie nonconformably on a low-relief Precambrian metamorphic and igneous terrane (Kisvarsanyi, this volume) and are overlain with apparent conformity by the Lower Ordovician Gasconade Dolomite. The Cambrian is 790–1,495 ft thick, thickening generally from northwest to southeast (fig. 3). Outcrops of Cambrian rocks are limited to the Osage River Basin in the north-central part of the quadrangle and a small area in the Decaturville structure (Middendorf, this volume).

Lithofacies cross sections, slice maps, and isolith maps were constructed from 39 drill-core logs. Definition of lithofacies is based on macroscopic characteristics alone. Depositional models proposed here are based on analysis of the sequence and distribution of these lithofacies and on several analogues (Larsen, 1977; Markello and Read, 1981; Read, 1985).

The Lamotte Sandstone is mostly a transgressive sequence, consisting of facies that represent environments ranging from proximal alluvial fan at its base to marine shoal, tidal flat, and local shallow intrashelf basin near the top. The westernmost intrashelf basin and other facies of the upper part of the Lamotte Sandstone were deposited contemporaneously with carbonate-dominated Bonneterre sediments in the eastern three-fourths of the quadrangle.

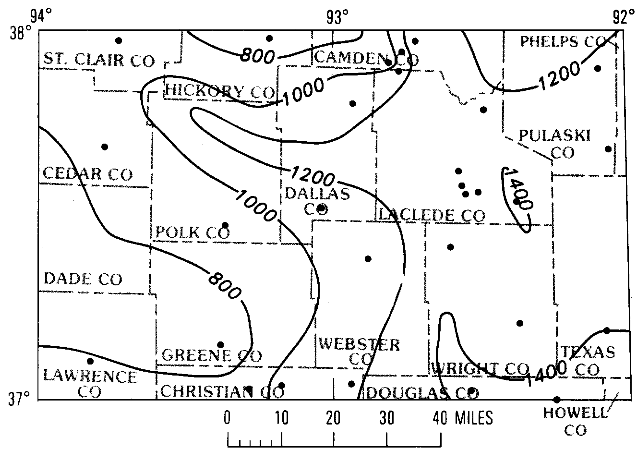
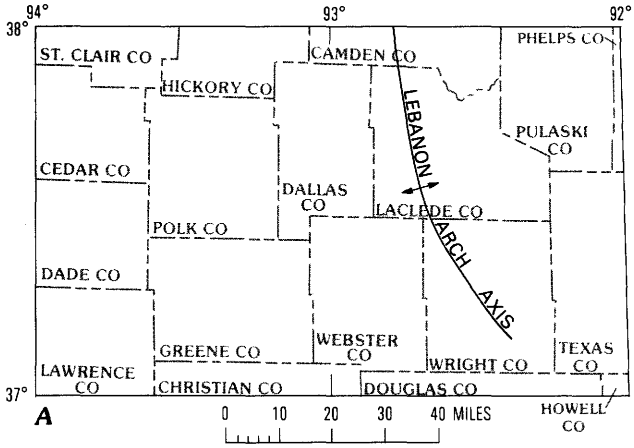



**Figure 3.** Isopach map of the Cambrian System, Springfield 1°×2° quadrangle. Contour interval 200 ft.

The lower part of the Bonneterre and PBC lithofacies between intrashelf basin and platform areas change by carbonate ramp-style facies transitions. Unlike the Bonneterre Formation of southeastern Missouri, the Bonneterre in the Springfield quadrangle contains no facies indicative of tidal flat deposition, whereas the PBC has shallow-subtidal, intertidal, and supratidal facies. The Bonneterre Formation is also a grossly transgressive sequence but is interrupted by a middle regressive or progradational facies. The PBC is generally an upward-shallowing (regressive) sequence that follows the major transgression marked by the base of the upper part of the Bonneterre Formation but locally shows important transgressive facies relationships.

The two members that constitute the upper part of the Bonneterre, the Sullivan Siltstone and Whetstone Creek Members, are made up mostly of siliciclastic rocks ranging from shale and quartzose sandstone to carbonate mudstone and grainstone. The Whetstone Creek is distinguished by

[1]Missouri Geological Survey, P.O. Box 250, Rolla, Missouri 65401.



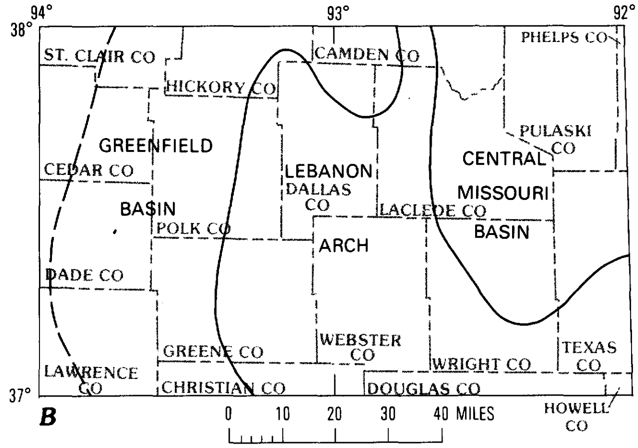
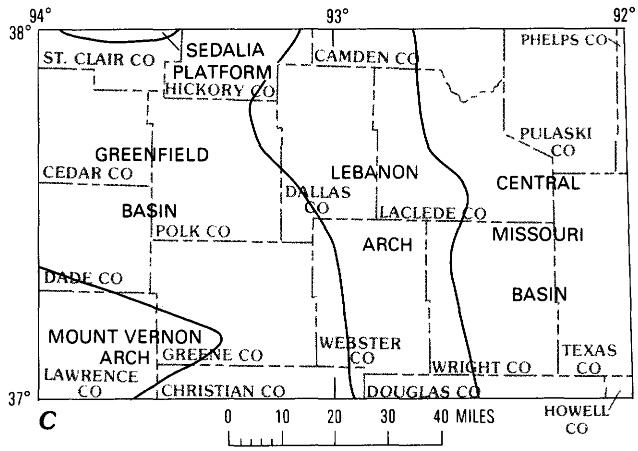




**Figure 4** (above and facing column). Paleotectonic-depositional framework for the area of the Springfield 1°×2° quadrangle during Cambrian time. *A*, Early Lamotte time. Lamotte sandstones (basal facies) are thickest near the Lebanon arch and are less mature and less well sorted sediments of proximal alluvial fan origin than sediments to the east and west of the arch, which are more mature and better sorted distal fan or alluvial plain deposits. *B*, Early Bonneterre and equivalent Lamotte time. The Lebanon arch is indicated by grainstone and interbedded wackestone and packstone (all of which are widely dolomitized) of ramp shoal and shallow ramp origin. The Central Missouri basin contains interbedded shale and limestone of intrashelf basin origin, and the Greenfield basin contains interbedded shale and sandstone of intrashelf origin. Shallower shelf conditions are indicated to the west of the Greenfield basin (west of dashed line) where sandstone of barrier and subtidal flat origin is present. *C*, Post-Bonneterre Cambrian time. The Lebanon arch is again indicated by the presence of dolomitized grainstone, packstone and interbedded wackestone, and cryptalgal boundstone of platform, shoal and shallow ramp origin. The Central Missouri and Greenfield basins are indicated by shale and interbedded limestone of intrashelf and deep ramp origin. Coarsely dolomitized rocks in the northwestern corner of the map area are probably of platform origin. Dolomite in the southwestern corner of the map area may be shallow ramp facies.




abundant pelletal glauconite, which is present only locally in the Sullivan Siltstone Member (Kurtz and others, 1975). These members were deposited as part of an intrashelf basin complex eastward of crossbedded shoal and burrowed shallow-subtidal sandstone in equivalent Lamotte Sandstone. They record a period of clastic influx across the Bonneterre carbonate "shelf" during regional late Dresbachian transgression.

Two major periods of intrashelf basin development are interpreted, the first represented by the lowermost Bonneterre Formation and westward coeval Lamotte Sandstone and the second represented by the upper part of the Bonneterre through the Davis Formations. Distribution of lithofacies and interpretations of depositional environments suggest a regional paleogeographic-depositional framework that includes, for the Lamotte, a low-relief surface and a central north-south–trending highland area—the Lebanon arch (fig. 4*A*)—and, for the Bonneterre and PBC, an eastern Central Missouri basin and western north-trending Greenfield basin on either side of the Lebanon arch (figs. 4*B*, *C*).

The stratigraphic study of Kurtz and others (1975) established a framework for lithofacies correlations used in this report. Figure 5 compares that sequence with the one used herein. Kurtz and others recognized several major facies changes within the Cambrian including (1) lateral changes in the Bonneterre Formation from carbonate rocks on the east to "nearshore sandstone" (their "Reagan Sandstone") on the west; (2) changes in the Davis Formation from shale and limestone to brown dolomite in the Douglas County area of their cross section; and (3) changes in the Potosi Dolomite from brown dolomite containing quartz druse (chalcedony and megaquartz) to a "green clay residue facies" (also in the Douglas County area). The "green clay residue facies" is also colloquially known as "whiterock" in the Southeast Missouri mining district and includes in part the dolomitized planar stromatolite and burrowed carbonate mud facies of Howe (1968). Kurtz and others also recognized two formal members of the upper part of the Bonneterre, the Sullivan Siltstone and Whetstone Creek Members. V.E. Kurtz (oral commun., 1985) has contributed additional biostratigraphic

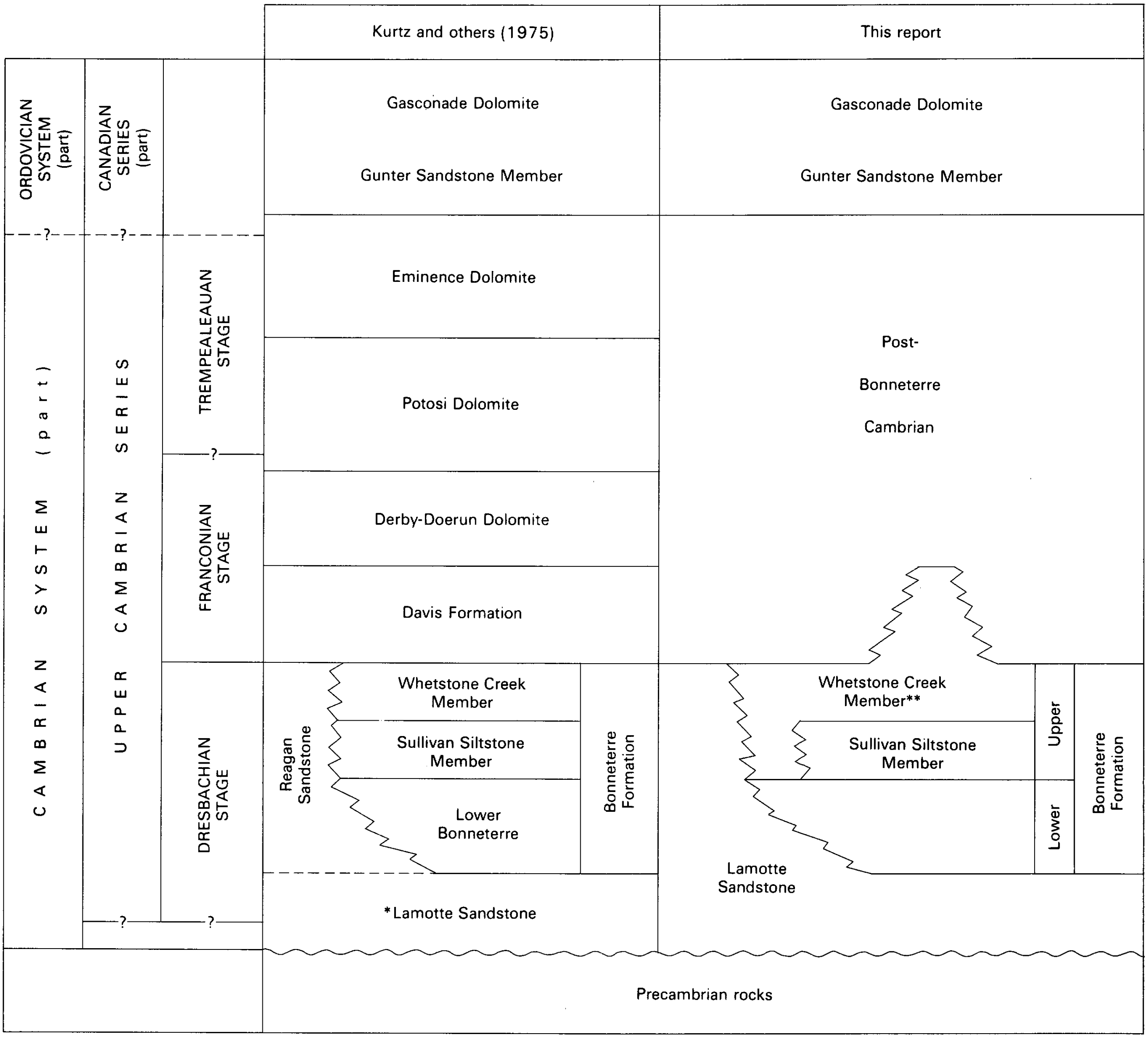



**Figure 5.** Stratigraphic correlation chart for the Springfield 1°×2° quadrangle. *The age of the lowermost Lamotte Sandstone may be Middle Cambrian in some places. **At some places in the eastern part of the quadrangle, the Davis Formation and Whetstone Creek Member are indistinguishable such that the rocks overlying the Sullivan have been mapped as Davis.

correlations, based on cores near and within the Springfield quadrangle, that confirm the results of Kurtz and others.

## LAMOTTE SANDSTONE

Basal Cambrian sandstones in most of southern Missouri consist of quartz sandstone and local conglomerate, arkose, clay matrix, and bedded shale-rich facies (Ojakangas, 1963; Howe and others, 1972; Kurtz and others, 1975; Houseknecht and Ethridge, 1978; Yesberger, 1981). The term "La Motte Sandstone" ("Lamotte Sandstone" of most recent papers) was introduced by Winslow (1894) for the basal Paleozoic sandstone in southeastern Missouri. The age of the Lamotte is uncertain because no index fossils have been recovered from it. Howe and others (1972) assigned a pre-*Cedaria* Zone (Late Cambrian) age to the Lamotte and suggested that the lower part of the Lamotte could be pre-Upper Cambrian.

Kurtz and others (1975) applied the term "Reagan Sandstone" to the time-transgressive basal Cambrian clastic rocks in southwestern Missouri (fig. 5). Use of the term "Reagan Sandstone" has been confusing because similar Cambrian clastic lithofacies are present across all of southern Missouri. Reagan sandstones have not generally been differentiated from clastic deposits of the Lamotte Sandstone, and the term Lamotte Sandstone is used herein. In the Springfield quadrangle, the uppermost Lamotte

Sandstone (upper part of Reagan of Kurtz and others, 1975) probably correlates with the Whetstone Creek Member (uppermost Dresbachian Stage) of the upper part of the Bonneterre Formation (Kurtz and others, 1975) and is also biostratigraphically equivalent to the Whetstone Creek Member (V.E. Kurtz, oral commun., 1985), whereas the lowest (nonfossiliferous) Lamotte is presumably of early Late Cambrian age.

The basal Cambrian sandstones lie nonconformably on an erosional surface having local relief of several hundreds of feet atop Precambrian igneous and metamorphic rocks and are conformable with the overlying Bonneterre or Davis Formations. In the Greenfield basin, where sandstones and shales of the Lamotte are equivalent to the Bonneterre Formation, they are apparently conformably overlain by the PBC (Kurtz and others, 1975). The Lamotte is 123-337 ft thick.

## Lithofacies

The Lamotte Sandstone in the Springfield quadrangle consists of four major lithofacies, in part the same as those described by Houseknecht and Ethridge (1978) and Yesberger (1981) for southeastern Missouri. A simple, nongenetic stratigraphic subdivision may be made between lower, poorly sorted sandstone and conglomerate, and upper, mostly sorted sandstone. Rocks of the shale and interbedded sandstone lithofacies are present as lentils within the upper sorted sandstone interval. A transgressive depositional model is inferred for the Lamotte, grading upward from (1) alluvial fan and (2) aeolian plain (?) to (3) marine barrier, (4) tidal flat, and (5) shaly slope and shallow basin environments.

### Basal Conglomerate and Sandstone Facies

Basal Lamotte Sandstone facies are of three major types: (1) massive conglomerate, (2) hematite-rich feldspathic and lithic quartzose sandstone and conglomerate (hereafter referred to as HFL sandstone and conglomerate), and (3) quartzose sandstone and conglomerate. The first two are basal and proximal to the Lebanon arch, whereas the latter is distal.

Massive conglomerate has been found only in the drill holes nearest the Lebanon arch and is as thick as 23 ft. The conglomerate consists of angular to subangular, metamorphic, igneous, and quartzite clasts as much as 6 cm in diameter and is red or brownish in color. Clasts are supported by poorly sorted and angular feldspathic quartzose sandstone. Rare clay-matrix-supported conglomerate is also found proximal to the Lebanon arch and is 0–5 ft thick. No other primary sedimentary structures can be discerned in cores of the massive conglomerate. Hematite and silica are the most abundant cements. Locally, hematitic clay has been reduced to a green clay along fractures and less commonly in porous sandstone matrix. Massive conglomerate has sharp contacts with overlying HFL sandstone and conglomerate, some of which appears to be scoured.

Rocks of the HFL sandstone and conglomerate facies are 0–120 ft thick and restricted to the Lebanon arch area. This facies consists of fining-upward sequences of generally well segregated, reddish beds that ideally have (1) gravel bases (lags as thick as 2 ft), (2) crossbedded, fining-upward sandstone (from inches to 8 ft thick), and (3) parallel-laminated, gray or red sandy shale (about 1 in. thick or less). The conglomerate is clast supported and contains subangular metamorphic, igneous, and second-cycle sandstone clasts as much as 1.5 in. diameter; it may be graded but rarely is crossbedded. Sandstone consists of medium- to coarse-grained, subangular to subrounded quartz, lithic fragments, and feldspar. Some sandstone may be planar crossbedded, becoming parallel laminated at tops of sets. Sandy shale is reddish or gray and slightly micaceous and commonly contains some fine to medium, subangular sand grains in parallel laminae. Hematite and silica cements are approximately equal in abundance; pyrite and an unidentified white clay locally are minor cements. The frequency, thickness, and grain size of gravel beds decrease upward, and the HFL sandstone and conglomerate facies becomes the quartzose sandstone and conglomerate facies by way of gradational or interbedded contacts.

Rocks of the quartzose sandstone and conglomerate facies are 20–135 ft thick and are present throughout the study area. They are similar to HFL sandstones in that they consist of sequences of conglomeratic, fining-upward cycles. The conglomerate is in thin beds (lags as thick as 4 in.); it is composed of subangular to subrounded, polycrystalline quartz or quartzite. Sand grains are fine to medium subrounded quartz. Thin, gray, sandy, and micaceous shale beds are 1 in. thick or less. The sandstone is commonly crossbedded; it is as thick as 8 ft between gravel lags and locally contains upper parallel laminated beds of 2 ft or less. Silica cement is most abundant; pyrite and an unidentified white clay are local minor cements.

The quartzose sandstone and conglomerate facies is interpreted as an alluvial-fluvial complex similar to that described for the Lamotte in southeastern Missouri by Houseknecht and Ethridge (1978) and Yesberger (1981). The complex is a fining- and thinning-upward megasequence (conglomerate beds decrease in thickness and number) that suggests fan retreat and indicates local relative tectonic stability in the absence of repetitive coarse sequences (Nilsen, 1982). Rocks of the basal facies become more mature away from the central part of the quadrangle: quartzose sandstone and conglomerate replace both HFL sandstone and conglomerate and massive conglomerate to the east, west, and south. The distribution of massive conglomerate and HFL sandstone and conglomerate in the central part of the quadrangle defines the location of the Lebanon arch in these lower facies.

Massive conglomerate is associated with basement knobs in southeastern Missouri and has been interpreted as "conglomerate-dominated fan deposits" (Houseknecht and Ethridge, 1978). In Camden County, massive conglomerate is on the flanks of a basement topographic high centered at about drill core DB–1 (fig. 6). Drill core DB–1 has no massive conglomerate, whereas drill cores TD–1 and 63W34 each have as much as 23 ft of massive conglomerate. These massive conglomerates are interpreted as debris flows (sandstone matrix conglomerates) and mud-flows (clay matrix-supported conglomerates). Such deposits are restricted to the heads of alluvial fans (Bull, 1963) and suggest that some local relief was present on the Pre-cambrian surface. If the DB–1, TD–1, and 63W34 sequences represent a preserved knob with debris flows along its flanks, then the regional distribution of HFL sandstone and conglomerate and massive conglomerate probably indicates a series of paleotopographic knobs along the Lebanon arch.

As in southeastern Missouri (Houseknecht and Ethridge, 1978; Yesberger, 1981), both the HFL sandstone and conglomerate facies and the quartzose sandstone and conglomerate facies in the Springfield quadrangle are interpreted as gravel-based channel deposits, sandbars, laminated sheet-flood deposits, and overbank deposits (from bottom to top through each fining-upward sequence). Fluvial facies of the Lamotte in southeastern Missouri indicate southeast-directed regional paleocurrents except in the vicinity of paleotopographic knobs, which profoundly controlled paleodrainage (Houseknecht and Ethridge, 1978; Yesberger, 1981). Paleodrainage also may have been southeastward in the Springfield quadrangle. Many of the clastic rocks in the lower quartzose sandstone and gravel facies may have been derived from the west and north, well outside the Springfield area.

All drill cores studied in the quadrangle have marine facies in the upper part of the Lamotte Sandstone. In southeastern Missouri, localities near pinchouts of Lamotte Sandstone over Precambrian knobs commonly have marginal-marine or possibly fan-delta facies in the upper part of the Lamotte (Yesberger, 1981). Because marginal-marine and nonmarine facies are absent in drill core of the upper part of the Lamotte Sandstone in the study area, there probably are no local pinchouts of Lamotte over Pre-cambrian knobs; however, if pinchouts are present, they are probably along the Lebanon arch.

Rocks of the quartzose sandstone and conglomerate facies are overlain conformably by white, well-sorted rocks of the parallel-laminated fine-grained quartzose sandstone

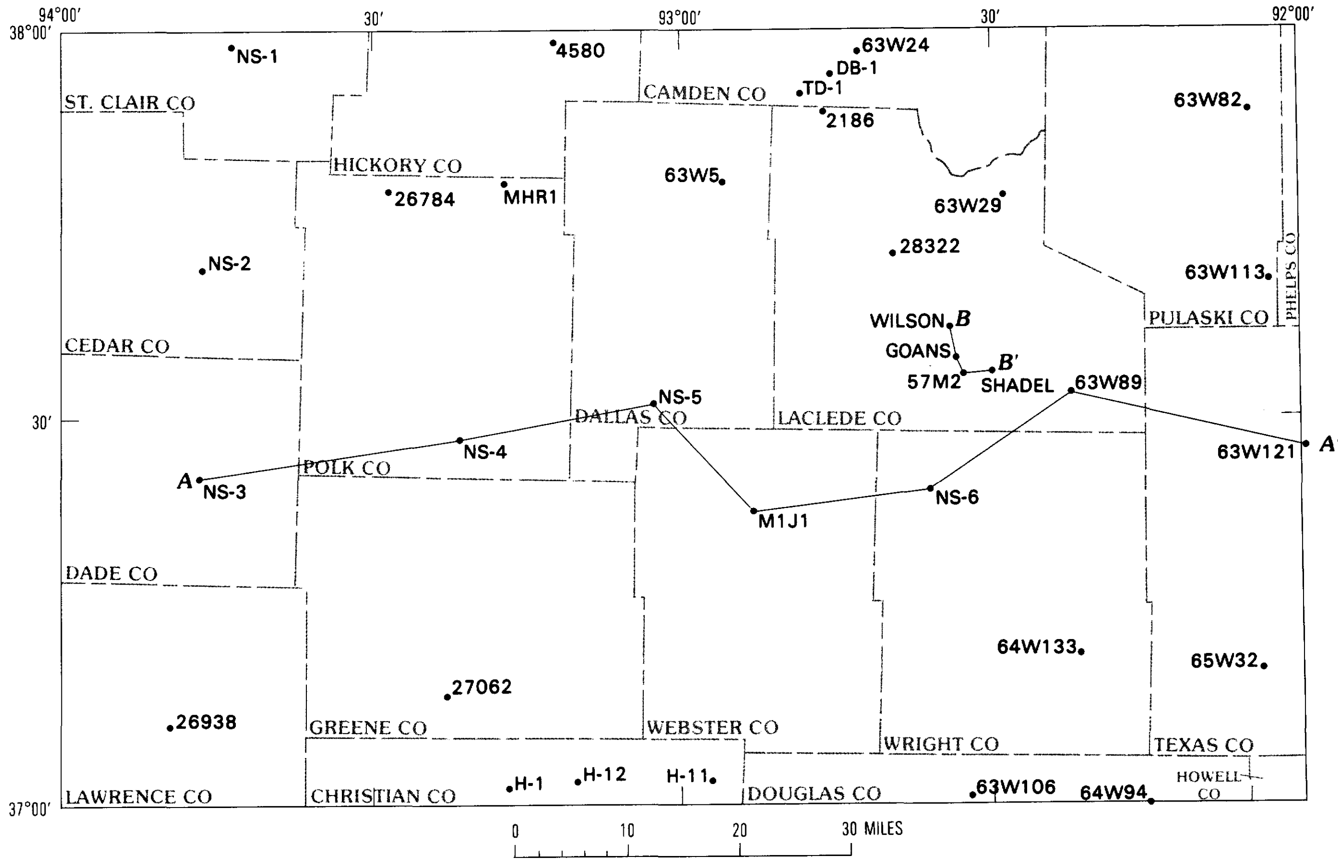



**Figure 6.** Drill holes used in study, Springfield 1°×2° quadrangle. Lines of section *A-A′* and *B-B′* also shown.

facies or disconformably by rocks of the high-angle crossbedded and burrowed quartzose sandstone facies.

### Parallel-Laminated Fine-Grained Quartzose Sandstone Facies

Rocks of the parallel-laminated fine-grained quartzose sandstone facies (PLFG sandstone) are widespread in the quadrangle and are 0–120 ft thick. They are composed mostly of very fine to fine grained, well-sorted, rounded and subrounded quartz. Isolated, laglike occurrences of medium, subrounded quartz grains are present locally along some laminae. Thin, gray shale beds, 0.5 in. thick or less, are very rare in this facies. The most common sedimentary structures are parallel laminae, but some crossbedding is present. Poorly developed, small, climbing-ripplelike structures common in rocks of this facies are similar to adhesion ripples described in Reineck and Singh (1980) or to the pseudoripples of Kocurek and Fielder (1982). Samples from drill core NS–1 contain numerous ghosts of single gypsum crystals and swallow-tail twins, which presumably were an authigenic poikilotopic cement in a thin intercept of PLFG sandstone facies. The most common cement in rocks of this facies is quartz, with minor local pyrite.

Rocks of the PLFG sandstone facies are very similar to those of the upper part of the Lamotte Sandstone section EB of Yesberger (1982, p. 107–110), which he interpreted as local interdune eolian deposits within a fluvial plain. The eolian interdune sandstones described by Yesberger are 1.5–7.8 ft thick and in lens-shaped bodies associated with fluvial sandstone. Thin parallel-laminated sandstone within basal sandstone and conglomerate in the Springfield quadrangle may be similar to rocks in the section described by Yesberger and may represent very local periodic eolian reworking of fluvial sands. PLFG sandstones in the Springfield quadrangle, though, are widespread, thick, and apparently disconformably overlain by marine crossbedded sandstones. No large-scale high-angle crossbedding sets were identified within the PLFG sandstone facies. The PLFG sandstones are interpreted here as a series of interdune deposits that were intermittently wet as indicated by adhesion ripples. As widespread as rocks of this sandstone facies are, they nonetheless probably represent the interdune parts of an extensive dune field that might be identified with more detailed logging. Alternatively, extensive dune deposits may have been eroded from atop the PLFG sandstone facies by the Cambrian marine transgression.

The contact between PLFG sandstone and overlying marine sandstone is probably a subregional disconformity. This relationship is dramatically illustrated in the northern part of the Lebanon arch, where rocks of the PLFG are from 123 to 0 ft thick (drill holes 63W29 to DB–1). Where rocks of the PLFG facies are absent, rocks of the crossbedded and burrowed sandstone facies directly overlie quartzose sandstone and conglomerate.

### High-Angle Crossbedded and Burrowed Quartzose Sandstone Facies

Rocks of the high-angle crossbedded quartzose sandstone and burrowed quartzose sandstone (simply crossbedded and burrowed sandstone hereafter) are present in all drill cores in the study area and are 40–130 ft thick. Crossbedded sandstone is light gray or white and consists of medium and coarse, well-rounded, frosted quartz grains. Above the basal few feet of crossbedded sandstone, unidentified black inarticulate brachiopods are common, as either broken fragments or poorly preserved valves. Crossbed sets may be as thick as 5 ft and may be mostly trough style.

Burrowed sandstone is medium to dark gray, and, although locally mud rich (wacke), it otherwise is medium to coarse in grain size, similar to the crossbedded parts of this facies. Inarticulate brachiopods are abundant locally and may be whole but poorly preserved. Trace fossils have not been systematically studied but include both vertical and horizontal traces. Some vertical traces are as long as 16 in. and may be escape burrows.

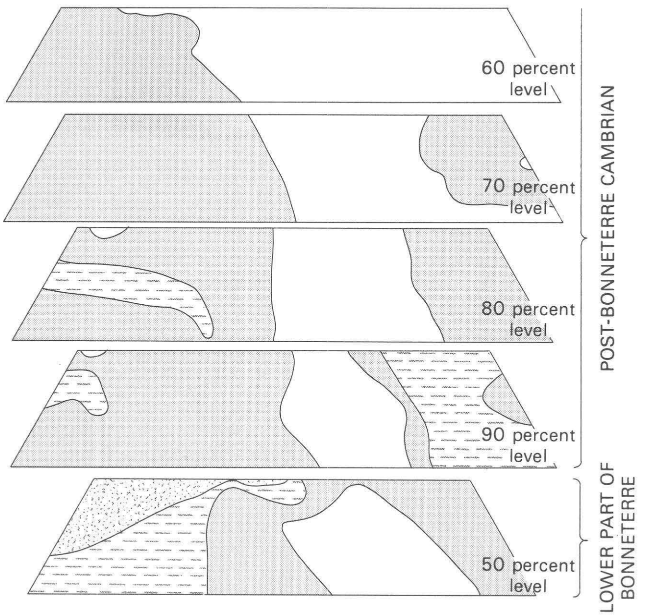
Cement is silicic in the basal parts of sections and dominated by xenotopic brown to clear dolomite in the upper parts. Pyrite and white clay locally are common.

In some drill cores crossbedded sandstone extends upward from the underlying rocks of the nonmarine sandstone facies to the base of the Bonneterre, but in other drill cores sandstones are slightly to completely burrowed and churned.

Crossbedded sandstones of the upper part of the Lamotte differ from underlying nonmarine crossbedded sandstones in that they (1) are better sorted, (2) have rounded to well-rounded and frosted quartz grains, and (3) contain locally abundant fossil debris and pelletal glauconite.

Crossbedded and burrowed sandstones represent the Late Cambrian marine transgression (T1) in the Springfield quadrangle. They are similar to the marine sandstone of Houseknecht and Ethridge (1978) and Yesberger (1981) and are interpreted as a relatively nearshore barrier and shallow tidal flat complex.

In the eastern three-fourths of the quadrangle, rocks of the crossbedded and burrowed sandstone facies are overlain directly by the Bonneterre Formation. In the Greenfield basin this facies represents in part the Reagan Sandstone of Kurtz and others (1975). Reagan crossbedded and burrowed sandstone facies are probably equivalent in part to the Lamotte sandstone and shale facies (discussed later) and to parts of the Bonneterre Formation (figs. 7, 8*A*). In the Greenfield basin these sandstones probably are conformably overlain by PBC carbonate ramp facies (fig. 8*A*).




**EXPLANATION**

**Slope, barrier, and tidal flat sandstone facies**—Lamotte Sandstone facies that are stratigraphically equivalent to the Bonneterre Formation: thinly bedded and horizontally burrowed fine sandstones (described in text as quartzose sandstone-siltstone interbedded with shale facies) and crossbedded, medium- to coarse-grained quartz sandstone and highly burrowed quartz sandstone (high-angle crossbedded and burrowed quartz sandstone facies)

**Intrashelf basin facies (described in text as shale-intrashelf basin lithofacies)**—In the lower part of the Bonneterre Formation and equivalent Lamotte Sandstone this facies is green and dark-gray shale and thin quartz sandstone; in the post-Bonneterre Cambrian (PBC) this facies is the Davis Formation and is green to blue-gray shale, thin carbonate-clast-supported conglomerate, nodular mudstone and wackestone, thinly bedded pelletal glauconitic fine quartz sandstone, and minor thrombolite boundstone

**Deep to shallow ramp facies**—In the Bonneterre Formation these include ribbon rock, thin fining-upward sequence of ooid-skeletal packstone to mudstone or wackestone and thin shale, ooid skeletal packstone and grainstone interbedded with mudstone-wackestone, and very minor thrombolite boundstone; in the PBC the same rock types are present but in different quantities; thrombolite-bound wackestone-mudstone and ribbon rock are the most common, and thinly interbedded packstone-grainstone and mudstone-wackestone are minor

**Platform facies**—In the Bonneterre Formation these are ooid-skeletal grainstone and packstone and thin and minor burrowed wackestone; PBC platform rocks include grainstone and packstone, thrombolite to stromatolite boundstone, mudstone and cryptalgalaminate, and crystalline carbonate rocks, some of which may be early karst collapse breccias

**Figure 7.** Quasi-isometric view of slice maps showing generalized distribution of lithofacies of the lower part of the Bonneterre and post-Bonneterre Cambrian (PBC), Springfield 1°×2° quadrangle. In the PBC, "60 percent level" (the uppermost map) refers to a 10-ft interval at 60 percent of the distance from the top of the PBC to the base, and so forth. The map for the lower part of the Bonneterre is a 10-ft interval at the middle of the lower Bonneterre and equivalent Lamotte Sandstone. The Bonneterre map shows broad ramp and shoal rocks in the Lebanon arch area, intrashelf basin rocks in the Greenfield basin, and shallow-water sandstones in the northwestern corner of the map area. The post-Bonneterre maps show platform and shallow ramp rocks along the Lebanon arch, which prograde across intrashelf basin sedimentary rocks as shown in the progressively higher slice maps. Modified from Palmer (1986) using plate 1 (this volume).

## Quartzose Sandstone-Siltstone Interbedded with Shale Facies

Rocks of the quartzose sandstone-siltstone interbedded with shale facies (sandstone and shale hereafter) are in the upper part of the Lamotte in westernmost drill cores only (Greenfield basin) and are 0–38 ft thick. Shale beds are from a few inches to 3 ft thick and consist of variably pyritic, blue, green, and almost black shale. Sandstone-siltstone beds are less than 2 ft thick and consist of siltstone to fine-grained quartzose sandstone. Fine quartz grains are well rounded. Other grains in sandstone include inarticulate brachiopod, trilobite, and hyolithid fragments and pelletal glauconite. Sandstone interbeds are parallel laminated and rippled and horizontally burrowed or, rarely, crossbedded. Local slumps involve sediment thicknesses of as much as 5 ft. Most cements are mostly silicic but include dolomite and pyrite.

The lower contact of the sandstone and shale facies appears to be disconformable in drill core NS–3 (fig. 8*A*) and in other western border drill cores. In drill core NS–4 (fig. 8*A*) this contact may be conformable. Upper contacts with crossbedded and burrowed sandstone are conformable. Correlated as shown in figures 5 and 8, Lamotte sandstone and shale facies are equivalent to the upper part of the Bonneterre to the east. Alternatively, sandstone and shale facies may correlate with parts of *both* the lower and upper parts of the Bonneterre Formation in the eastern three-fourths of the quadrangle.

Rocks of the sandstone and shale facies are unlike any other described Lamotte rocks of eastern Missouri but are somewhat analogous to some sandstone and shale beds of the Davis Formation in eastern Missouri. The facies is tentatively interpreted as a transgressive intrashelf basin facies because of its apparent lateral equivalence with certain Bonneterre ramp facies and because of its position in the stratigraphic sequence overlying the lowermost carbonate rocks, yet underlying and separated from the Davis Formation shales (fig. 8*A*). Following this interpreted transgression, better sorted barrier sandstones were deposited atop this sandstone and shale intrashelf basin. This system resulted in west to east onlap of the carbonate facies of the lower part of the Bonneterre by siliciclastic-rich facies of the upper part of the Bonneterre Formation.

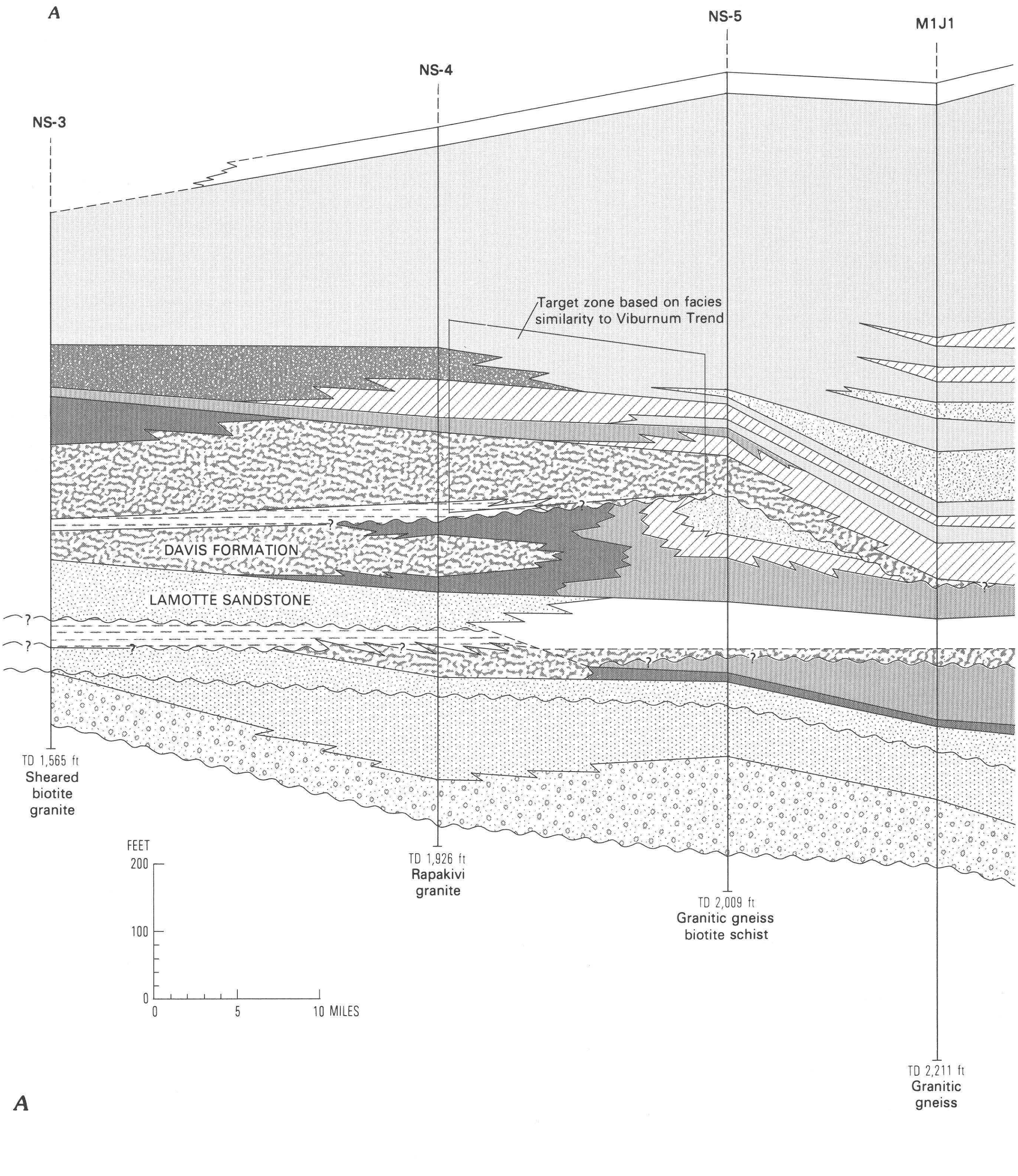
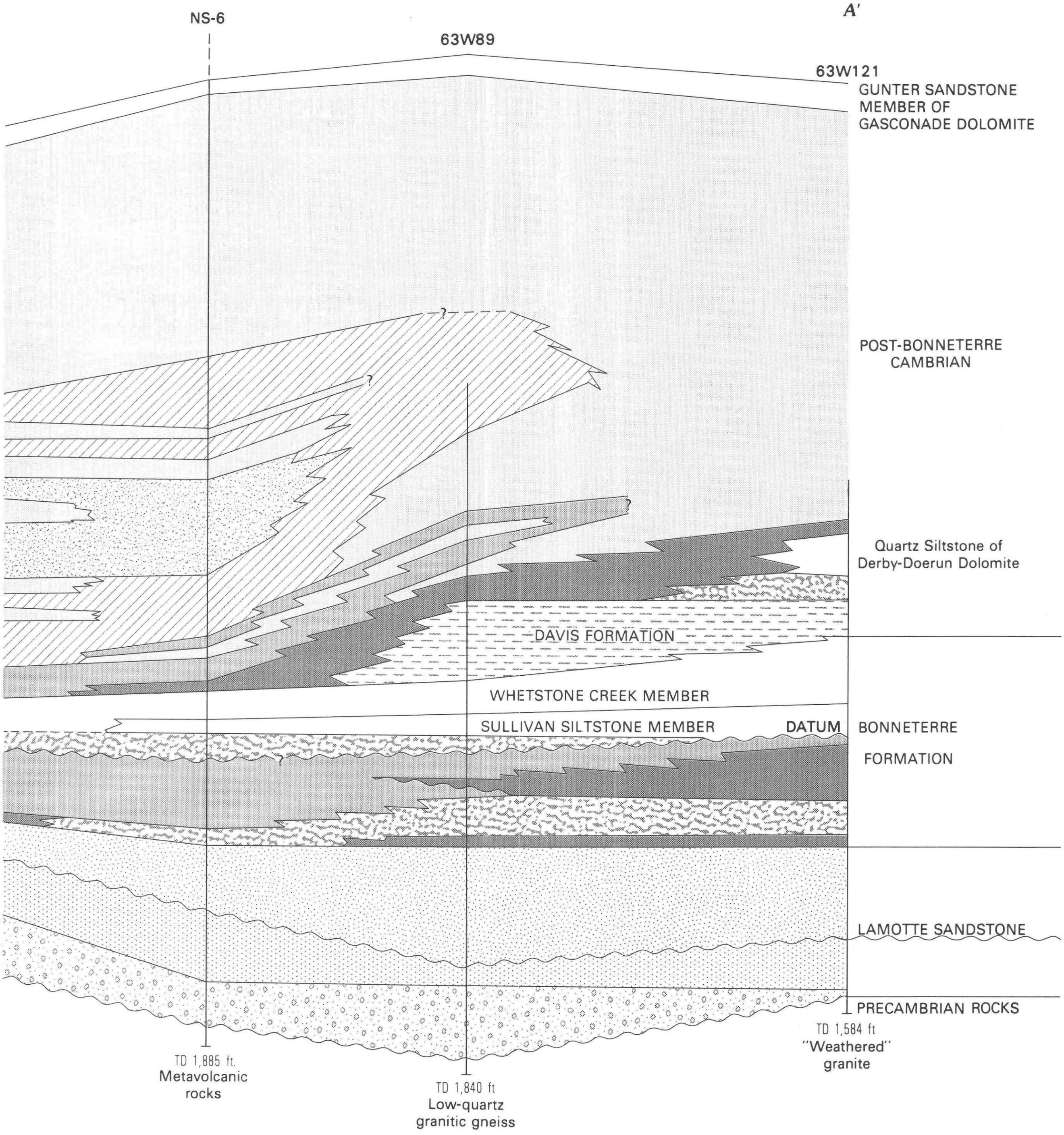



**Figure 8** (above and following pages). Lithofacies relationships of Cambrian rocks, Springfield 1°×2° quadrangle. Locations of lines of sections shown on figure 6. TD, total depth.

The Sullivan Siltstone Member and the Whetstone Creek Member in the east are interpreted to correlate with the sandstone and shale facies and the crossbedded and burrowed sandstone facies in the west (fig. 8*A*).

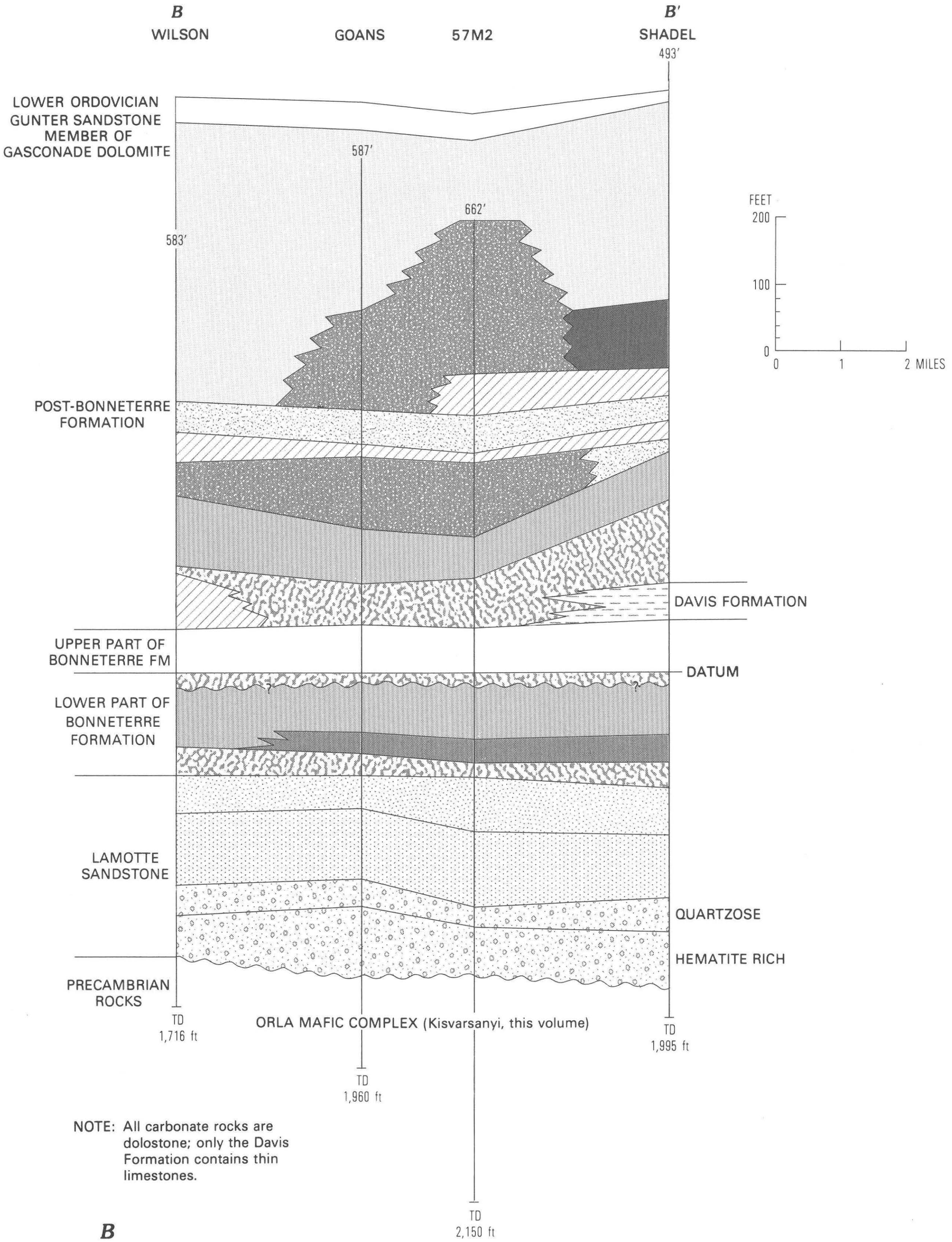
The time of the filling of this western Lamotte and Bonneterre basin is believed to be near the bottom of the *Apsotreta expansa* Zone (Kurtz and others, 1975, pl. 1), which is also the approximate stratigraphic break between




the lower and upper parts of the Bonneterre in western Missouri.

## POST-LAMOTTE STRATIGRAPHY

For discussion in this report, the post-Lamotte stratigraphic sequence is divided into two major lithostratigraphic units, the Bonneterre Formation and the post-Bonneterre Cambrian (PBC) (fig. 5). The Bonneterre may be further divided into a lower carbonate-dominated unit and two formal upper members, the Sullivan Siltstone Member and Whetstone Creek Member (Kurtz and others, 1975). Both upper members are terrigenous clastic rich. The Bonneterre is 0-220 ft thick. The PBC includes the Davis


B
B′
WILSON
GOANS
57M2
SHADEL
493′
587′
662′
583′
LOWER ORDOVICIAN GUNTER SANDSTONE MEMBER OF GASCONADE DOLOMITE
POST-BONNETERRE FORMATION
DAVIS FORMATION
UPPER PART OF BONNETERRE FM
DATUM
LOWER PART OF BONNETERRE FORMATION
LAMOTTE SANDSTONE
QUARTZOSE
HEMATITE RICH
PRECAMBRIAN ROCKS
TD 1,716 ft
ORLA MAFIC COMPLEX (Kisvarsanyi, this volume)
TD 1,995 ft
TD 1,960 ft
TD 2,150 ft
FEET
200
100
0
0
1
2 MILES
NOTE: All carbonate rocks are dolostone; only the Davis Formation contains thin limestones.

**B**

EXPLANATION

Light-colored crystalline carbonate dolostones

Coarse crystalline carbonate rocks–"Whiterock" dolostones

Thrombolite to stromatolite boundstone cycles

Cyclic bedded thrombolite boundstone and wackestone to grainstone

Thrombolite bound mudstone to packstone

Thick packstone-grainstone

Mudstone-wackestone interbedded with packstone and grainstone

Sullivan Siltstone Member and Whetstone Creek Member of Bonneterre Formation

Ribbon rock

Quartzose sandstone-siltstone interbedded with shale

High-angle crossbedded and burrowed quartzose sandstone

Parallel-laminated fine-grained quartzose sandstone

Basal conglomerate and sandstone

493′ Drill hole
Top of core

TD 1,995 ft Total depth

Formation, the Derby-Doerun Dolomite (as used by the Missouri Geological Survey), the Potosi Dolomite, and the Eminence Dolomite and is treated as a lithologic-sedimentologic unit. The PBC is 540–930 ft thick. On a regional scale the same facies are present in both the Bonneterre and the PBC.

The stratigraphic relationship between the upper and lower parts of the Bonneterre is conformable across parts of the quadrangle; however, in Douglas County (fig. 6) the Sullivan Siltstone Member overlies rocks of the lower part of the Bonneterre—rocks of carbonate platform origin—in apparent disconformity. Elsewhere in the quadrangle the Sullivan Siltstone Member overlies ribbon rock facies of the uppermost lower part of the Bonneterre. Within the lower part of the Bonneterre the sequence probably is mostly conformable. The PBC/Bonneterre contact also probably is conformable. Locally in the Central Missouri basin the Whetstone Creek Member of the upper part of the Bonneterre becomes a lateral facies of the PBC (Davis Formation) shale facies. Across the Lebanon arch the Sullivan Siltstone Member is absent because it changes to glauconite-rich Whetstone Creek Member rock types (fig. 8*A*). The Bonneterre is early Dresbachian (*Cedaria* (?) Zone) to early Franconian (*Elvinia-Linnarssonella* Zone) in age (Kurtz and others, 1975; V.E. Kurtz, oral commun., 1985).

PBC facies have generally been given formational status in the outcrop area of southeastern Missouri. This study in the Springfield quadrangle highlights some concerns about the stratigraphic nomenclature in the Cambrian. For simplicity and to tie together previous terminology, the following generalizations can be made.

1. The term "Davis Formation" should be restricted to bedded shale and limestone where these rock types overlie the Bonneterre; V.E. Kurtz (oral commun., 1985) suggested that the Whetstone Creek Member would be better assigned to the Davis Formation than to the Bonneterre because of its clastic and glauconitic character.

2. Rocks of the Derby-Doerun and Potosi Dolomites are not easily distinguished from each other across the study area; the principal difference between these two units in the outcrop area is based on the presence of quartz and chalcedony in the Potosi and their absence in the Derby-Doerun. In the study area these units should be considered as a single unit of brown dolostone above the Davis Formation in the Central Missouri and Greenfield basins; in the Lebanon arch area, however, brown dolostone directly overlies the Whetstone Creek Member of the Bonneterre.

3. The Eminence Dolomite should be restricted to a series of light-colored crystalline carbonate dolostone that overlies brown dolostone of the Derby-Doerun and Potosi and underlies the Gasconade Dolomite.

The base of the PBC is basal Franconian (near base of *Elvinia-Linnarssonella* Zone) (Kurtz and others, 1975). The base of the Franconian is just below the top of the Bonneterre Formation near the Bonneterre type area. The top of the Cambrian System is recognized as the contact between the Eminence Dolomite and the Gunter Sandstone Member of the Gasconade Dolomite (Bridge, 1930; Dake, 1930; Howe and others, 1972; Kurtz and others, 1975). In the Springfield quadrangle the Gunter Sandstone Member is absent locally because of apparent facies changes from quartzose sandstone to dolostone, but the contact between the PBC and Gasconade Dolomite is mostly conformable. Trilobite (Stitt, 1977) and conodont zonations (Kurtz, 1981) suggest that the Cambrian-Ordovician biostratigraphic boundary in Missouri is within the upper part of the Eminence Dolomite. In the Lake of the Ozarks region (north-central part of the Springfield quadrangle) this biostratigraphic boundary is 26–55 ft below the Eminence (uppermost PBC)-Gunter contact (Kurtz, 1981).

## Post-Lamotte Lithofacies

Apart from the classical stratigraphic units, the Upper Cambrian sequence in Missouri has long been recognized as a facies complex (Howe, 1968); hence my use of the concept of "post-Bonneterre Cambrian" (PBC) as discussed earlier. To more accurately characterize the lithology of this large unit, I have used facies subdivisions that reflect and support Howe's interpretation. This makes possible direct comparisons of the Bonneterre Formation MVT host facies with Upper Cambrian rocks and sequences in the Springfield quadrangle because such MVT host facies are not unique to the Bonneterre Formation.

At the beginning of this project an attempt was made to apply the Bonneterre Formation facies subdivisions of Larsen (1977) to the rest of the Upper Cambrian sequence. Larsen described four large-scale lithologic and depositional facies units in the Bonneterre Formation: (1) basinal micrite and shale, (2) platform slope oolitic, (3) platform margin digitate stromatolite, and (4) platform interior planar stromatolite and burrowed carbonate mud (of Howe, 1968). However, detailed logging of cores in the Springfield quadrangle showed that these generalized facies subdivisions were inadequate to fully describe the rocks in the Upper Cambrian sequence. Consequently these subdivisions are modified here to reflect more recent carbonate shelf studies: (1) intrashelf basin facies (shale), (2) carbonate ramp facies, (3) shoal complexes, and (4) submergent to emergent platform interiors. Within these four generalized depositional environments are distinct lithologic types, which can be grouped into 10 post-Lamotte facies.

| FACIES | DEPOSITIONAL ENVIRONMENT |
|---|---|
| Clastic facies | |
| Shale | Intrashelf basin within regional carbonate shelf system |
| Clastic-dominated middle ramp | Slope or ramp |
| Carbonate ramp facies | |
| Ribbon rock | Deep ramp |
| Mudstone-wackestone interbedded with packstone-grainstone | Foreshoal shallow ramp |
| Thick packstone-grainstone | Homoclinal ramp shoal complex |
| Thrombolite bound mudstone to packstone | Deep to shallow ramp buildups |
| Carbonate platform facies | |
| Cyclic bedded thrombolite boundstone and wackestone to grainstone | Submerged tidal channel |
| Cyclic thrombolite to stromatolite boundstone | Peritidal platform interior cycles |
| "Whiterock" dolostone | Tidal-supratidal flats and local paleokarst |
| Light-colored crystalline carbonate dolostone | Shallow platform and tidal flat |

The lithologic types in this Upper Cambrian carbonate shelf are remarkably similar to those in the southern Appalachian Cambrian Nolichucky intrashelf basin system described by Markello and Read (1981, 1982). As in the Nolichucky, the transition from shaly intrashelf basin to shallower water carbonates is along a carbonate ramp.

The descriptions and interpretations of these 10 facies are given here in the order in which they commonly appear, which is a shallowing-upward sequence.

## Clastic Facies

### Shale (Intrashelf Basin) Lithofacies

#### Description

The shale lithofacies in the Cambrian sequence of the Springfield quadrangle comprises dark-green, blue, and blue-gray shale, thin to thick limestone interbeds, and minor local thin sandstone interbeds. The carbonate interbeds include matrix- and clast-supported carbonate conglomerate, Renalcis and Epiphyton thrombolite boundstone, skeletal wackestone and packstone, dark-colored mudstone and nodular mudstone, and thin ooid-pelletal packstone and grainstone. Conglomerate beds, skeletal wackestone and packstone, and ooid-pelletal packstone and grainstone commonly have thin, dark-colored mudstone caps. The thin sandstone is mostly parallel-laminated pelletal glauconitic quartzose sandstone and is rippled or cross laminated and horizontally burrowed locally. In the Cambrian outcrops of southeastern Missouri, one such major shale lithofacies sequence is formally recognized as the Davis Formation (Buckley, 1908). The shale facies described here is in part the same as the "offshore facies" of Gerdemann and Myers (1972) and the "micrite and shale facies" of Kurtz and others (1975) and Larsen (1977). These previous workers restricted "micrite and shale" to include only Bonneterre Formation shale facies.

Rocks of the shale facies of the Bonneterre Formation in the study area are 0–25 ft thick; the thickest units are in the northeasternmost part of the quadrangle. (Just east of this northeastern corner, the Bonneterre Formation is almost all shale and is more than 150 ft thick.) Shale beds are from 6 in. to 2 ft thick and green to dark blue gray. Locally, shale may have abundant small tool markings. Interbedded rock types include:

1. Ooid-skeletal-intraclast packstone, 3–4 in. to 3 ft thick, containing trilobite, echinoderm, and *Chancelloria* spp., and hyolithid fragments. Grapestonelike composite or accretionary grains and multiple-generation clasts may be present. These beds are commonly graded and have thin mudstone caps and sharp basal contacts with underlying shale. Some packstone interbeds have truncated hardground surfaces (figs. 9*B*, *D*, *F*).

2. Conglomeratic lithoclast grainstone and packstone, 1–3 ft thick, with matrices of trilobite-echinoderm skeletal (rare hyolithids) wackestone or packstone (fig. 9*B*). Some intraclasts are laminated, burrowed, and locally bored mudstone to fine grainstone-packstone (ribbon rock lithology). Intraclasts are as long as 10 in. and are thin plates (0.5–1 in. thick). Clasts are variously oriented; some are almost vertical, particularly in upper parts of beds. Lower contacts do not truncate shale bedding, nor does lithoclast conglomerate contain shale clasts or shale matrix; however, shale beds may show differential compaction at contacts

with conglomerate. Upper contacts may be scoured and abruptly overlain by lime mudstone or shale and locally by Renalcis-Epiphyton thrombolite boundstone (rare in the Bonneterre Formation but common in the Davis). Other types of thrombolite boundstones are not restricted to shale facies, but Renalcis-Epiphyton thrombolites are generally present only as caps on lithoclast conglomerate beds within the shale facies.

3. Quartzose, very fine grained sandstone, 1–2 in. thick, with pelletal glauconite, commonly separated by shale laminae, 1–2 in. thick; these sandstones have parallel laminae, minor cross laminations and ripples, and horizontal burrow traces on uppermost surfaces. In the Bonneterre and Davis they are restricted to the lower parts of shale facies sequences and are common only in the Central Missouri basin cores.

Rocks of the Davis Formation shale facies are from 0 to more than 175 ft thick. The thickest sections are relatively close to the Lebanon arch and are conformably overlain by brown dolostone of the PBC, the lateral equivalent of shale facies in the Lebanon arch area (figs. 8*A*, *B*). In addition to the features described above (with the exception of *Chancelloria* spp. fragments), Davis Formation shale facies contain fine peloid-ooid packstone in beds as thick as 5 ft (Shadel core only) and dark-colored mudstone to very fine grained skeletal wackestone as nodular limestone (common only in cores of the extreme eastern edge of the study area and in sequences as thick as 30 ft). Nodular mudstones in shale may contain 20 percent or less shale but are included in this category because they are subjacent, superjacent, or adjacent to thick-bedded green shale. Greenfield basin shale facies are almost exclusively nodular mudstone-shale subfacies (fig. 9*A*). Slumps are present locally in some shale facies and involve no more than 2–3 ft of sediments. Most of the carbonate interbeds are limestone, but fine-grained dolomite locally has replaced some calcite mud grains, fossil grains, and the centers of ooids. Dolomite has also replaced most calcite in limestone of the upper few feet of shale facies intercepts in Davis-PBC sections.

#### Inferred Depositional Environment

The shale facies in the Cambrian of the Springfield quadrangle is interpreted to represent intrashelf basin sediments deposited within a regional carbonate shelf system. It comprises the basal parts of large-scale shallowing-upward sequences that have facies transitions from shale facies to ribbon rock facies, to mudstone/wackestone interbedded with packstone/grainstone facies, to thick-bedded packstone and grainstone facies. Areas of shale facies in the Bonneterre and PBC are designated herein as the Central Missouri basin and Greenfield basin (figs. 4*B*, *C*, 8*A*). The thickest shale facies sequence in the Springfield quadrangle is in the PBC (Davis Formation) and is 175 ft thick at the basin margin adjacent to the Lebanon arch.

The fauna of the shale facies is relatively abundant and diverse (Kurtz and others, 1975; Stitt, 1983), especially as compared to other facies. Other features characteristic of shale facies such as abundant pelletal glauconite, predominance of horizontal burrows and trails as compared to vertically oriented trace fossils, and local hardgrounds and truncated surfaces within carbonate interbeds (figs. 9*B*, *D*, *F*) suggest slow, periodic deposition in a marine subtidal setting (Cloud, 1955; Wilson, 1975).

Peloid-radial ooid packstone beds in the Davis of the Shadel core (Laclede County) are not present in laterally equivalent ribbon rock facies of core 57M2 (fig. 8*B*). Peloids and ooids possibly were transported down ramp from shoal areas at the margin of the Lebanon arch. Peloid-radial ooid packstone is similar to Cambrian Nolichucky Shale subtidal sandsheets, which were interpreted to have been reworked only during storms (Markello and Read, 1981, 1982).

Lithoclast conglomerate beds are thicker and more abundant at the intrashelf basin margin adjacent to the Lebanon arch. They are similar to debris and fluidized flow deposits (summarized *in* Cook and Mullins, 1983) in that (1) they are clast-supported conglomerate having a skeletal wackestone or packstone matrix; (2) they generally have randomly oriented clast fabrics in which some clasts project above the upper surface of the conglomerate bed; (3) clasts locally are oriented subvertical to vertical within dewatering structures; and (4) clasts include ribbon rock and shallow ramp wackestone and packstone and multiple-generation clasts. The dewatering structures contain no shale or sand dikes and are similar to fluid escape "pipes" along which clasts are oriented in the direction of flow. The fluid that made the dewatering structures most likely came from the conglomerate bed itself.

These conglomerate beds are interpreted to be storm-generated mass-flow deposits that moved from deeper parts of the ramp. The presence of internally truncated conglomerate beds and multiple-generation clasts indicates that the beds may be resedimented conglomerates from the ramp. Presumably they moved down slopes of a few degrees or less.

The Renalcis-Epiphyton thrombolite mounds and encrustations that are present locally on conglomerate beds have mottled or clotted cryptalgal fabrics and are more characteristic of subtidally deposited boundstones (Aitken, 1967). Thrombolites and associated beds in shale facies lack features common to intertidal flats such as birds-eyes, laminar stromatolitic fabrics, and light-colored laminite mudstones (Roehl, 1967; Shinn, 1968, 1983), all of which are common features within other PBC dolostone facies. Renalcis-Epiphyton mounds are found only on carbonate substrates, almost exclusively conglomerate beds within shale facies. They probably indicate that the intrashelf basin margin facies, in which the thrombolites are common, was deposited within the photic zone.

PBC shale facies are thickest near carbonate ramp and platform facies and thin toward the geographic center of the shale depositional basins. Substantial parts of shale facies nearest the ramp consist of thick, numerous carbonate interbeds that decrease in thickness and number away from ramp areas.

Estimated water depths within the intrashelf basin areas are 90–200 ft. These depths are based on the thickness of the overlying ramp and shoal facies and the assumption of laterally prograding ramps and do not allow for compaction. Preserved total thickness of each lithofacies of the shallowing-upward sequence is assumed to be a measure of the vertical distribution of that lithofacies on the sloping carbonate and shale ramp and basin. The vertical sequence at any place was formed by progradation of the entire sloping ramp-basin system across that place through time (Walther's law; Walther, 1894).

## Clastic-Dominated Middle Ramp Facies

### Description

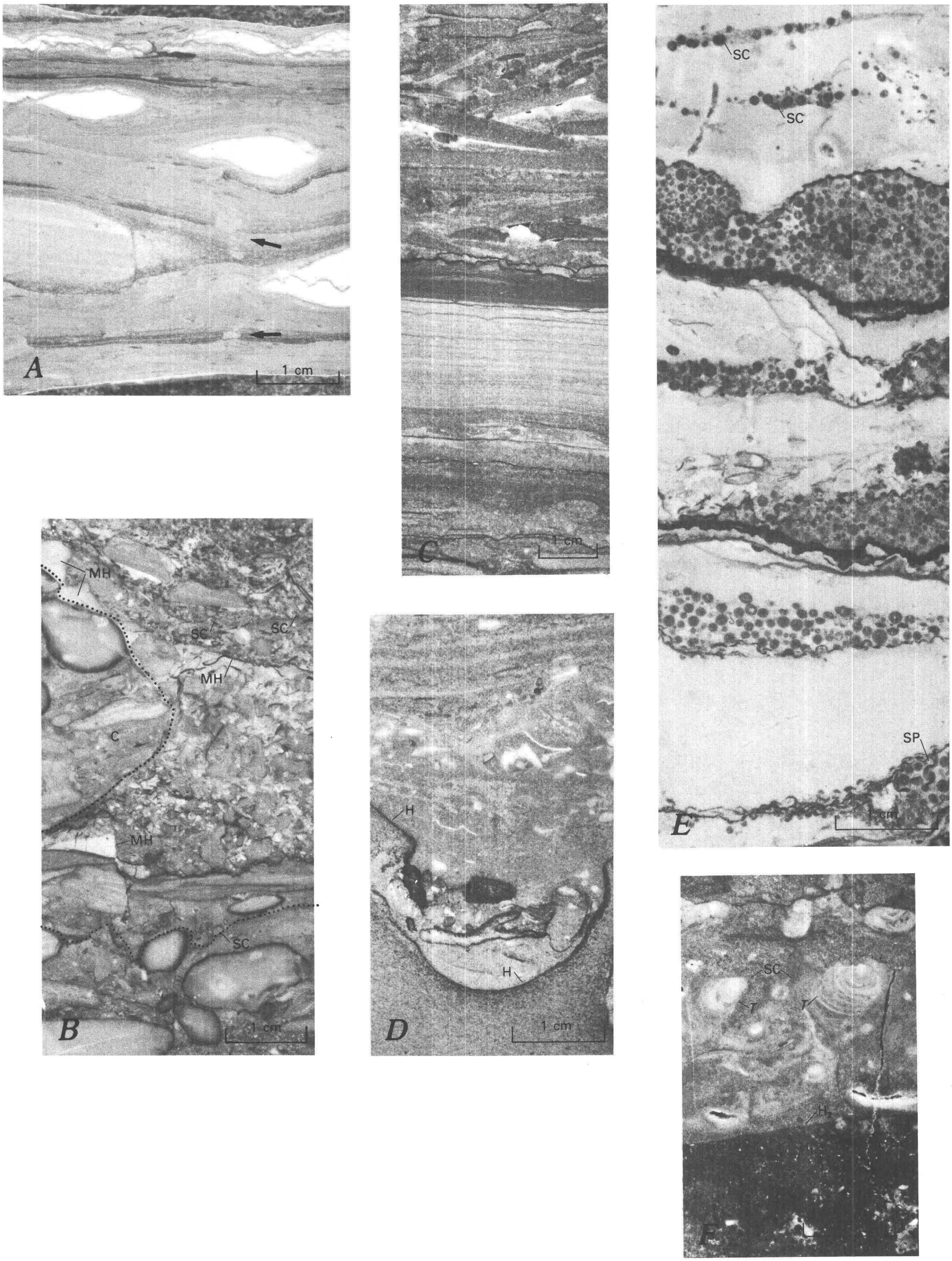
The Sullivan Siltstone Member is a quartzose fine sandstone to siltstone; its thickness ranges from 0 ft at the Lebanon arch to more than 60 ft in the Central Missouri basin. Cements in the Sullivan are silica and calcite in the Central Missouri basin and silica and dolomite near and within the Lebanon arch. The facies herein referred to as Sullivan Siltstone Member is restricted to parallel-laminated, cross-laminated, and horizontally burrowed quartzose siltstone and fine sandstone. Clast-supported siltstone-sandstone-intraclast, flat-pebble conglomerate beds as thick as 2 ft are also locally present (fig. 9*C*). Conglomerate matrix is commonly trilobite wackestone.

A very similar quartzose siltstone facies directly overlies the PBC (Davis Formation) shale facies in the northeasternmost drill cores of the quadrangle. This unnamed siltstone within the Derby-Doerun Dolomite has lateral and downward transitions to ribbon rock dolostone in the PBC. It is thickest (100 ft) in Pulaski County (63W82) and pinches out to the south and west; it was not present in drill holes 65W32, 63W89, 63W29, or 63W34 (fig. 6).

The contact between the Sullivan and the lower part of the Bonneterre in most of the Central Missouri basin probably is conformable, with ribbon rock facies in gradational contact with the base of quartzose Sullivan (fig. 8*A*), although the underlying ribbon rocks themselves apparently disconformably overlie shallower, platform facies of the lower part of the Bonneterre. In Douglas County the Sullivan Siltstone Member itself overlies ooid-skeletal grainstone in apparent subregional disconformity, and in the Lebanon arch area, between drill-holes NS–6 and MIJ1 (fig. 8*A*), the Sullivan grades laterally westward to shaley and very glauconitic rocks of the Whetstone Creek Member that directly overlie the lower part of the Bonneterre in apparent disconformity. The upper contact of the Sullivan is a gradational, interbedded contact marked by first occurrence of thin-bedded shale of the Whetstone Creek.

The Whetstone Creek Member of the upper part of the Bonneterre is 0–94 ft thick and mostly siliciclastic. Pelletal glauconite grains are locally abundant in all Whetstone Creek rock types. Beds of pelletal glauconite are locally as thick as 18 in. Pelletal glauconite is replaced by hematite in thin intervals. The Whetstone Creek was described as a heterogeneous depositional mosaic by Kurtz and others (1975), and attempts to map lithofacies trends in the middle of this unit for this study were not successful; however, at the base and the top of the Whetstone Creek, broad north-trending facies belts can be mapped. A wide range of rock types is present in the Whetstone Creek Member, and these rock types are generally thinly interbedded with one another: (1) shale interbedded with quartz- and (or) calcite- or dolomite-cemented siltstone and sandstone; (2) shale interbedded with carbonate mudstone to fine skeletal grainstone; (3) pelletal glauconitic, skeletal, and quartz-sand–rich wackestone to grainstone; (4) quartz- and (or) calcite- or dolomite-cemented, pelletal glauconitic, burrowed, laminated and cross-laminated quartzose siltstone and sandstone; and (5) clast-supported, wackestone- to packstone-matrix–supported lithoclast conglomerate.

**Figure 9** (facing page). Deep and shallow ramp facies. *A*, Lenticular bedded shale, pelletal lime mudstone (light gray), and very fine grained, laminated grainstone (medium gray); deep ramp environment. The slab shows differential compaction of shale around carbonate lenses and a compacted vertical burrow (arrows). *B*, Half of a 14-cm-thick complex limestone bed of polymictic lithoclast conglomeratic grainstone from the Davis Formation (deep ramp environment) showing features of complex resedimentation and early submarine cementation. MH, micrite-cemented hardground with truncated trilobite test or bed; SC, other scoured surfaces; C, multigeneration lithoclast. *C*, Brown dolomite-cemented, wavy- and parallel-laminated quartz siltstone and bed of flat-pebble, intraclast conglomerate from the Sullivan Siltstone Member of the Bonneterre Formation; deep ramp environment. *D*, Hardground surfaces (H) marked by concentrations of hematite and pyrite (dark gray) from the Sullivan Siltstone Member; deep ramp environment. Hardgrounds are overlain by intraclast-skeletal-quartz sand packstone and then by fine-grained cross-laminated grainstone. *E*, Stylolite-bounded, thinly interbedded mudstone and ooid-skeletal grainstone, packstone, and wackestone from the mudstone-wackestone interbedded with packstone-grainstone (MWPG) facies; shallow ramp environment. SC, scoured surface; SP, spastolith (sheared ooid). Both horizontal and vertical burrows are present near top of photograph. *F*, Ooid grainstone and packstone bed (dark) with two truncated hardgrounds (H, $H_2$) overlain by burrowed wackestone (light); MWPG facies; shallow ramp environment SC, scoured surface within wackestone; *T*, *Teichichnus* burrows.


A
1 cm
B
MH
SC
C
C
1 cm
D
H
E
SC
SP
F
T

In the Central Missouri basin, the Whetstone Creek Member changes to a shale facies that is indistinguishable from the overlying Davis Formation. The Sullivan Siltstone Member thus becomes an important stratigraphic marker because it separates the shale facies of the lower part of the Bonneterre from the shales of the combined Whetstone Creek Member and Davis Formation. In the Greenfield basin, the Whetstone Creek changes facies to crossbedded and burrowed quartzose sandstone similar to that of the upper part of the Lamotte Sandstone (figs. 5, 8*A*).

The contact between the Whetstone Creek Member and overlying PBC facies appears to be everywhere conformable.

#### Inferred Depositional Environment

Lithofacies units interpreted as middle ramp deposits are pelletal glauconitic and clastic-rich basal Bonneterre, the Sullivan Siltstone Member, the Whetstone Creek Member, and the unnamed siltstone facies in the Derby-Doerun Dolomite. These facies occupy stratigraphic positions and regional settings that are transitional between intrashelf basin shale facies and carbonate ramp facies.

The Sullivan Siltstone Member changes facies laterally to the Whetstone Creek Member in the Lebanon arch area and to ribbon rock facies ("micrite facies" of the Sullivan Siltstone Member; Kurtz and others, 1975) in eastern Missouri (approximately 48 mi east of the Springfield quadrangle). The Sullivan has sparse infauna (Kurtz and others, 1975), and most trilobites are in the wackestone-packstone matrix of clast- and matrix-supported conglomerate beds of this unit. Clasts vary from flat quartzose sandstone and siltstone pebbles in sandstone-siltstone matrix to flat pebbles of ribbon rock facies carbonate clasts in wackestone-packstone matrix. Both conglomerate types are interpreted as storm-generated, possibly debris-flow deposits. Conglomerate containing sandstone or siltstone clasts is interpreted as autochthonous, whereas conglomerate containing clasts of ribbon rock facies in a trilobite wackestone to packstone matrix may be allochthonous and derived from an upramp source. Horizontal burrows in the Sullivan suggest subtidal deposition. The siltstone facies in the lower part of the Derby-Doerun has fewer conglomerate beds and almost no burrows as compared to the Sullivan. The Derby-Doerun siltstone facies changes to ribbon rock facies in the Lebanon arch area and also overlies ribbon rock facies in the Central Missouri basin (fig. 8*A*, drill hole 63W121). Because the Sullivan conformably overlies ribbon rock facies in the Bonneterre in parts of the Central Missouri basin and disconformably overlies platform lithofacies of the Bonneterre in parts of Douglas County, it is interpreted as a transgressive facies. The Derby-Doerun siltstone facies has lower and upper contacts conformable to PBC ribbon rock facies and may also be the base of a transgressive-regressive cycle. Because of their stratigraphic positions, primary sedimentary structures, and regional setting, these siltstone facies are interpreted as slope or ramp clastic rocks deposited below normal wave base but within storm wave base.

The basal glauconitic lower parts of the Bonneterre and the Whetstone Creek Member are more complex and heterogeneous units than the two siltstone facies. They contain normal marine faunas including trilobites, echinoderms, and inarticulate brachiopods and locally abundant pelletal glauconite. They have horizontal burrows and local hardgrounds, some of which are multiple, particularly in the Whetstone Creek Member. These features suggest slow deposition (Wilson, 1975). Both the basal Bonneterre and Whetstone Creek Member lie above siltstone or sandstone units and below intrashelf basin-facies shales and have subregional transgressive erosional surfaces at their bases.

The Whetstone Creek Member changes to shale facies in the Central Missouri basin and to crossbedded and burrowed pelletal glauconitic sandstone in the Greenfield basin. These transitions illustrate that the Whetstone Creek is a middle facies tract between intrashelf basin facies and the shoal and flat, crossbedded and burrowed sandstone.

Matrix- and clast-supported conglomerates in these units are also interpreted as storm generated; most of these rocks probably were deposited within storm-wave base, approximately middle ramp in depth. Local crossbedded quartzose sandstones within the Whetstone Creek suggest some wave-base or current influence in those areas. Basal Bonneterre and Whetstone Creek have conformable relationships with intrashelf basin shales in the Central Missouri basin, and ribbon rock deep ramp facies in the Lebanon arch area strongly suggest a middle-ramp interpretation. Both units drown shallower shelf deposits, the Lamotte Sandstone and uppermost lower part of the Bonneterre, respectively.

These middle ramp facies are widespread in the subsurface of southern Missouri, absent only from the platform areas of the St. Francois Mountains in southeastern Missouri and from the Lebanon arch. They are important regional stratigraphic markers that represent the beginnings of major regional transgression and the development of intrashelf basin systems. Following the biostratigraphic zonations of Kurtz and others (1975), the basal Bonneterre glauconitic facies is a lower (?) Dresbachian (lower) *Crepicephalus* Zone or upper *Cedaria* Zone (?). The regional transgressions represented by the ribbon rock facies in the uppermost lower part of the Bonneterre and the Sullivan Siltstone Member are middle to upper Dresbachian (upper) *Crepicephalus* Zone and continue through the lower Franconian (lower) *Elvinian-Linnarssonella* Zone.

## Carbonate Ramp Facies

Using the carbonate platform models of Read (1985), various types of ramps and shoal complexes can be recognized in the Upper Cambrian sequence of Missouri. The dominant type probably is a homoclinal ramp with barrier ooid-pellet shoals complex. The carbonate facies interpreted as ramp units include (1) ribbon rock facies to nodular and argillaceous mudstone (deep ramp); (2) horizontally burrowed mudstone-wackestone thinly to thickly interbedded with packstone-grainstone (shallow ramp); and (3) thrombolite digitate boundstone containing muddy internal sediment (deeper ramp) or packstone to grainstone internal sediment (shallow ramp). Locally, variations of other ramp models (all after Read, 1985) are preserved in these transitions. These include (1) distally steepened ramps (indicated by slumps within the PBC deep-ramp ribbon rocks and shale facies and by debris/grain flows in shale facies); (2) ramps with fringing banks (on the west side of the quadrangle where PBC-thrombolite boundstones comprise the entire ramp and submerged platform sequence and pass laterally and vertically into tidal flat deposits); and, possibly, (3) ramps with isolated ramp-downslope buildups (represented by low-relief thrombolite mounds and tabular or biostromal thrombolite boundstones no more than 6 ft thick in the Bonneterre and PBC). All of these units are interbedded with one another and have interfingering relations on a very broad scale, as much as several miles across.

### Ribbon Rock (Deep Ramp) Facies

#### Description

Rocks of the ribbon rock facies (terminology adopted from Markello and Read, 1981) are brown to gray limestone and dolostone that have thin, rhythmic flaser and lenticular and wavy bedding. The thin and very thin beds (0.02–4 in.) consist of cyclic alternations of a basal, very fine grainstone (calcisiltite), locally containing skeletal debris and fine pelletal glauconite, grading upward to lime mudstone, and capped by thin shale (fig. 9*A*). Shale is sparse to absent in some sequences. Carbonate intraclast conglomerate is common and is clast supported with skeletal packstone or grainstone matrix (fig. 9*B*). Most conglomerate clasts are thin plates of ribbon rock. Scoured and truncated surfaces below and within fine grainstone and conglomerate are also common. Almost all burrow traces are horizontal. Minor and rare slumps involve no more than 6 ft of sediment. The ribbon rock facies is in part the same as the "micrite and shale" facies of Larsen (1977). Some sections formally recognized as Derby-Doerun Dolomite contain a significant thickness of ribbon rock, mostly just above the Davis Formation contact. In the Springfield quadrangle, the net thickness of ribbon rock facies is 0–107 ft in the Bonneterre Formation and 0–287 ft in the PBC. The ribbon rock facies occupies a stratigraphic and lateral position between the shale facies and coarser grained non-shaley facies such as the mudstone-wackestone interbedded with packstone-grainstone facies and the thick packstone-grainstone facies.

#### Inferred Depositional Environment

Rocks of the ribbon rock facies are interpreted as deposits of the deep ramp at or just below fair-weather wave base. They lack fenestral or cryptalgalaminate fabrics and herringbone cross laminations, features characteristic of tidal flats (Shinn, 1983). They are subjacent to thick grainstone and stromatolitic rocks and contain local pellet glauconite, normal marine fauna, and horizontal burrows, all of which indicate subtidal deposition. Scoured and truncated surfaces, preserved primarily within the grainstone or base of each "cycle," suggest early cementation, prior to removal of some amount of overlying sediment by strong storm-generated currents.

Stronger storms probably account for the two types of high-energy deposits in ribbon rock facies: (1) flat-pebble-intraclast matrix-supported conglomerate, on scoured bases, of debris or fluidized flow origin and (2) coarsening-upward skeletal-intraclast packstone that has nonerosive basal contacts, presumably of grain flow origin. Because depositional slopes were quite shallow, storms were the most effective method of generating gravity-style deposits that were driven well down the ramp and into the intrashelf basin margin. Flat-pebble conglomerate in ribbon rock facies is most abundant in the PBC along the flanks of the Lebanon arch but is also present in parts of the lower part of the Bonneterre. Skeletal-intraclast grain flows are most common in the PBC along the margin of the Greenfield basin but are also present along the east flank of the Lebanon arch in the lower part of the Bonneterre.

Slumps in ribbon rock facies that suggest the ramp was locally distally steepened are present in some drill cores flanking the Central Missouri and Greenfield basins. The best example of a slide is in the PBC of drill core MHR1, Polk County, and involves 6 ft of ribbon rock facies. Other slumps may be present along depositional strike of the east flank of the Lebanon arch.

### Mudstone-Wackestone Interbedded with Packstone-Grainstone (Shallow Ramp Facies)

#### Description

The mudstone-wackestone interbedded with packstone grainstone (MWPG) facies consists of horizontally burrowed mudstone to wackestone interbedded with ooid-skeletal packstone and grainstone (fig. 9*E*). Beds are a few inches to about 18 in. thick. These rocks are medium to dark brown and consist of ooids, fragments of trilobites, echinoderms, brachiopods, sparse *Chancelloria* spp. (in the Bonneterre), rare hyolithids and oncoliths, composite grains (large 1–2 in. grapestone clasts), and local pelletal glauconite. Locally, packstone-grainstone beds have truncated and hardground surfaces. Commonly, medium-bedded packstone-grainstone grades upward into thin-bedded mudstone-wackestone through a transition from packstone to wackestone.

MWPG net thicknesses are 0–97 ft in the Bonneterre Formation and 0–95 ft in the PBC. In conformable sequences, this facies lies stratigraphically above the ribbon rock facies and below the thick packstone-grainstone facies. In some drill cores, thrombolite-bound mudstone to packstone is in the lithofacies position of MWPG.

#### Inferred Depositional Environment

MWPG facies are interpreted as foreshoal shallow ramp deposits. They are a coarser and thicker bedded variant of ribbon rock facies and are interpreted as storm- to fair-weather-generated cycles of grainstone to packstone to wackestone and mudstone.

Beds of ooid-skeletal packstone-grainstone interpreted as storm deposited generally are nonburrowed or have minor horizontal burrows in their upper parts. Basal contacts with mudstone-wackestone may or may not be scoured and are not burrowed. This is unlike modern subtidal platform sands, which tend to be homogenized to a "burrowed and churned fabric" (Ball, 1967). Locally, shelter pores in storm lags have geopetal sediments of mudstone that filtered into the lag deposit during fair weather. Truncated surfaces within some packstone-grainstone suggest strong storm-current scour of early cemented packstone-grainstone. Ooid and abraded skeletal grains in these beds were presumably transported from shoal areas by these same storm currents.

Thin wackestones at the bases of mudstone-wackestone parts of cycles commonly have a few horizontal burrows. The mudstone-wackestone beds are unlaminated but have locally abundant horizontal burrows suggestive of subtidal deposition. The mudstone-wackestone beds lack fenestral or cryptalgalaminate fabrics common to tidal flat muds (Shinn, 1983) and to other parts of the Cambrian section in the quadrangle. Instead, the MWPG has relatively abundant diverse shelly fauna (in the Bonneterre Formation), horizontal burrows, local pelletal glauconite, and subtidal episodic storm-generated bedding common to shallow shelf sedimentation (Cloud, 1955; Wilson, 1975).

### Thick Packstone-Grainstone Facies

#### Description

The thick packstone-grainstone (TPG) facies of the Bonneterre Formation is medium- to light-brown limestone or dolostone that contains ooids and lesser oncoliths, trilobite-echinoderm fragments, pisoliths (large ooids, not a paleosol pisolith), and grapestone intraclasts. Local hardgrounds are not uncommon. Within some Bonneterre packstone-grainstone beds, ooid-skeletal wackestone to packstone interbeds are burrowed and churned. Thick ooid-skeletal packstone-grainstone facies in the Bonneterre Formation are distributed over almost 4,000 mi$^2$ in the Springfield quadrangle.

Thick packstones-grainstones of the PBC include both ooid-dominant facies and indeterminant grain dominant facies and are light medium brown to dark brown. All PBC packstones-grainstones are dolostones. They are crossbedded locally and only rarely burrowed. Net thicknesses are 0–150 ft in the Bonneterre Formation and 0–133 ft in the PBC.

#### Interpreted Depositional Environment

Thick packstones and grainstones in the Bonneterre Formation are ooid-skeletal sands arranged in a broad north-trending body that is interpreted to be the top of a regional east-sloping homoclinal ramp. Bonneterre carbonate sand bodies are interpreted to be bank-style accumulations. Crossbedding in Bonneterre ooid-skeletal sandstones was not observed in available drill core; however, thin beds of ooid-skeletal intraclasts and grapestone clasts over scoured hardground surfaces may represent lags between barrier sand bars.

The only other rocks in Bonneterre TPG facies are minor thin, burrowed and homogenized wackestone-packstone beds (fig. 9*F*) interpreted to be similar to the "burrowed and churned" fabric of platform interior sands in modern partly stabilized flats (Ball, 1967).

Bonneterre carbonate sands adjacent to ramp facies probably formed barriers or marine sand belts. Bonneterre ooid-skeletal packstone and grainstone have normal marine faunas and are locally horizontally burrowed (burrowed wackestone-packstone), yet they lack features common to intertidal flats such as stromatolites, keystone voids, laminites, and herringbone crossbeds (Shinn, 1983). Facies transitions of the lower part of the Bonneterre resemble those of a distally steepened ramp (Read, 1985), but cyclic peritidal facies are nowhere present at the tops of shallowing-upward sequences.

Thick PBC packstone-grainstone facies also are interpreted to be deposits of the top of a homoclinal ramp (which is also distally steepened locally) but differ from Bonneterre carbonate sands in four ways: (1) they lack burrowed wackestone-packstone, (2) they have extremely sparse shelly fauna and only rare trilobite fragments, (3) they only locally contain ooids and instead are dominated by fine indeterminate grains, and (4) they generally have vertical and lateral transitions to some sort of cryptalgal boundstone facies. This latter characteristic makes PBC sections in the Springfield quadrangle similar to Bonneterre facies of the Viburnum Trend area.

The lack of an infauna and epifauna in packstone-grainstone and microbial boundstone of the PBC suggests a stressed local environment (Kepper, 1974).

Interpretive subsurface lithofacies maps of the Springfield quadrangle (Palmer, 1986) show thick packstone-grainstone facies in the PBC as relatively narrow linear belts fringing both sides of the Lebanon arch between platform and ramp facies. In southern Laclede County, unpublished net isolith maps of the PBC packstone-grainstone facies outline what may be interpreted as a large spit-shaped body that accreted southward. These rocks are probably marine sand belt in origin because they form linear north-south tracts and are the margin of platform interior facies.

## Thrombolite Bound Mudstone to Packstone Facies

### Description

Thrombolite boundstones are present within the ribbon rock, MWPG, and cyclic platform facies discussed in the next two sections, as well as in shale facies described previously. The present description pertains to boundstones restricted to facies that lie stratigraphically below thick grainstone-packstone facies. These thrombolite boundstones occupy a central position between shale facies and thick grainstone-packstone facies; that is, they probably were deposited on carbonate ramps. Bonneterre thrombolite boundstones are 0–35 ft thick and areally restricted to Camden and western Laclede Counties; PBC boundstones are 0–62 ft thick. These thrombolite boundstones commonly are dark "columns" or "fingers" as much as a few centimeters in diameter, and they have internal sediments of mudstone to wackestone and packstone. Almost all bound portions lack internal structure or have a clotted fabric, and are fine crystalline (fig. 10*B*). The fabric of some grades upward from nonbedded and clotted to digitate or columnal; the columns may have drapes of dark matter at their edges, presumably of microbial origin, that intertongue with concave-upward layers of internal sediment. Internal sediment grains include echinoderm and trilobite fragments, oncoliths, irregularly shaped small dark-gray spot clasts, and small lithoclasts. Not all internal sediments are layered. Locally, some thrombolite columns appear to have been bored or burrowed. Burrows in internal sediments between columns are very uncommon.

Boundstones within ribbon rock facies commonly encrust lithoclast conglomerate beds. Contacts between boundstone and ribbon rock are abrupt, and locally they may be at high angles to core axes; apparent slumping of overlying ribbon rocks suggests that they were deposited on a mound. In part, these boundstones are like the "digitate stromatolite reef" of Howe (1966) and Gerdemann and Myers (1972), and they are probably much like the bioherms in the Bonneterre Formation of the Old Lead Belt of southeastern Missouri (Snyder and Gerdemann, 1968).

These thrombolite boundstones, with mudstone to packstone internal sediments, are distinguished from other boundstones in the sequence by their position between shale facies and thick packstone-grainstone facies and by their general lack of lamination within cryptalgal structures.

### Inferred Depositional Environment

Muddy thrombolite boundstones are present locally in the Bonneterre and are widespread in the PBC. They are interpreted to be deep- to shallow-ramp facies, and they have close spatial relationships to other ramp facies. Thrombolite boundstones have clotted rather than laminated internal fabrics and are interpreted to be subtidal microbial structures (Aitken, 1967). These ramp thrombolite boundstones are dominantly branching columnal types that resemble columnal stromatolites in gross morphology, except that the columns are clotted internally and only rarely are weakly laminated. Thrombolite bound mudstone to packstone may begin as small isolated structures and coalesce outward and upward, to mound-shaped bioherms as wide as tens of feet, to perhaps very broad lens- or tabular-shaped biostromal-like bodies as wide as a mile.

Mound-shaped bioherms in the Bonneterre Formation in the Old Lead Belt of southeastern Missouri were important host rocks for ore (Ohle and Brown, 1954a, b; Snyder and Gerdemann, 1968). These mounds are stacked locally, and maximum depositional relief on individual mounds is a few feet. Sediments between the mounds are bedded mudstone, wackestone, and thin packstone-grainstone that show onlap-offlap and drape relationships to individual mounds in the stack (Wagner, 1960; Snyder and Gerdemann, 1968). The intermound sediments probably are ribbon rock or MWPG facies.

Stacked mound thrombolite boundstones like those of the Old Lead Belt may be present in the PBC of the Springfield quadrangle, as indicated by interbedding of MWPG facies with thrombolite sequences. Local draping over mounds is indicated by slumped bedding overlying some PBC thrombolite boundstone. This facies, as contrasted with the cyclic bedded thrombolite boundstone to grainstone facies discussed next, is in the lower parts of PBC sequences and overlies or supplants ribbon rock facies (fig. 8*A*, drill cores NS–5, M1J1; fig. 8*B*, drill cores Goans to Wilson). These deeper ramp boundstones have muddier sediment between columns, and interbedded sediment is generally mudstone dominant.

Thrombolite bound mudstone to packstone directly beneath TPG facies generally does not have interbeds of carbonate sand but does have intercolumn sediment of packstone-wackestone and only minor mudstone. Thrombolite boundstone nearest TPG facies is interpreted as shallower ramp boundstone and was probably widespread across the ramp in the PBC. It may have formed sheetlike or tabular bodies. Thrombolite bound mudstone to packstone facies that locally built across the ramp into platform interior areas appears to grade laterally and upward to cyclic and stromatolitic platform units (PBC, fig. 8*A*, drill cores M1J1, NS–5).

## Carbonate Platform Facies

### Cyclic Bedded Thrombolite Boundstone and Wackestone to Grainstone Facies

#### Description

Rocks of the cyclic bedded thrombolite boundstone to grainstone facies (CBG) are only in the PBC of the Springfield quadrangle and are gray to brown dolostones. The cycles consist of a base of ooid wackestone, packstone, or grainstone as thick as about 2 ft overlain by nonlaminated microbial, digitate or columnal, bound mudstone-wackestone 1–6 ft thick. Locally mudstone-wackestone grades upward to burrowed peloidal grainstone as thick as 3 ft and then upward to hemispheroidal cryptalgalaminate at the tops of cycles. The thrombolitic parts of these cycles commonly have a branching habit similar to Pethei Group columnar stromatolites in Canada described by Hoffman (1974), except that the PBC microbial boundstones are only locally laminated (fig. 10*A*). The tops of boundstone beds are commonly scoured beneath succeeding ooid wackestone-grainstone beds. The CBG facies is widespread over the western half of the study area and has a net thickness of 0 to more than 220 ft.

Rocks of the CBG facies generally overlie thick bedded packstone-grainstone facies in the PBC; however, in some cores, particularly NS–2, CBG rocks overlie and pass laterally into a thrombolite bound mudstone facies sequence that in turn passes into and supplants part of a ramp sequence. In these cores these two boundstone facies appear to supplant the normal shallow-ramp stratigraphic sequence of MWPG facies to thick packstone-grainstone facies. In the central part of the quadrangle, the CBG facies is as thick as 150–220 ft in the Goans and 57M2 drill cores; however, within a distance of 2 mi (Wilson and Shadel cores) this facies is a light, mottled, coarse-crystalline dolostone. Thick sections of CBG facies are present in only a few other cores, mainly in the central part of the quadrangle (along the Lebanon arch). This facies is not as widespread as other boundstone facies.

#### Inferred Depositional Environment

These rocks are interpreted as submerged tidal channel facies. They pass laterally off platform to thrombolite bound mudstone or to TPG facies. Shoreward transitions are to muddy subtidal-intertidal units (thrombolite-stromatolite cycles) and to supratidal laminite within whiterock dolostone. Local shoaling to the intertidal zone within this facies may be indicated by stromatolitic caps on some thrombolites. Where this facies passes laterally to facies more characteristic of intertidal flats, it is more definitely related to submerged platform deposition.

These cyclic bedded platform facies, as well as the thrombolite to stromatolite facies described later, are somewhat like cyclic platform facies of the Cambrian Elbrook and Honaker Formations and Copper Ridge and Conococheague Formations (Markello and Read, 1981), where cycles formed as a result of cyclically repeated platform submergence followed by progradation of subtidal thrombolite and tidal flat stromatolitic facies.

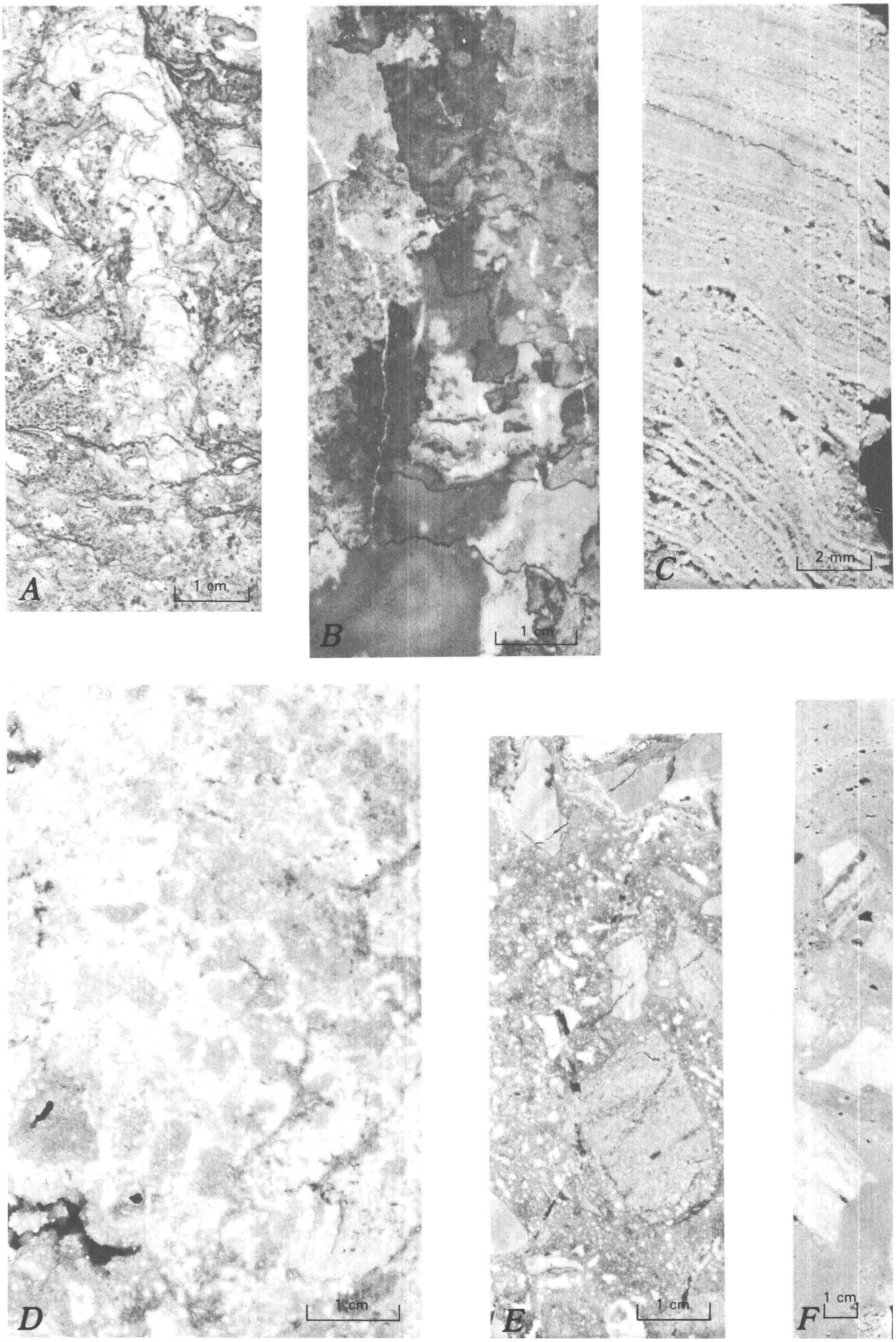
Bleached upper parts of some thrombolitic boundstones overlain by whiterock coarse crystalline dolostone in the PBC are similar to bleached and disconformable horizons in the Bonneterre Formation of the Viburnum Trend (Mouat and Clendenin, 1977) and the Asarco West Fork mine (Paul R. Dingess, ASARCO Inc., oral commun., 1988).

### Thrombolite to Stromatolite Boundstone Cyclic Facies

#### Description

Rocks of the thrombolite to stromatolite boundstone cyclic facies are present only within the PBC in the Springfield quadrangle. They are from 0 to at least 100 ft thick but are common only in drill cores across the Lebanon arch. The facies consists of light-gray or brown dolostone that has a base of mottled to branching thrombolite and a top of apparently large stromatolite (or cryptalgalaminate) hemispheroids (fig. 10*C*) to small-scale laterally linked hemispheroids. The base of the cycle is branching columnal thrombolite, essentially like the thrombolite in the CBG

**Figure 10** (facing page). Boundstone, cryptalgalaminite, and whiterock fabrics. *A*, Digitate stromatolite boundstone, in part thrombolitic, containing packstone to wackestone internal sediments. Thrombolite-bound mudstone to packstone facies; ramp environment. *B*, Thrombolite boundstone containing mudstone to packstone internal sediments (medium gray, left side of photograph). Dark-gray color may represent an early micritic-cemented area. Cyclic bedded thrombolite boundstone to grainstone facies; platform-submerged tidal channel environment. *C*, Coarse-crystalline carbonate dolostone from the margin of a large hemispheroidal cryptalgalaminite. Whiterock dolostone facies; shallow platform interior environment. *D*, Netted fabric crystalline carbonate dolostone. Whiterock dolostone facies; shallow platform interior environment. *E*, *F*, Whiterock-clast dolostone breccias. Rock shown in *E* was later cut by fractures that are now filled by partial saddle dolomite cements. Whiterock dolostone facies; shallow platform interior environment.


A
1 cm
B
1 cm
C
2 mm
D
1 cm
E
1 cm
F
1 cm

facies. The base grades upward, commonly through burrowed peloidal grainstone, to stacked and laterally linked, hemispheroid cryptalgalaminate. Locally, some cycle tops have dololaminite and thin conglomerate of dololaminite clasts. Thin ooid or pellet packstone, nonmottled mudstone, and flat-pebble intraclast conglomerate within dololaminite are common only locally. The upper stromatolitic caps of these cycles are bleached locally.

This facies commonly overlies the CBG facies described above and in at least one instance is a lateral facies equivalent of the same. The locally bleached caps on upper bedding surfaces in this facies may grade upward to whiterock coarse-crystalline carbonate rocks and locally to white, finely laminated and mudcracked dolostone.

#### Inferred Depositional Environment

Thrombolite to stromatolite boundstone cycles were probably deposited shoreward, toward the platform interior from CBG facies. They are also interpreted as shallowing-upward sequences formed by progradation after each cycle of rapid submergence of the carbonate platform. The bases of these cycles must have been deposited at shallow subtidal or greater depths to be consistent with interpretations for origins of thrombolites (Aitken, 1967). Tops of cycles have features characteristic of intertidal flats (Logan and others, 1964; Roehl, 1967; Shinn, 1983).

An example of interrelated boundstone facies of the PBC is shown in figure 8*B*. It is a boundstone complex above the uppermost whiterock dolostone and is shown in approximate depositional strike section between the Goans, 57M2, and Shadel cores; the facies changes occur in a distance of less than 5 mi. This local series of interrelated boundstone facies is interpreted as a channel sequence (CBG) bordered by thrombolite-stromatolite boundstone from shallow subtidal to intertidal flats; the basal unit shown is thrombolite bound mudstone to packstone and grades upward to cyclic thrombolite-stromatolite. Similar complex relationships between adjacent boundstone facies are present in the Bonneterre of the Viburnum Trend but not in the Bonneterre of the Springfield quadrangle. Not all microbial boundstone was deposited in the same depositional setting; as noted earlier, columnal-branching thrombolite is present in both ramp and platform facies associations.

### Whiterock Dolostone Facies

#### Description

The term "whiterock" has been used for years in the Southeast Missouri mining district to refer to coarse-crystalline white, light-gray, or light-brown dolostone. The whiterock dolostone facies is in part the same as the "burrowed carbonate mud and planar stromatolite facies" of Howe (1968) and "back reef facies" of Larsen (1977). In the study area, whiterock dolostones are present only in the PBC, mostly in the Lebanon arch area. Net thicknesses are 0–165 ft. For the most part these rocks have no apparent preserved primary depositional fabrics, but they have ghost textures familiar from Howe (1968) that suggest they were deposited in the very shallow platform interior.

Whiterock dolostones contain three distinct rock types:

1. White to gray breccia (figs. 10*E*, *F*). Dolomite clasts are ghosts in a rehealed breccia but have light-colored margins as if they were bleached. Green clay lithoclasts are also present, and some green clay may be present as internal sediment in pre-brecciation cavities and illuviated into post-breccia vugs. These breccias are matrix supported; however, both matrix and clasts are recrystallized, commonly to a medium-grained (200–500 microns), xenotopic mosaic (Friedman, 1965) dolomite (may be type 2 dolomite as defined later). Some coarse (about 5 mm), white saddle dolomite crystals float in cavity-filling green clay matrix.

2. Netted fabric dolostone. Brown, fine crystalline (100–150 microns), hypidiotopic to xenotopic (Friedman, 1965) mosaic groundmass (type 2 dolomite as defined later) is in a network or boxwork of medium to coarse (350 microns–5 mm), white, cloudy-centered and clear-rimmed, idiotopic dolomite crystals (type 3) that locally are saddle shaped (fig. 10*D*). Green clay commonly occludes intercrystalline pores and forms the floor of vugs and connected vugs; the clay was presumably derived from clasts and cavities in overlying whiterock dolostone or from breccias described previously.

3. Various laminites. Fine-crystalline (type 2) to coarse-crystalline (3–7 mm) and porphyrotopic laminites are composed, respectively, of white xenotopic to hypidiotopic dolomite and saddle-shaped dolomite (type 3). Fine-grained dolostone commonly appears to be cryptalgalaminate or thinly layered mudstone in layers about 0.3–1 cm thick. The mudstone commonly is atop beds that comprise normally graded dolomite crystal sizes. It is mudcracked locally and may have thin interlayers of brown xenotopic mosaic dolomite (150-200 microns, type 2). Coarse crystalline laminite may not have evolved by recrystallizing fine-crystalline laminite. Fine-crystalline laminite commonly overlies thrombolite-stromatolite cyclic facies conformably and has interbedded ghost textures of laterally linked, hemispheroid, cryptalgal structures and flat-pebble conglomerate locally. Coarse crystalline laminite (fig. 10*C*) caps some whiterock breccia, commonly with apparent disconformity.

Most whiterock dolostone has gradational bleached lower contacts with facies that have reasonably well preserved primary depositional fabrics. Contacts between whiterock dolostone and overlying facies commonly are sharp and may be disconformable.

#### Inferred Depositional Environment

Whiterock dolostone is an important facies of the Bonneterre Formation in southeastern Missouri. The pinch-out of whiterock dolostone is closely associated with ore in the Viburnum Trend (Snyder and Gerdemann, 1968; Gerdemann and Myers, 1972; Larsen, 1977). Gerdemann and Myers (1972) and Grundmann (1977) recognized tidal flat characteristics in some whiterock dolostone of the Bonneterre. Whiterock dolostone is known to be present to some extent in Cambrian formations above the Bonneterre in southeastern Missouri (Howe, 1968; Gerdemann and Myers, 1972). Whiterock dolostone has a complex diagenetic (and possibly epigenetic) history (Howe, 1968; Lyle, 1977) that obscures most primary depositional fabrics.

Whiterock dolostone in the PBC of the study area is in the uppermost parts of shallowing-upward platform cycles. It contains some laminite, mudcracks, ghosts of laterally linked hemispheroid structures, and minor flat-pebble conglomerate, all of which are characteristic of tidal-supratidal flats (Roehl, 1967; Shinn, 1983). It also contains coarsely crystalline laminite and dolomite breccia that might be interpreted as caliche and vadose zone (paleokarstic) solution breccia, respectively. The platform interior position of this facies at the top of shallowing-upward cycles suggests that early meteoric diagenesis could account for some textural features that superficially resemble tidal flat laminite and even stromatolite, as evidenced by modern subaerial crusts and breccias (Esteban and Klappa, 1983; Shinn, 1983). Because whiterock dolostone has undergone extensive solution and recrystallization, including both fabric- and nonfabric-selective and other vug-creating dissolution, interpretation of preserved fabrics as depositional is suspect.

The importance of recognizing these PBC whiterock dolostones is to emphasize similarities between these PBC facies and ore-host dolostone facies of the Bonneterre in southeastern Missouri. Bonneterre ore-host dolostone is in cyclic bedded relationships with cryptalgal boundstone (Larsen, 1977), as are PBC whiterock and boundstone (figs. 8*A*, *B*).

### Light-Colored Crystalline Carbonate Dolostone Facies

#### Description

Light-colored crystalline carbonate dolostone consists of fine to coarsely crystalline (150–1,000 microns), idiotopic and hypidiotopic dolomite, and lesser interlayered xenotopic mosaic dolomite near the base. Local porphyrotopic textures consist of euhedral to subhedral dolomite (type 2 dolomite) crystals as long as 5–6 mm in a groundmass of finer crystalline dolomite. Depositional fabrics are not well preserved in the idiotopic-hypidiotopic parts of this facies, ghosts of various cryptalgal boundstones, crossbeds, and burrows being locally present. Some pre-dolomite cherts preserve thin (6 in. or less) pelletal packstone, grainstone, and mudstone, though these are not very common. Some channel cavities in this facies have quartz sandstone and (or) green clay fills. Minor fine quartzose sandstone is interlayered with light-colored crystalline carbonate rocks locally in the upper parts of sections.

This facies has been correlated regionally as the Eminence Dolomite. It is present throughout the Springfield quadrangle in the PBC and is from 140 to more than 600 ft thick.

Light-colored crystalline carbonate rocks are interlayered with a variety of other facies in the basal parts of this facies. The upper contact of this facies with the Gunter Sandstone Member of the Gasconade Dolomite marks the Cambrian-Ordovician System boundary. Dolomite of the lower part of the Gasconade is also predominantly light colored, crystalline carbonate dolostone and has textures of mostly medium crystalline (200–500 microns), idiotopic dolomite and minor medium crystalline, xenotopic mosaic dolomite.

#### Inferred Depositional Environment

Light-colored coarsely crystalline dolostone is mostly interlayered with platform interior rocks and only locally with shallow- and deep-ramp carbonate rocks. Dolostone is present in the uppermost part of the Cambrian section. The overlying basal Ordovician dolostone is also predominantly type 3 coarsely crystalline carbonate rocks and has a similar complex dolomite fabric. Though widespread, the crystalline carbonate facies of idiotopic to hypidiotopic dolomite (type 3) is probably a diagenetic or epigenetic facies. Fluctuating water tables and a succession of pore fluids of varying temperatures and compositions may account for the complex fabric.

The few, widely separated preserved ghosts of depositional fabric (fig. *10*C) are indicative of shallow platform and tidal flat deposition. These dolostones are as thick as 600 ft, however, and may contain some deep- to shallow-ramp facies, the depositional textures of which were long since destroyed by recrystallization.

Though the contact between this facies (Eminence Dolomite) and the overlying Lower Ordovician is classified herein as conformable, minor local quartz sand in formerly connected vugs in the uppermost Eminence may indicate some amount of pre-Lower Ordovician dissolution.

## CARBONATE DIAGENESIS

Detailed carbonate petrography was beyond the scope of this study, but observations made using a binocular microscope during core logging indicate a complex series of diagenetic and epigenetic features and products. Five types of dolomite are present in the study area, as have been alluded to earlier. Types 1 through 4 are groundmass dolomites. Type 1 is early diagenetic, whereas types 2, 3, and 4 are probably all later diagenetic or epigenetic. Type 5 is saddle dolomite and is clearly epigenetic. The numbering does not necessarily imply a paragenetic sequence.

Type 1 dolomite is a fine-crystalline, probably almost micron-scale (Friedman, 1965), sedimentational-fabric-mimicking dolomite. It is common in the middle parts of the lower part of the Bonneterre, rare in shale facies of the Davis Formation, and unknown in PBC dolostone upsection from shale facies. Type 1 is probably early diagenetic and replaces carbonate mud and allochems alike. It is uncertain whether the precursor carbonate minerals were aragonite, high-magnesium calcite, or calcite.

Type 2 dolomite is xenotopic-hypidiotopic mosaic dolomite, mostly brown, and has a normal crystal size of 100–500 microns. Type 2 dolomite may be the same as the basal dolomite of the Bonneterre, identified in areas near and within the study area and interpreted as an epigenetic dolomite formed by reactions with basinal brines (Gregg, 1985). Type 2 dolomite is abundant in the basal Bonneterre, upper part of the Bonneterre, and middle to lower PBC dolostone; it is rare to absent in shale facies, middle part of the Bonneterre, and upper PBC. It generally has only ghosts of primary fabric and has crystal boundaries that cut across matrix-allochem boundaries. It is also the groundmass dolomite type in netted or boxwork dolostone.

Type 3 dolomite is coarse crystalline, white to clear, and idiotopic; it locally forms the phenotopes of porphyrotopic dolostone. Type 3 dolomite crystals have cloudy centers and clear rims. Type 3 forms the "net strings" or "boxes" in netted fabric dolostone within whiterock dolostone facies. Time relations between types 2 and 3 are unclear.

Type 4 dolomite is idiotopic, generally 150–1,000 microns, cloudy centered, and clear rimmed; it is mostly in the uppermost Cambrian and basal Ordovician. It may be related to type 3 dolomite. Strongly ferroan, zoned idiotopic dolomite, yet another dolomite type described from this region (Gregg, 1986; Freeman and Medary, 1987), is known to precede the basal Bonneterre xenotopic epigenetic dolomite of Gregg (1985) but was not recognized in the course of logging for this study.

Type 5 dolomite is a regional epigenetic dolomite that postdates types 3 and 4 and is present in intercrystalline mesopores, vugs, and solution-enlarged fractures. It is a complexly iron- and manganese-zoned saddle dolomite that is tan to white or clear to pink. It has a regionwide cathodoluminescent microstratigraphy and is inter-ore to post-ore in age in southeast Missouri Bonneterre orebodies (Rowan and others, 1985; Voss and Hagni, 1985). Within the study area, type 5 is common only in the PBC. It is followed in time by scalenohedral calcite.

Silica minerals can be related in time to the five types of dolomite. "Early" fabric-mimicking chert formed before types 2, 3, and 4 dolomites. "Late" siliceous mineralization of (1) dark microcrystalline quartz, (2) chalcedony, and (3) megaquartz followed a dissolution event after type 4 dolomite. Late siliceous minerals are in mesospores, vugs, and solution-enlarged fractures. Early chert is mostly in upper PBC dolostone. Late siliceous minerals are sparse in lower PBC dolostone, abundant in middle PBC dolostone, and mostly dark microcrystalline quartz in upper PBC rocks.

Regionwide fracturing and dissolution occurred prior to precipitation of type 5 dolomite and late siliceous mineralization. Late siliceous minerals both precede and are interlayered with type 5 dolomite as crustifications on vug and fracture walls. Regional sulfide genesis also follows the same regional fracturing and dissolution event and is in part coeval with type 5 dolomite.

Regional dolomitization in the Bonneterre and the abundance of type 5 dolomite in the PBC approximately correlates with the distribution of Davis Formation shale facies in the study area. This distribution also roughly correlates with the limestone/dolomite distribution of underlying Bonneterre because the 0-percent limestone isolith in the Bonneterre is beneath the Davis Formation shale facies but very near the area where the Davis changes from shale facies to dolostone ramp facies of the PBC. The Bonneterre may be either limestone or dolostone where the overlying Davis is shale, but it is dolostone where the overlying Davis equivalent is dolostone. Type 5 dolomite is abundant in the PBC, particularly in the southern Lebanon arch area where the Davis shale facies is absent. PBC rocks above shale facies have a zonation of late siliceous cements beginning with sparse megaquartz in the lower part of the PBC, grading upward to abundant microcrystalline quartz, megaquartz, and chalcedony in the middle PBC, and dominated by microcrystalline quartz in the upper PBC.

These diverse diagenetic and epigenetic products and features demonstrate a complex postdepositional history for the PBC. Bonneterre facies within the study area do not have as complex a history and in fact generally lack vuggy porosity. In contrast, Bonneterre facies near the Viburnum Trend have a complex diagenetic history (Lyle, 1977; Gregg, 1985; Voss and Hagni, 1985). In the Springfield quadrangle, only PBC rocks have a correspondingly complex, but not necessarily identical postdepositional history.

## DEPOSITIONAL HISTORY

The distribution of Cambrian lithofacies strongly suggests basement-topographic control of regional features such as the Lebanon arch and the flanking Central Missouri basin and Greenfield basins (figs. 4*A*-*C*). Initial Late Cambrian sedimentation was in an alluvial fan–fluvial plain system; alluvial fans developed around low hills in the north-central part of the quadrangle and passed laterally to a braided fluvial plain (fig. 11*A*). Drainage across the plain may have been southeasterly (Houseknecht and Ethridge, 1978; Yesberger, 1981). Local dune fields may have developed within this fluvial plain.

In the first Late Cambrian transgression (referred to as T1, time 1, for discussion here), burrowed tidal flat and shoal sandstone facies were distributed disconformably across the middle part of the Lamotte. The clastic shelf facies of the upper part of the Lamotte were in turn overlain by basal Bonneterre ramp-dominated facies. This may mark an early Dresbachian transgression (T2a) that was followed by development of widespread ooid-skeletal bank facies of the middle part of the Bonneterre in the Lebanon arch and shallow- to deep-ramp facies in the Central Missouri and Greenfield basins (fig. 11*B*). The siliciclastic nature of westernmost equivalent facies of the lower part of the Bonneterre indicates that a clastic shelf bordered the Greenfield basin on the west (see fig. 11*B*). T2a initiated the widespread development of shallow intrashelf basin facies, across which the western clastic shelf facies and Lebanon arch platform and ramp prograded. A somewhat later and minor transgression (T2b) may be indicated by ramp-facies onlap of ooid-skeletal bank deposits (fig. 8*A*) in drill hole 63W89. After T2b, ooid-skeletal bank and shallow ramp facies prograded across a large part of the quadrangle (fig. 7, 50-percent level Bonneterre slice map; figs. 8*A*, *B*).

A late Dresbachian transgression (T3a, upper *Crepicephalus* Zone) began in the upper lower part of the Bonneterre and is indicated clearly by a subregional disconformity across the ooid-skeletal bank. T3a culminated in another drowned shelf by *Aphelaspis* Zone time and apparently coincided with filling of the Bonneterre-time Greenfield basin, which perhaps allowed a thin blanket of clastic sediments to spill eastward across the shelf. PBC intrashelf basin development began near the Dresbachian-Franconian boundary (T3b), possibly at the *Aphelaspis-Apsotreta* Zone boundary.

Differential subsidence at about T3b may have allowed ramp and platform facies to nucleate in separate areas on the Lebanon arch and locally in the northwestern and southwestern corners of the quadrangle, and deeper water deposition began in the Central Missouri and Greenfield basins.

Prograding ramp and platform facies in the PBC locally are disconformably overlain by ramp ribbon facies (fig. 8*A*, drill cores NS–4 and NS–5 and perhaps M1J1 and NS–1). This subregional middle-upper Franconian transgression (T4) may indicate that PBC intrashelf basins perhaps even expanded at times during the Franconian.

Following T4, PBC ramp and platform facies prograded across intrashelf basin areas (figs. 7, 11*C*) outward from the Lebanon arch. This shoaling trend continued through the rest of the Cambrian (Franconian and Trempealeauan). Small-scale shallowing-upward cycles within platform boundstone facies are related to progradation and cyclic rapid subsequent submergence and are late Franconian (?) and Trempealeauan. Interbedded and possibly disconformable relationships between platform boundstone and whiterock dolostone (fig. 8) may indicate an early Trempealeauan age. Possibly two of these larger scale regressive-transgressive cycles are present in the PBC.

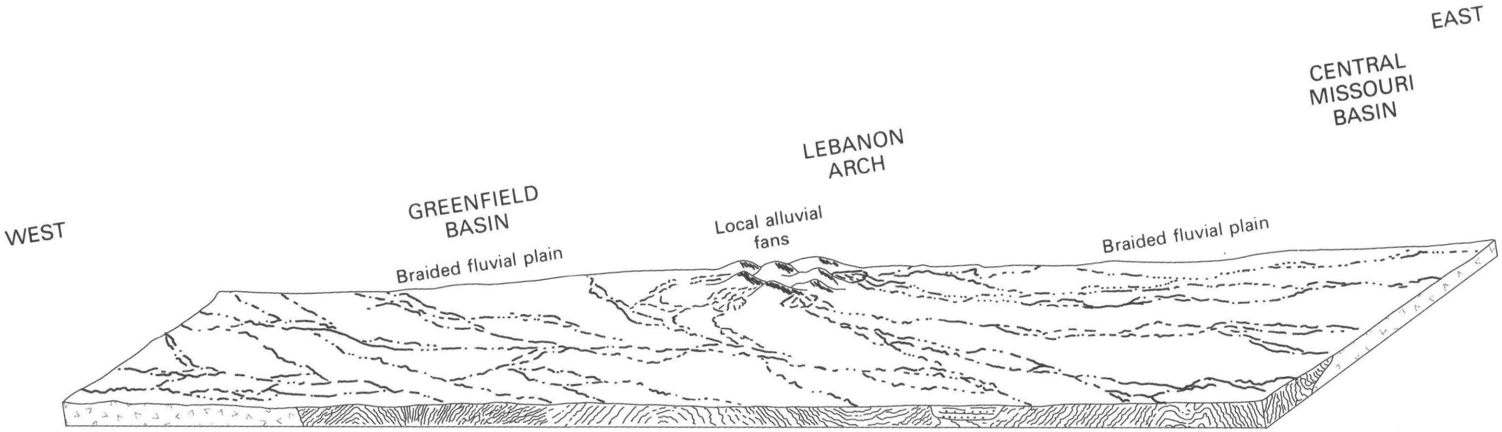
The Cambrian is shown thickening to the south and east (fig. 3), consistent with interpreted down-to-the-southeast subsidence in Bonneterre time (Larsen, 1977). Lamotte thicknesses, however, reflect thickening adjacent to the Lebanon arch and in the northwestern part of the quadrangle. The Bonneterre in the quadrangle thickens from the west to northeast and southeast. The PBC is thickest along the Lebanon arch and thins to the west and east across the Central Missouri and Greenfield basins. Regional subsidence seems to be more complicated than a uniform down-to-the-southeast sagging.

## FACIES ARRANGEMENTS SIMILAR TO THE BONNETERRE FORMATION IN THE VIBURNUM TREND

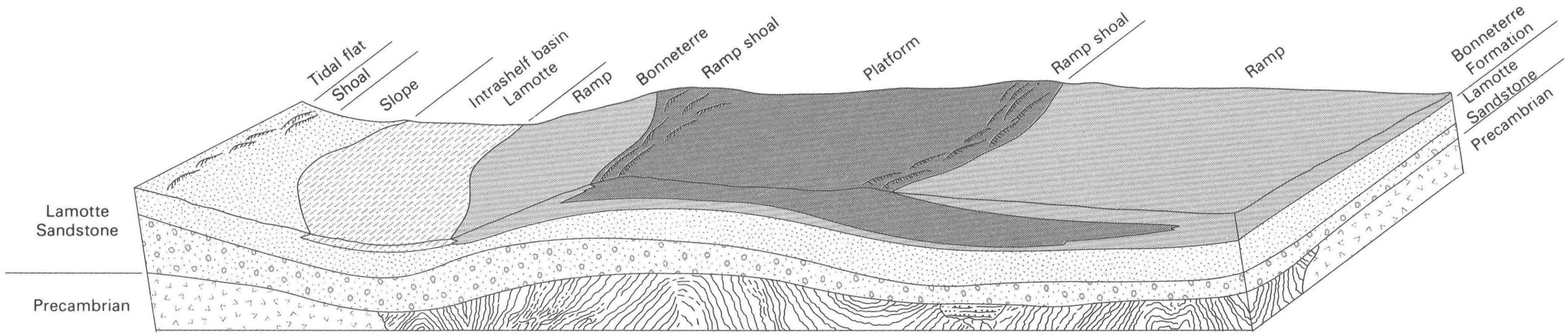
Facies arrangements strikingly similar to those of the Bonneterre Formation of the Viburnum Trend are found in the PBC along the east and west flanks of the Lebanon arch.

1. Platform interior boundstone and whiterock dolostone disconformably overlain by ramp facies rocks are present in drill core NS–5 (fig. 8*A*) and other western Lebanon arch drill cores (the disconformity marks the T4 transgression). In the Viburnum Trend, considerable ore is found in offshore facies rocks (probably deep to shallow ramp) that disconformably overlie a dominantly regressive sequence of grainstone, boundstone, and whiterock dolostone (Evans, 1977; Mouat and Clendenin, 1977; Sweeney and others, 1977). The PBC facies on the western flank of the Lebanon arch lack the capping shale found in the Viburnum Trend.
2. Platform cycles of prograding boundstone overlain by whiterock dolostone are common within the PBC of the Lebanon arch and are also recognized in the Viburnum Trend (Larsen, 1977).
3. Smaller scale cycles of prograding cyclic platform boundstone to whiterock to boundstone are present in the PBC (fig. 8*B*, Goans, 57M2 and Shadel drill cores). Similar cycles probably are present in the Viburnum Trend (Larsen, 1977; Mouat and Clendenin, 1977).

Thus, the PBC facies are interbedded ramp and platform types similar to the Viburnum Trend ore-hosting dolostone. PBC dolostone also contains locally abundant ore-stage type 5 gangue dolomite and marcasite-pyrite. From among the drill cores logged for this study, the most interesting and complex facies and mineral associations are in the southern Lebanon arch at both of its margins. These cores have the thickest sections of very broadly interbedded intrashelf basin shale and limestone, ramp dolostone, and


WEST
GREENFIELD BASIN
LEBANON ARCH
CENTRAL MISSOURI BASIN
EAST
Braided fluvial plain
Local alluvial fans
Braided fluvial plain

A


Tidal flat
Shoal
Slope
Intrashelf basin
Lamotte
Ramp
Bonneterre
Ramp shoal
Platform
Ramp shoal
Ramp
Bonneterre Formation
Lamotte Sandstone
Precambrian
Lamotte Sandstone
Precambrian

B

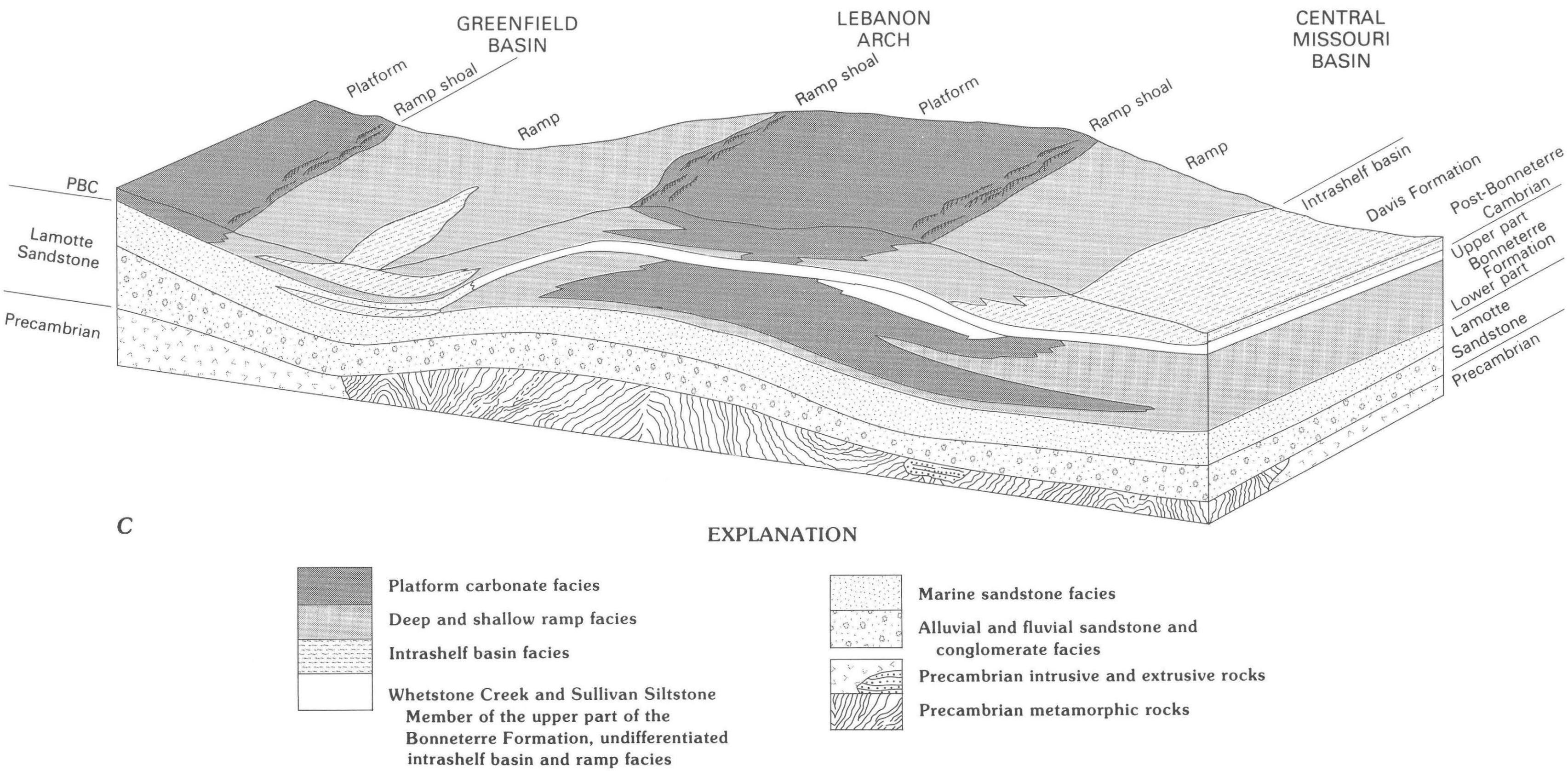



**Figure 11.** Block diagrams illustrating the development of the Cambrian stratigraphic sequence resulting from the interpreted depositional framework for the Springfield 1°×2° quadrangle. Not to scale. *A*, Basal Lamotte Sandstone. Most areas on the surface of the Precambrian were probably beveled to relatively low relief prior to deposition of the basal Lamotte Sandstone. The low knobs that remained in the north-central part of the quadrangle generated arkosic and hematitic alluvial fan deposits. These grade laterally into a quartzose-dominated braided fluvial plain. Regional drainage across the plain may have been to the southeast (Houseknecht and Ethridge, 1978; Yesberger, 1981). *B*, Lower part of Bonneterre Formation. This diagram represents approximately the upper part of the lower part of the Bonneterre Formation, just before the T3a transgression and deposition of the clastic-dominated, middle-shelf Sullivan Siltstone and Whetstone Creek Members of the Bonneterre. Three distinct regional paleodepositional elements are apparent. The Lebanon arch in the central part of the quadrangle has shallow ramp and shoal or subtidal platform carbonate rocks, whereas the Central Missouri basin has only deep ramp or shallow ramp carbonate rocks. Shale facies (shale with thinly interbedded sandstones) in the Greenfield basin grade westward into progradational shallow shelf sandstones (unnamed shelf area). *C*, Lower post-Bonneterre Cambrian (PBC). Following the T3 transgression, the Lebanon arch area again became the site of shallow ramp and platform carbonate deposition. These ramp and platform sediments prograded across intrashelf basin shales in the Central Missouri and Greenfield basins. Shallow ramp carbonate rocks may also have been deposited in the far western part of the quadrangle and prograded eastward into the Greenfield basin. The minor T4 transgression locally superposed shale facies and ribbon rock facies over shallow ramp and platform carbonate rocks. Shoaling continued after the T4 transgression throughout the Late Cambrian. Differential subsidence across the Lebanon arch and in the Central Missouri basin contributed to thicker Cambrian sequences in those areas.

cyclic platform dolostone, as well as complex diagenetic-epigenetic features and products.

## CONCLUSIONS

1. Fourteen lithofacies were identified and mapped in the subsurface Cambrian Lamotte Sandstone, Bonneterre Formation, and post-Bonneterre Cambrian rocks (PBC) of the Springfield quadrangle. These facies are arranged mostly in north-south tracts. The depositional trends define the location of the Lebanon arch across the middle of the quadrangle, flanked by the Central Missouri and Greenfield basins east and west of the arch. The northwestern and southwestern corners of the quadrangle are dominated by shallow-shelf and platform-type rocks in the Cambrian similar to those of the Lebanon arch.

2. The lower sandstones of the Lamotte are alluvial fan dominated and hematitic near the Lebanon arch. They grade laterally and upward to dominantly quartzose, braided fluvial plain sediments that blanketed the entire quadrangle. Though Lamotte pinchouts at Precambrian knobs are not known from available drill holes, the Lebanon arch area is the most likely area in which to find a pinchout. Upper sandstones of the Lamotte are mostly shallow shelf sandstones and some barrier and tidal flat sandstones. The contact between these lower nonmarine and upper marine Lamotte facies is recognized as the initial Late Cambrian marine transgression (T1).

3. Regional drowning of the Lamotte shallow shelf led to widespread glauconitic and muddy Bonneterre carbonate ramp-style sedimentation. The contact between the Lamotte and the lower part of the Bonneterre is conformable but may represent a gradual, early Dresbachian transgression (T2a). In the western third of the quadrangle, upper sandstones of the Lamotte are laterally equivalent to the Bonneterre of southeastern Missouri (Kurtz and others, 1975) and to Bonneterre-age shale facies within the Greenfield basin. Westernmost Dresbachian sandstones of the upper part of the Lamotte are conformably overlain by PBC ramp dolostones that represent the beginning of the most widespread of the Cambrian transgressions—an early Franconian transgressive and shelf-drowning event (T3b).

4. Bonneterre and PBC facies record two major periods of intrashelf basin development in the Dresbachian and Franconian. These shallow basins of mixed shale and carbonate rocks grade laterally to prograding homoclinal carbonate- ramp- and -platform–style sedimentary rocks. Locally these ramps varied to distally steepened ramps, ramps with fringing banks, and ramps with isolated down-slope buildups (classification of Read, 1985). In the Springfield quadrangle the Bonneterre lacks intertidal facies and instead has a series of ooid-skeletal banks as the shallowest deposits of its ramp. PBC facies include well-developed shallow subtidal, intertidal, and supratidal carbonate dolostone deposited behind a generally thin shoal facies. These platform dolostones are arranged in small-scale and large-scale cyclic sequences. These carbonate-ramp sedimentational models can be used successfully to predict specific Cambrian lithofacies targets.

5. The PBC has an extensive and complex diagenetic and epigenetic history, as compared to the Bonneterre of the Springfield quadrangle. Epigenetic ore-stage gangue dolomites and iron sulfide minerals are common to abundant in PBC platform dolostone across the southern Lebanon arch area.

6. Facies most similar to the dolostones that host southeastern Missouri Mississippi Valley–type ores are found in the PBC of the Springfield quadrangle. The Bonneterre Formation in the Springfield quadrangle has very few similarities to Bonneterre rocks of southeastern Missouri.

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# Examples of Graphical Data Displays Used in the Resource Study

*By* John O. Kork

## INTRODUCTION

Spatial multivariate data are now routinely generated in large quantity in regional mineral-resource investigations. In addition, geologists rely heavily on graphical representations of these data. To support this activity, a variety of computer-generated graphical data displays was produced as part of the resource study of the Springfield 1°×2° quadrangle.

The programs used to generate the graphic data displays were written in BASIC and C for microcomputers compatible with an IBM personal computer and contain no proprietary code. The displays include annotated point plots, simultaneous display of geochemical analyses for drill-core data, and three-dimensional representations of the extent of dolomite in Cambrian rocks.

## DATA

Subsurface data for the Springfield quadrangle were obtained in two data sets: a set of more than 700 water-well logs and interpretations, and a set of analyses for as many as 32 geochemical variables from more than 50 cores. The water-well data were received from the Missouri Geological Survey on forms and entered into a microcomputer data base via keyboard. The borehole geochemical data were retrieved from the U.S. Geological Survey (USGS) RASS (Rock Analysis Storage System) data base in USGS STAT-PAC form on the USGS, Denver, MULTICS system and transferred to a microcomputer via telephone and modem.

The variables recorded for the water-well logs are hole location, collar elevation, depth to the top of each stratigraphic unit, and, for each unit, percent of clastic, carbonate, sandstone, shale, limestone, dolomite, chert, and silt. The borehole geochemical data include hole location and analyses for as many as 32 geochemical variables at 10-ft intervals down the hole. The quantity of data in these data sets can be imagined by considering that a typical record for one water well contains about 200 numbers and a typical core record contains about 5,000 numbers. Assimilation of all these numbers and the search for relationships between variables representing originally recorded values and artifically calculated values such as thicknesses and ratios are extremely difficult, and graphical displays of spatial relationships are therefore essential.

## LOCATIONS AND VALUES IN TWO DIMENSIONS

Geologists have traditionally used map overlays of spatial data in their work. These map overlays are constructed by calculating the value of a variable of interest for each location, plotting a symbol at the location, and placing the value next to the symbol. Contour maps that summarize the spatial distribution of the values are then constructed. If there are very many locations or variables, the time required to construct these maps limits the number of variables that can be considered. The time and effort saved when these maps are generated automatically by a computer allows the geologist to examine many more aspects of the data than is possible when the work is done by hand.

For the Springfield CUSMAP project, three types of maps of the water-well log data were constructed for each variable of interest: an annotated point plot, a contour map constructed from gridded data, and a contour map constructed using triangularization of the original data. More than 50 variables were considered and more than 150 maps were drawn. Maps showing the elevation of the top of each stratigraphic unit in the quadrangle (structure contour maps) and isopachs of each unit and of combinations of units were produced. For selected units and combinations of units, the values of the numeric variables in the data set and of certain ratios of these variables were also plotted. Two ratios of particular interest are the sandstone-mudstone and clastic-carbonate ratios.

For each variable of interest, a separate ASCII data file containing the location and the value to be plotted at that location was generated and an annotated point plot produced. The data in each of these files were then gridded using a weighted-average gridding algorithm, and contour maps of the gridded data were constructed. In addition, contour maps were constructed using a modification of a Voronoi triangle contouring algorithm described in Watson (1982). Overlaying the contour maps on the point plots allows the geologist to see the original data along with the spatial summary provided by the contour maps. Figures 12 and 13 show examples of these maps, in highly reduced form so that they can be displayed on a single manuscript page. The working maps corresponding to figures 12 and 13 are 31 by 22 in. in size, and at full scale the annotation is legible.

The maps constructed using the Voronoi triangularization method, although not as smooth and attractive as those generated from the weighted-average grid files, are quite informative for data analysis because they show the contours corresponding to exact linear interpolation between original data points. No intermediate modification of the data, such as gridding, was performed. Methods exist to smooth these contours, but it was decided that adherence to the exact data values provides more information to the geologist about the relationships between the data values themselves.

## PERSPECTIVE PLOTS OF GRIDDED DATA

Perspective surface plots in three dimensions can provide spatial summaries of areal data that can be quickly absorbed and compared. Both large-scale trends and local anomalies can be quickly perceived. Figure 14 is a perspective plot of the data shown in the contour maps in figures 7 and 8 and was drawn using a modification of ACM algorithm 483 as described by Watkins (1974). The viewing angle for the perspective plot is S. 30° W., with an angle of elevation of 15°.

Each of the gridded data files constructed for the Springfield quadrangle studies was plotted as a perspective

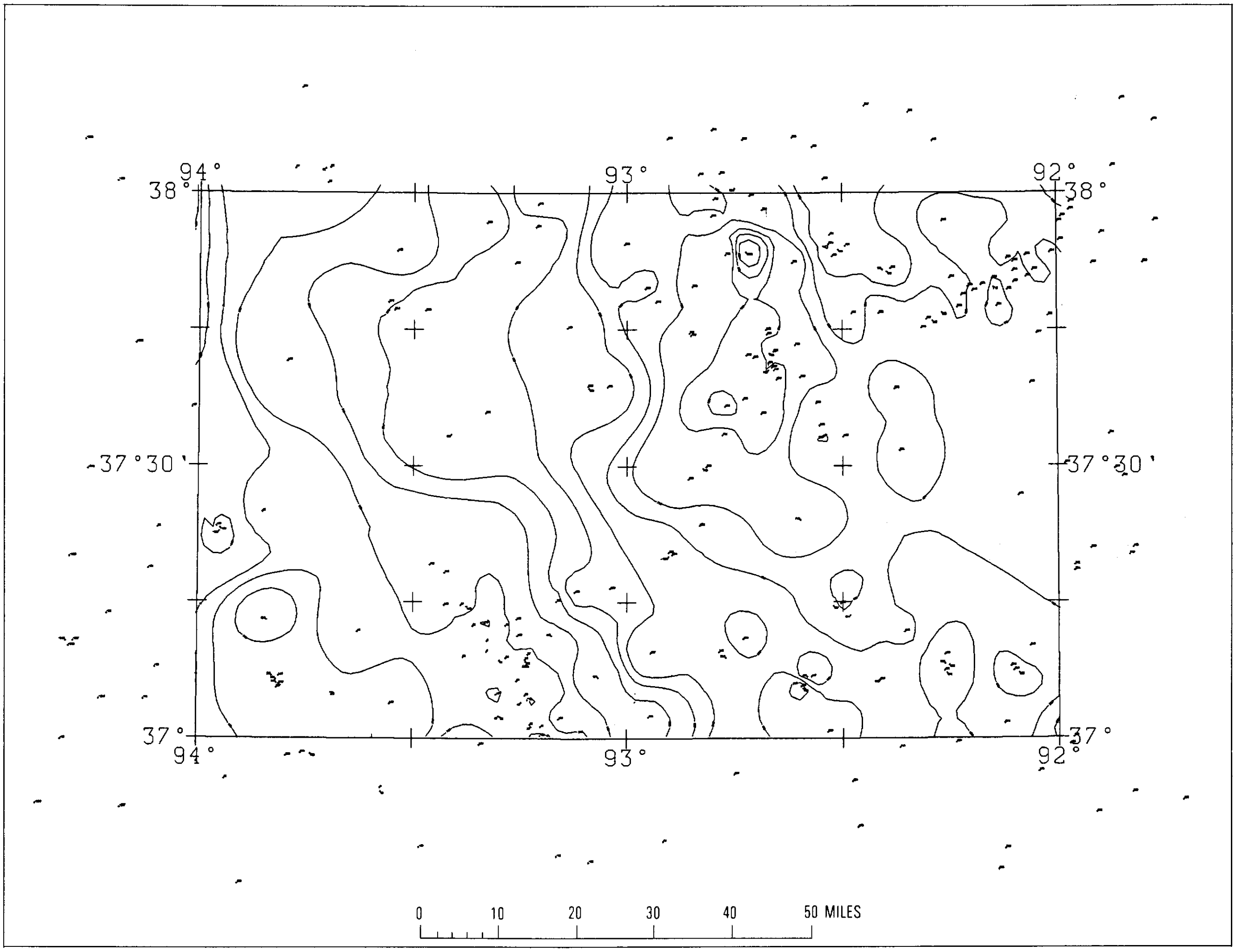


**Figure 12.** Annotated point plot and gridded contour plot of the elevation of the top of the Cambrian in the Springfield 1°×2° quadrangle, plotted at a scale to show general appearance only. Contour levels are from -200 to 1,000 ft in steps of 100 ft.

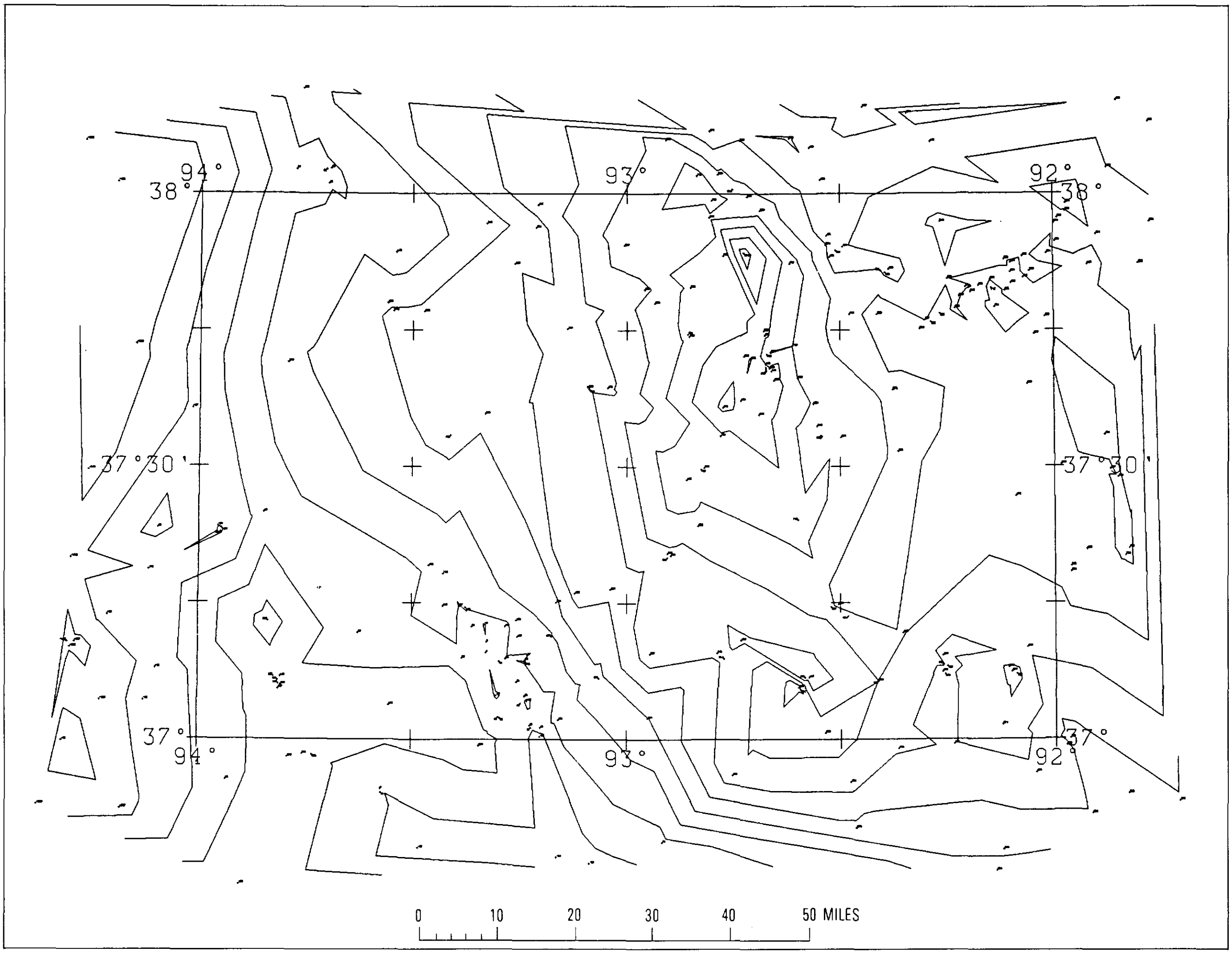


**Figure 13.** Annotated point plot and triangularization contour plot of the elevation of the top of the Cambrian in the Springfield 1°×2° quadrangle, plotted at a scale to show general appearance only. Contour levels are from -200 to 1,000 ft in steps of 100 ft. .

surface plot. If some features of the surface were hidden because of the choice of three-dimensional viewpoint, a number of such plots was made using different viewpoints.

## PLOTS OF BOREHOLE GEOCHEMICAL DATA

The core geochemical data consisted of analyses of as many as 32 geochemical variables at 10-ft intervals down each of 50 boreholes. To help the geologists find relationships between these data a program was written to display the magnitude of all the analyses for a hole on one plot.

The plot consists of a rectangular area with annotation along all four sides of the rectangle, as shown in figure 15. The annotation along the left side represents the depth from the surface in feet. The annotation along the top and bottom sides specifies the name of the STATPAC variable and the range of measured values for each of the variables analyzed. Because the plotting system was not programmed to plot percent (%) signs, a question mark was used instead for plotting the variable ID. Along the right side the names of stratigraphic units are plotted, and lines representing the depths of the contacts are drawn horizontally across the rectangular area.

The rectangular area is divided into 32 equal rectangular subareas within which vertically oriented curves are drawn. The boundaries of these subareas are omitted so that the relationships indicated by these 32 curves can be more easily perceived. The left boundary of each subarea represents the minimum measured data value for the variable being plotted in the subarea, and the right boundary represents the maximum measured value. Each individual measurement is scaled so that the magnitude of the measurement is represented by the horizontal distance

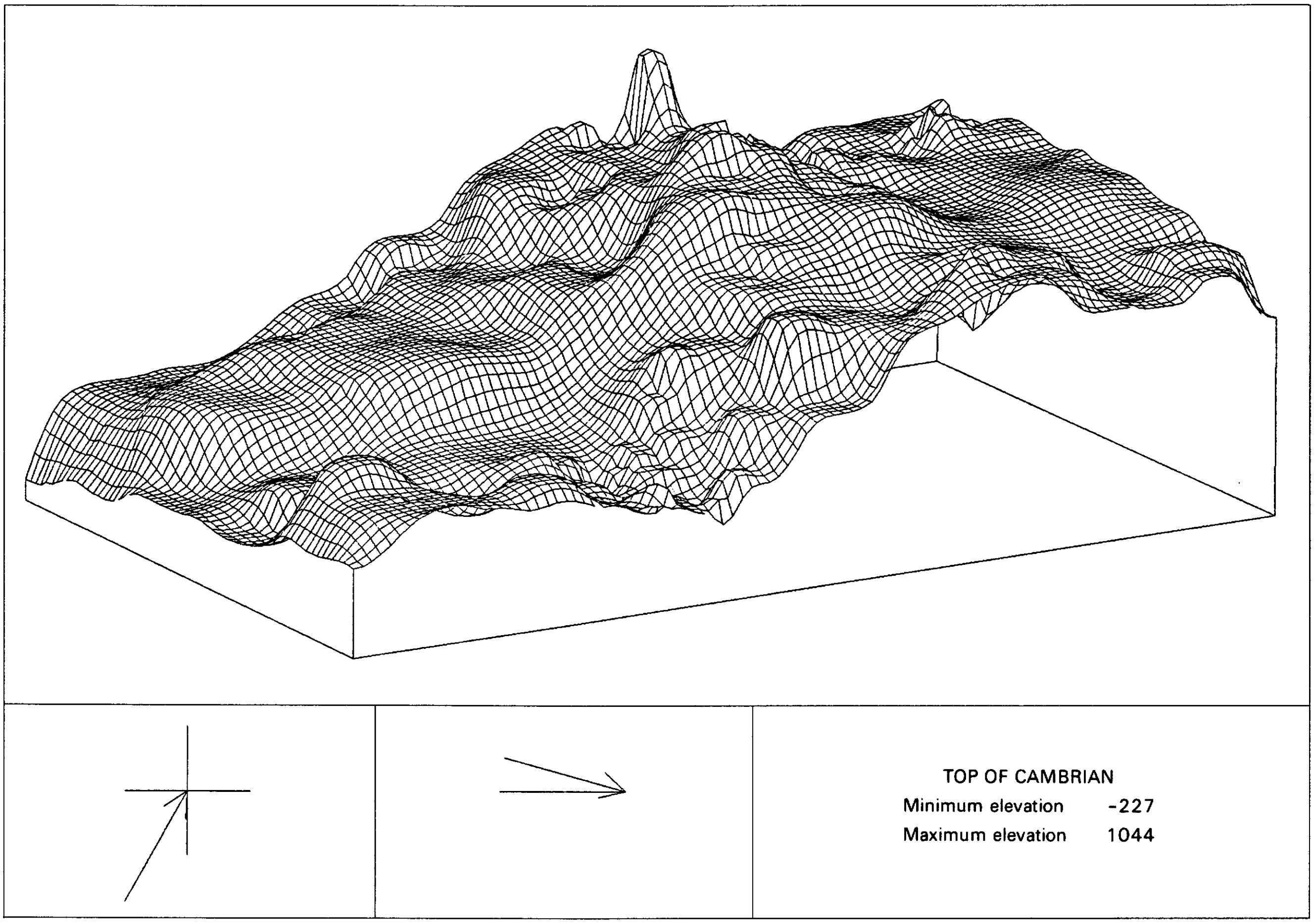


**Figure 14.** Perspective plot of the elevation of the top of the Cambrian in the Springfield 1°×2° quadrangle. Viewing angle is from S. 30° W., with an angle of elevation of 15° as shown by the arrow diagrams at the base of the plot. Elevations in feet.

between the left boundary and a point plotted at the corresponding depth. These plotted points are then connected to produce a vertically oriented curve that represents the relative magnitude of the variable as a function of depth from the surface. If the data for all 32 variables are displayed on the same plot, combinations of geochemical anomalies at a particular depth or within a particular stratigraphic unit can be identified.

## THREE-DIMENSIONAL PLOTS OF THE EXTENT OF DOLOMITE IN CAMBRIAN ROCKS

The spatial extent of dolomite within Cambrian rocks was of interest to the geologists studying the Springfield quadangle. Thirteen maps of the extent of dolomite within certain subintervals of Cambrian stratigraphic units were drawn by hand. The dolomite boundaries were then digitized, and the resulting files of boundary data were structured in a manner similar to the GIRAS file format described in Fegeas and others (1983). Two types of three-dimensional plots representing the extent of dolomite were constructed. An attempt was made to show the actual position of the dolomite in space, but the calculating and plotting precision available was not sufficient to show anything but a noninformative jumble on the resulting plot. Hence, the subintervals were drawn as if they were all the same thickness and were all oriented as horizontal planes in space.

The first type of plot, shown in figure 16, was constructed by drawing 13 two-dimensional maps of the dolomite boundary and filling the areas representing dolomite. These plots were then placed in a three-dimensional plot and ordered vertically to show the sequence of subunits in order. The viewing point for the

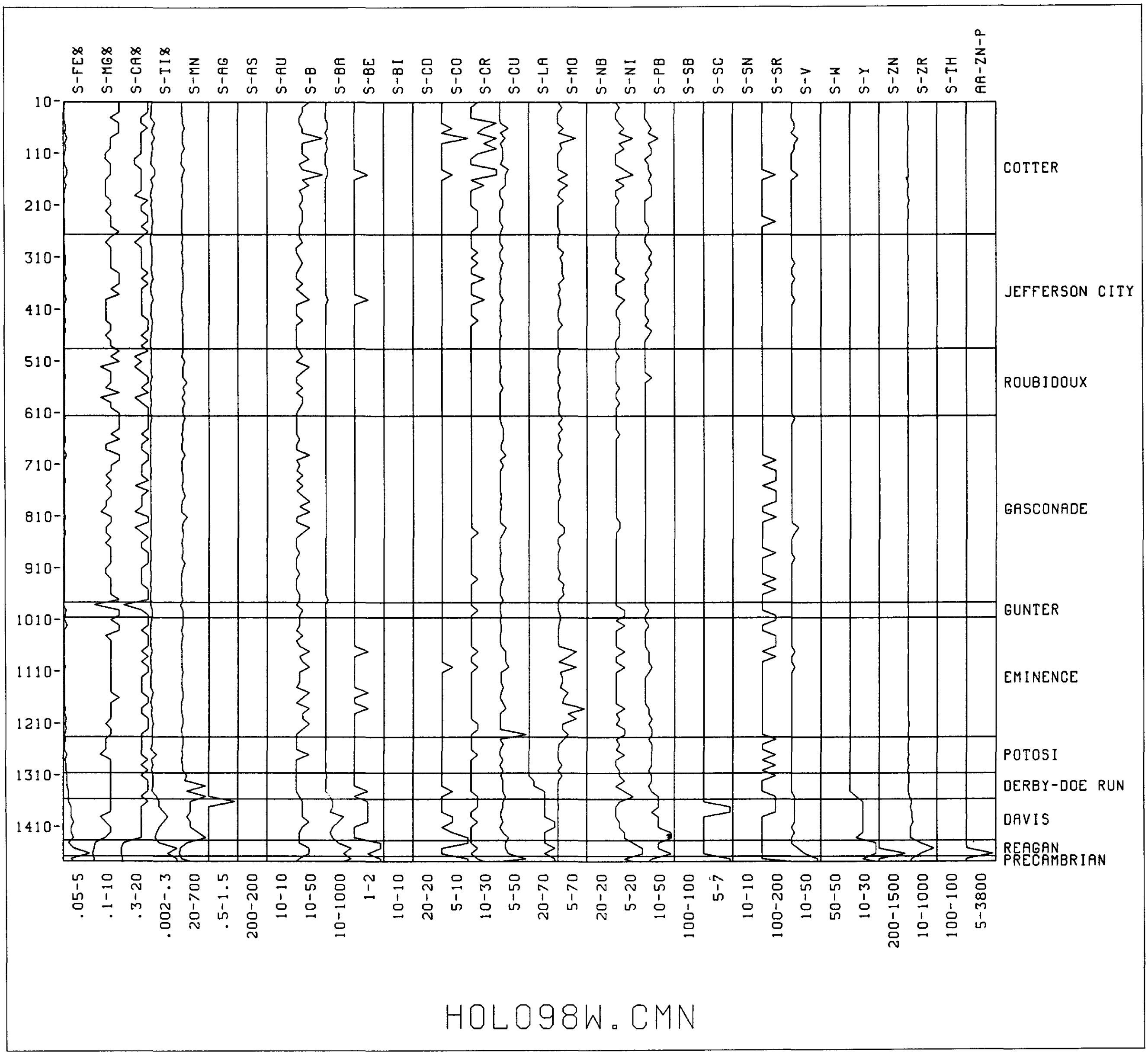


**Figure 15.** Borehole geochemistry plot showing the elevation of the tops of stratigraphic units and 32 geochemical variables simultaneously. Depth from the surface (in feet) is shown along the left side; STATPAC variable ID is shown at the top; range of values is shown at the right. The name of the computer file containing the data is shown at the bottom of the plot.

three-dimensional plot is from the direction S. 30° E., with an angle of elevation of 15°. Names of the subintervals are shown to the right of the subunit map.

The second type of plot was constructed by calculating a model of the dolomite consisting of a three-dimensional rectangular block of cells, each cell containing a 0 or 1. The value 1 represents the presence of dolomite, and the value 0 represents the absence of dolomite. Plots of this model were then drawn using a modification of ACM algorithm 475 as described in Wright (1974).

Figures 17–21 show examples of the plots of the dolomite model. The three boxes below the actual picture contain information about the viewing angle and the stratigraphic boundaries shown in the plot. The left box shows the horizontal viewing angle graphically. Viewing angles for figures 17–21 are S. 30° E., S. 30° E., S. 30° W., N. 30° W., and N. 30° E., respectively. The angle of elevation of the viewpoint is shown in the middle box. The viewing angle for figure 17 is 15° above the horizontal, and the viewing angle for the other four plots is 10° below the horizontal. The right box gives the name of the interval between the corresponding contacts that are indicated by letters on the plot.

## CONCLUSION

Examples of graphical displays of multivariate spatial data used in the mineral-resource study of the Springfield 1°×2° quadrangle were discussed. Because these displays can be produced quickly, easily, and inexpensively using a microcomputer, relationships can be easily investigated that might have to be ignored if the displays had to be drawn by hand.

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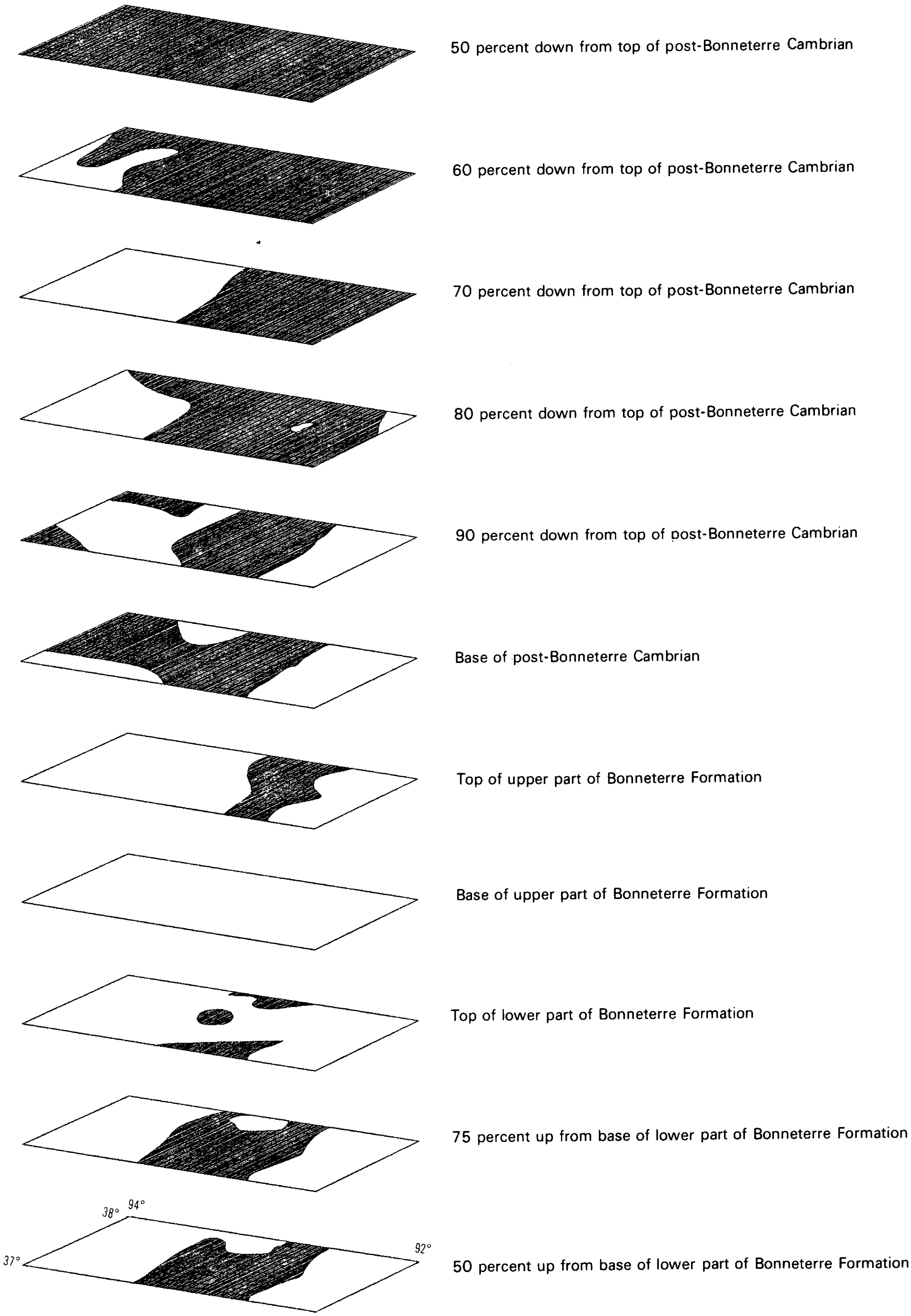


**Figure 16.** Simultaneous display of 11 shaded maps showing the extent of dolomite at a sequence of stratigraphic levels in Cambrian rocks in the Springfield 1°×2° quadrangle. The levels are identified at the right. Viewing angle is from S. 30° E., with an angle of elevation of 15°.

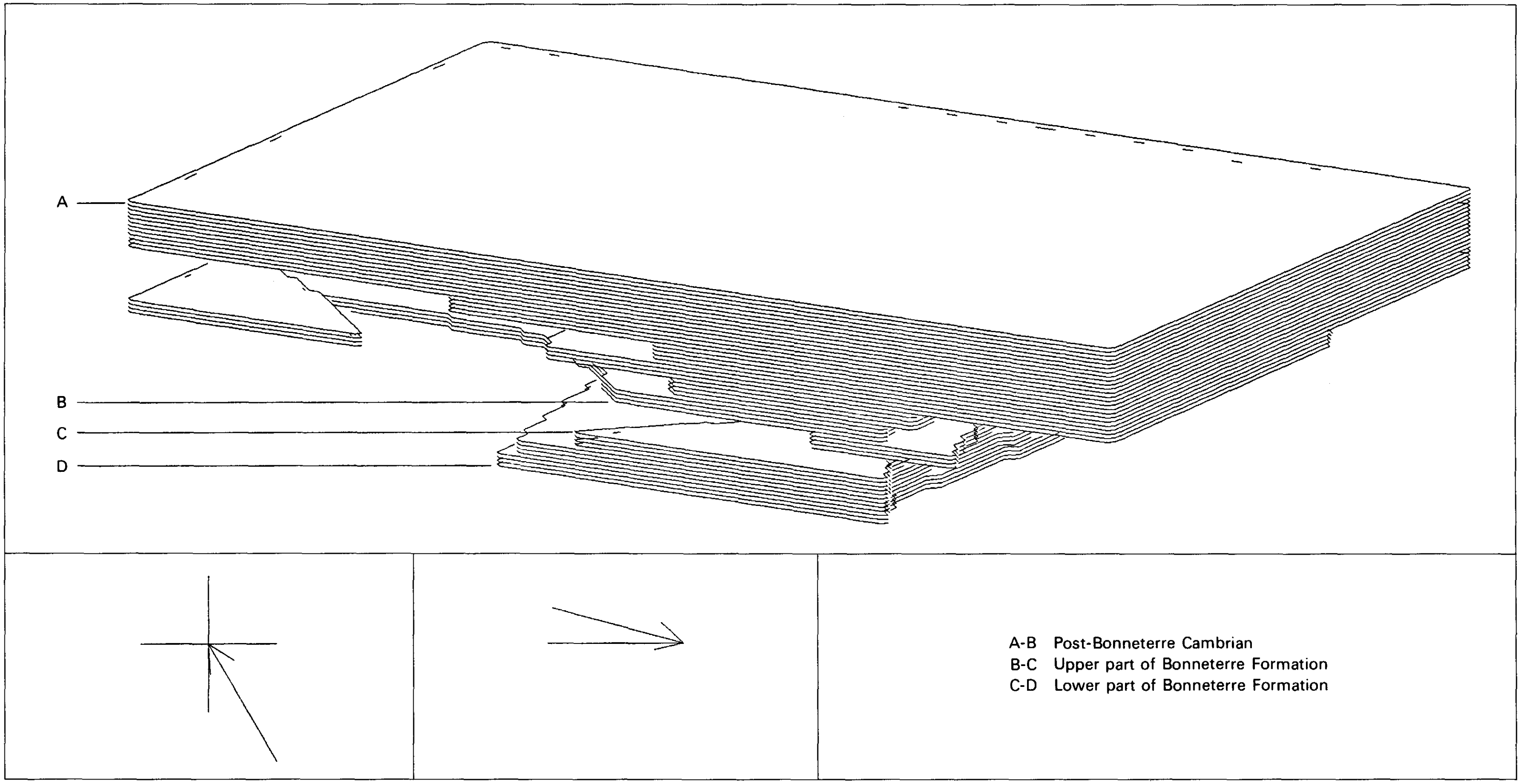


**Figure 17.** Perspective plot of an idealized three-dimensional model of the extent of dolomite in Cambrian rocks in the Springfield 1°×2° quadrangle. The model assumes that all levels shown are horizontal and that the sequence of intervals is equally spaced. Viewing angle is from S. 30° E., with an angle of elevation of 15°.

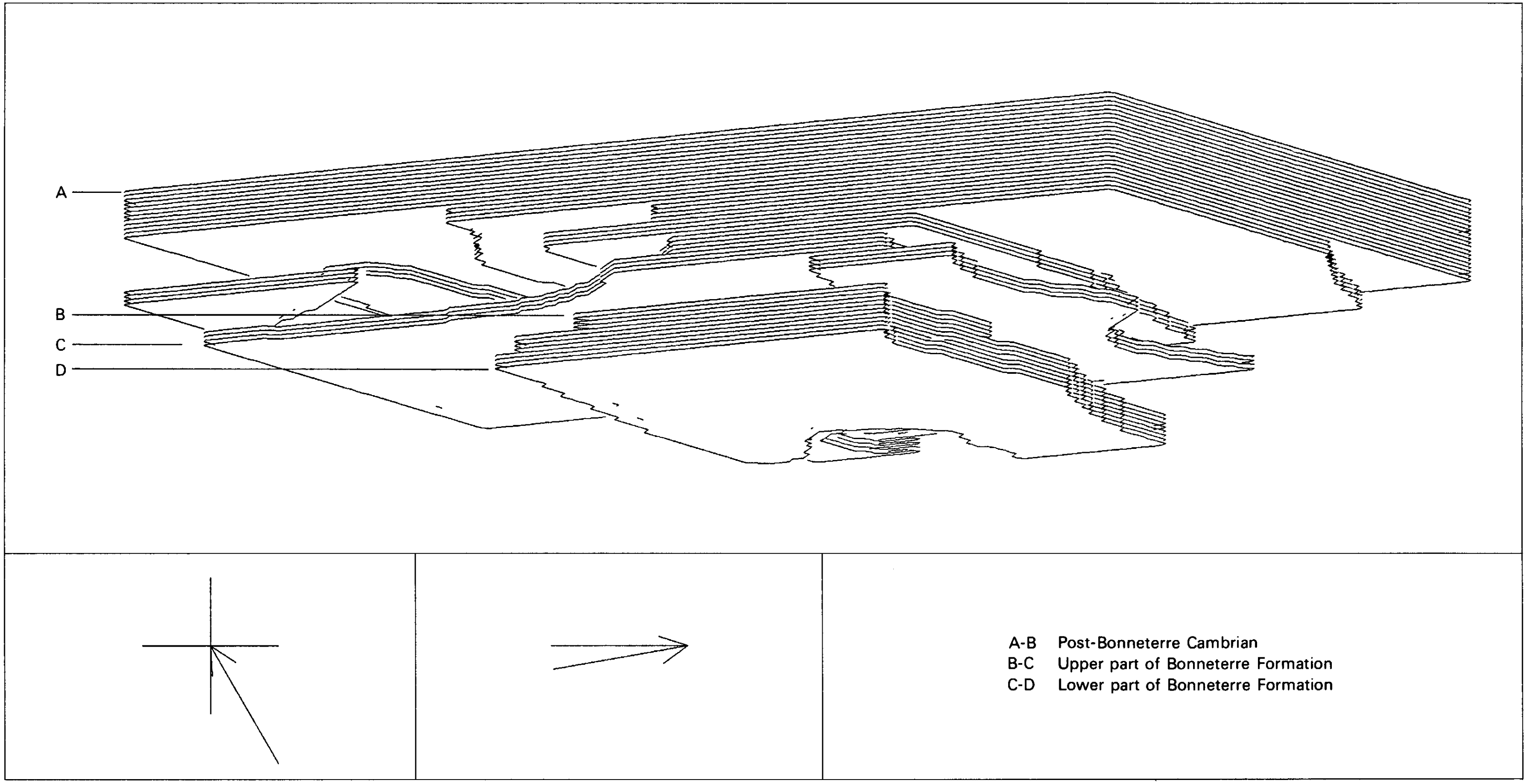


**Figure 18.** Perspective plot of an idealized three-dimensional model of the extent of dolomite in Cambrian rocks in the Springfield 1°×2° quadrangle. The model assumes that all levels shown are horizontal and that the sequence of intervals is equally spaced. Viewing angle is from S. 30° E., with an angle of elevation of -10°.

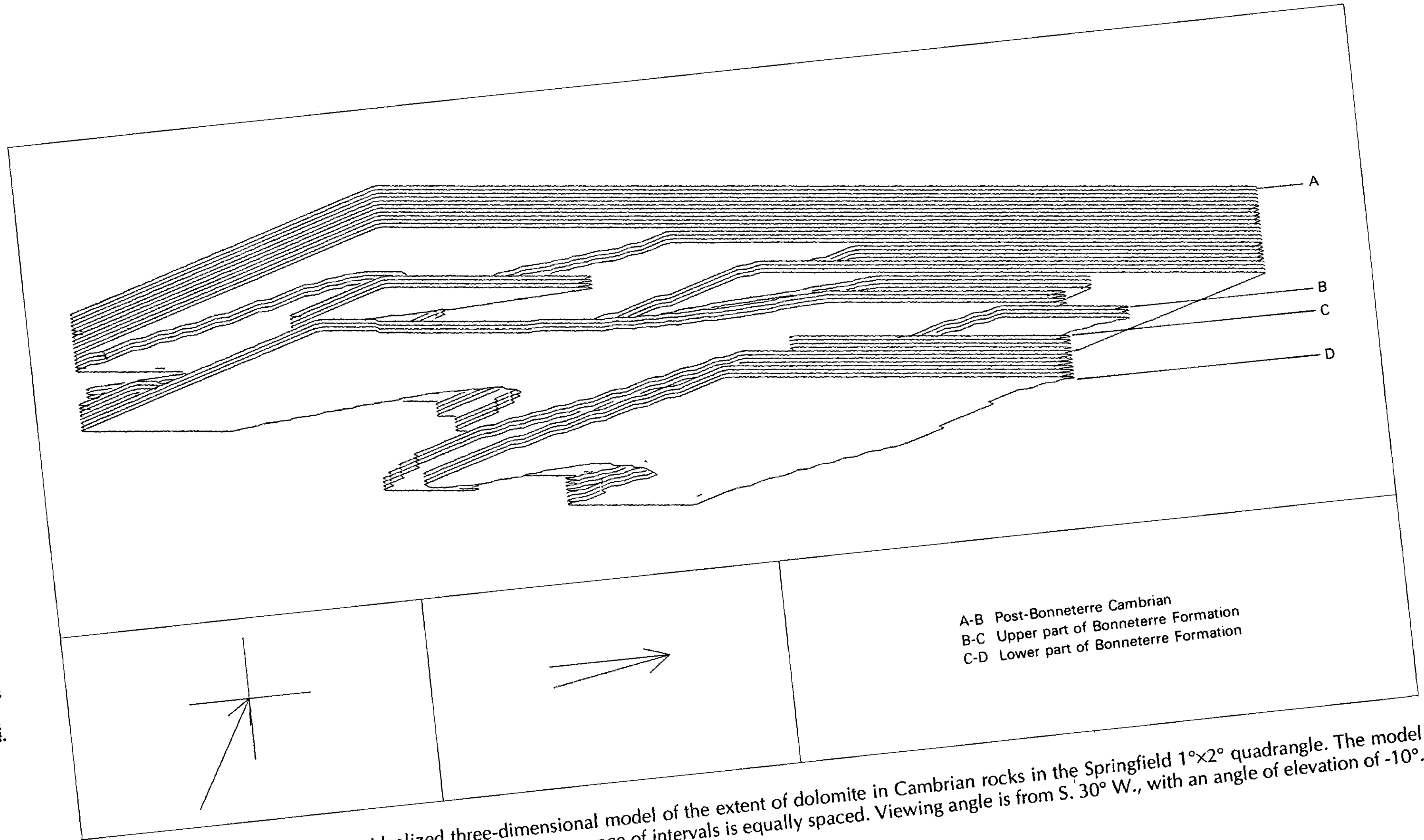


**Figure 19.** Perspective plot of an idealized three-dimensional model of the extent of dolomite in Cambrian rocks in the Springfield 1°×2° quadrangle. The model assumes that all levels shown are horizontal and that the sequence of intervals is equally spaced. Viewing angle is from S. 30° W., with an angle of elevation of -10°.

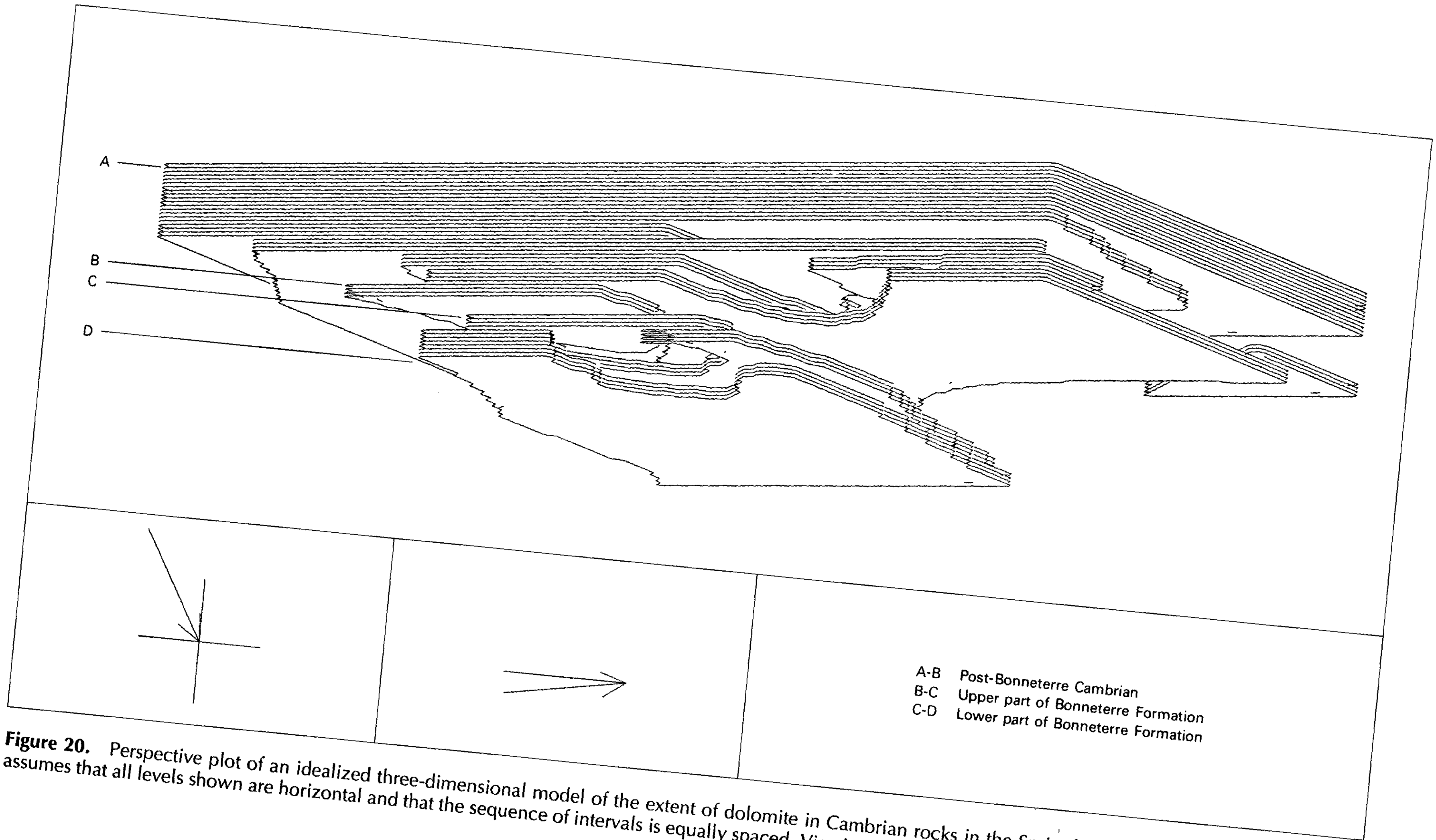


**Figure 20.** Perspective plot of an idealized three-dimensional model of the extent of dolomite in Cambrian rocks in the Springfield 1°×2° quadrangle. The model assumes that all levels shown are horizontal and that the sequence of intervals is equally spaced. Viewing angle is from N. 30° W., with an angle of elevation of -10°.

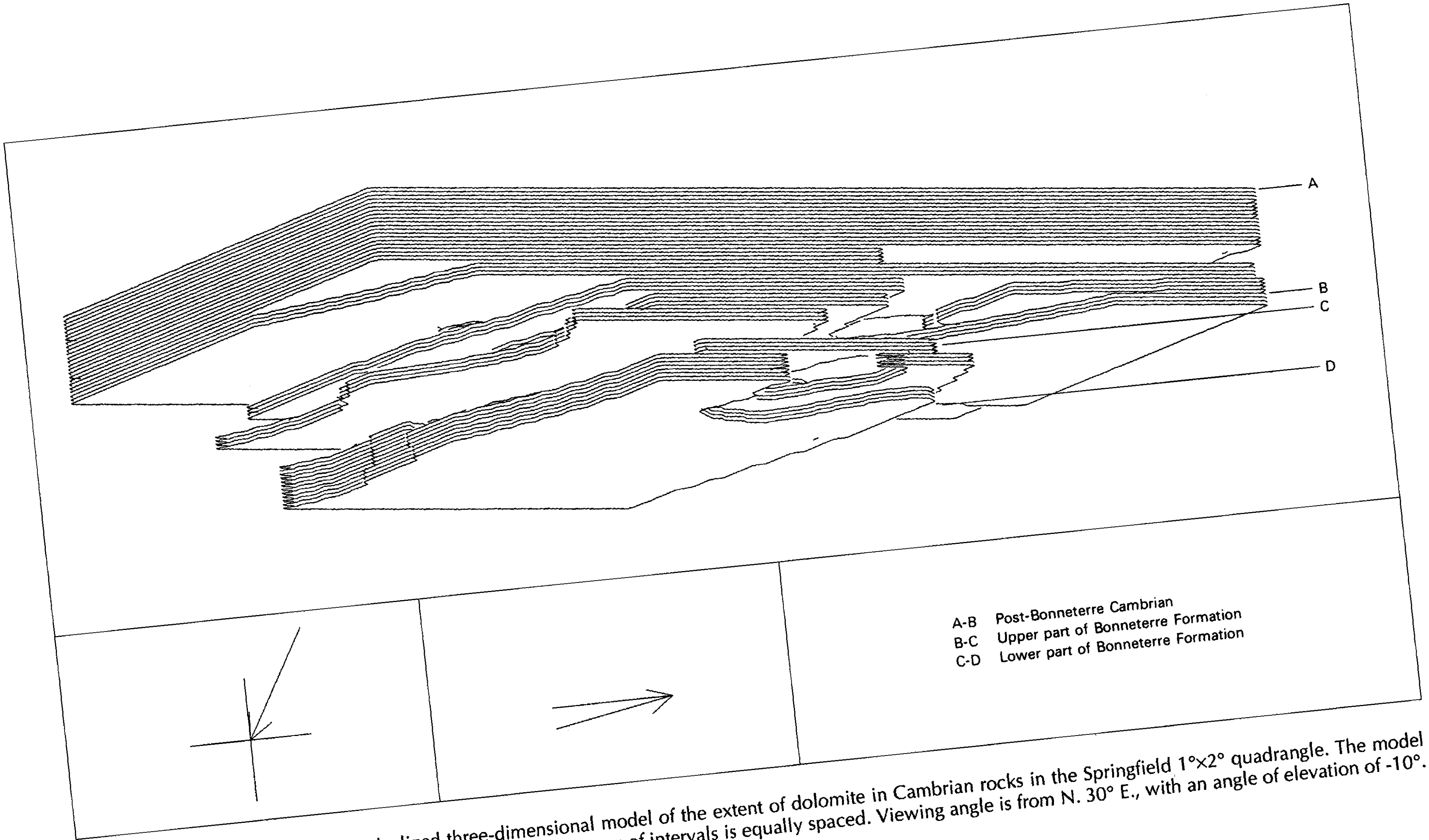


**Figure 21.** Perspective plot of an idealized three-dimensional model of the extent of dolomite in Cambrian rocks in the Springfield 1°×2° quadrangle. The model assumes that all levels shown are horizontal and that the sequence of intervals is equally spaced. Viewing angle is from N. 30° E., with an angle of elevation of -10°.

# Geochemical Studies of Subsurface Carbonate Rocks

*By* R.L. Erickson, M.S. Erickson, E.L. Mosier, *and* Barbara Chazin

This discussion was abstracted from U.S. Geological Survey Miscellaneous Field Studies Map MF–1830–A (Erickson and others, 1985). The reader is referred to that publication for maps and graphs showing details of the stratigraphic and areal distribution of anomalous metals in the Springfield 1°×2° quadrangle, which are the basis for the interpretations presented here.

Geochemical studies in the Rolla 1°×2° quadrangle to the east, completed in 1980, indicate that insoluble residues of carbonate rocks are a useful and informative geochemical sample medium in the carbonate environment (Erickson, Mosier, and Viets, 1978; Erickson, Mosier, Viets, and King, 1979). Spectrographic and chemical analysis of residues permit detection of trace amounts of elements, the presence of which in the barren whole rock is unsuspected and commonly not detected by using conventional whole-rock analytical methods. The resulting map patterns of the distributions and abundances of trace elements permit distinction between intrinsic and epigenetic suites of elements, recognition of rock units through which metal-bearing fluids have passed, and delineation of regional mineral trends. The geochemical maps of the Rolla quadrangle, based upon analyses of insoluble-residue samples from 62 regionally spaced drill holes, are an important part of the geoscience information that was used to appraise the metallic mineral resource of that quadrangle (Pratt, 1981). Therefore, the same type of geochemical study was done in the Springfield quadrangle. Only 24 drill holes that penetrate the stratigraphic section to the Precambrian basement or to a basal Cambrian sandstone were initially available for the Springfield quadrangle. To supplement the available subsurface data and samples, six core holes to Precambrian basement (NS1–NS6, plate 1, this volume) were drilled by the U.S. Geological Survey in 1983–1984 in the central and western parts of the quadrangle where no drill holes were available. In addition, samples from 34 drill holes outside but adjacent to the quadrangle were analyzed and the results plotted on the geochemical maps (Erickson and others, 1985).

Recent carbonate petrologic studies of drill cores in southern Missouri (Palmer, 1983a, b, 1985, this volume) indicate that the entire Cambrian section above the Bonneterre Formation—the Davis Formation and Derby-Doerun, Potosi, and Eminence Dolomites—changes character in central and southern Missouri such that many different carbonate depositional facies are present, including shallow cratonic basin to ramp to platform. Palmer informally refers to this group of rocks as the post-Bonneterre Cambrian sequence. His terminology is used here in discussion of the geochemical distribution and abundance of metals.

The drill-hole samples analyzed are splits of insoluble-residue samples from the sample library of the Missouri Department of Natural Resources, Division of Geology and Land Survey. The Missouri library is also the repository for the six U.S. Geological Survey cores. None of the holes is company confidential, and none intersects economically significant mineralized rock. Each sample is a composite of a 10-ft interval, and samples in each drill hole are contiguous. Each sample was analyzed semiquantitatively for 31 elements by a six-step D.C.-arc optical-emission spectrographic method (Grimes and Marranzino, 1968). The analytical results for selected elements (Pb, Zn, Cu, Mo, Ni, Co, As, Ag) in insoluble-residue samples are plotted on the maps in anomalous metal feet (AMF). (AMF is a reporting unit based on normalizing the ratio of the reported anomalous metal content to the minimum anomalous metal content, multiplied by the length of the sample interval in feet. The minimum anomalous metal contents of insoluble residues, in parts per million, are As, 200; Zn, 200; Pb, 100; Cu, 100; Ni, 70; Co, 30; Mo, 10; and Ag, 1. Thus, reported values of 500 ppm Pb and 3 ppm Ag for a 10-ft sample interval normalize to 50 AMF of Pb and 30 AMF of Ag.) The AMF values can be summed for an entire drill hole, or for each formation, or for individual metals.

In this study, drill holes that contain more than 3,000 AMF are considered to have high metal content. The distribution pattern of drill holes that contain the highest metal contents suggests that a mineralized zone in the post-Bonneterre Cambrian carbonate rocks in the subsurface extends from the Missouri-Arkansas border northwestward across the Springfield quadrangle. This possible new mineral trend was first reported by Erickson and others (1981) and has since been expanded by acquisition of geochemical data from additional drill holes (Erickson and others, 1983); it corresponds approximately to the central, light-shaded area on plate 1 (this volume). Undoubtedly, new drilling and closer spaced holes would reveal many barren areas within the postulated trend. Nevertheless, on the basis of our analyses of the drill-hole samples available to us, a northwesterly pattern is indicated. Further, the trend appears to follow a northwest structural grain. Ninety-five percent of the total metal content in the 21 drill holes that define the trend are in restricted platform flats, lagoon, and shoal lithofacies of post-Bonneterre Cambrian carbonate rocks, as described by Palmer (1983a, b, 1985). Most of the drill holes that have high anomalous metal content are along or near the projection of the Mansfield fault system in the southeastern part of the trend. The highest metal contents in each drill hole are in dark-gray to black, earthy, fine-grained mixtures of iron sulfide minerals and thermally degraded organic (?) material in expanded stylolites, vugs, and breccia zones in coarse, recrystallized dolomite. Marcasite probably is a more favorable host than pyrite. Ore minerals such as sphalerite, galena, and chalcopyrite were not detected during binocular examination of the insoluble-residue samples.

Several drill holes along or near the western edge of the trend have moderately high AMF values in Ordovician or Mississippian rocks (holes S3, S4, S5, S9, plate 1, this volume). Numerous small, inactive surface mines and prospects for zinc and (or) lead and numerous occurrences of sphalerite in drill-hole samples of Ordovician rocks are present in the southern part of the quadrangle (Searcy, 1981a, b). None of these occurrences has a significant or extensive trace-metal suite associated with it.

Several single drill-hole anomalies are in the northern part of the map area. Most are in the post-Bonneterre Cambrian rocks and probably are related to the central Missouri mineral district.

Although the Bonneterre Formation is the ore host in the Southeast Missouri lead district in the adjacent Rolla quadrangle, no significant anomalously high concentrations of metal were detected in the Bonneterre in the drill samples available to us for the Springfield map area. The data suggest that mineralizing fluids were in successively higher stratigraphic units with increasing distance from the St. Francois Mountains, so that in the Springfield quadrangle post-Bonneterre Cambrian rocks contain the high metal anomalies and the most extensive suite of metals (Pb, Zn, Cu, Mo, Ag, As).

The distribution and abundance of Pb, Ag, Cu, Zn, Mo, As, Ni, and Co in insoluble-residue samples in the quadrangle are shown in detail in Erickson and others (1985).

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# Geochemistry of Basal Cambrian Sandstones in Parts of Missouri, Arkansas, and Kansas

*By* E.L. Mosier

## INTRODUCTION

The Upper Cambrian Lamotte Sandstone and the facies-equivalent Reagan Sandstone are the lowermost sedimentary formations in Kansas, Missouri, and northern Arkansas. These formations lie directly on the Precambrian basement and are conformably overlain by the Cambrian Bonneterre Formation. The thickness of the sandstones ranges from less than 100 ft (30 m) in eastern Kansas, northwestern Arkansas, and western Missouri to 500 ft (150 m) in eastern Missouri (Ojakangas, 1963). Previous studies dealing with interpretation of the origin of the sandstones and their depositional paleoenvironment include Wallace (1938), Ojakangas (1963), Houseknecht and Ethridge (1977, 1978), and Yesberger (1981). These studies were concerned chiefly with sandstone of the St. Francois Mountains region in southeastern Missouri. Regionally, the units are predominantly clean orthoquartzite thought to be derived from Precambrian sedimentary rocks of the Lake Superior region and deposited in a shallow marine environment on a peneplaned Precambrian surface (Ojakangas, 1963). Some arkosic and lithic detritus was locally derived from the partly emergent St. Francois Mountains. The basal sandstones are crossbedded, generally well sorted, fine grained, friable, porous, and permeable. These extensive basal sandstones are regarded as a likely aquifer through which mineralizing basin waters migrated (Gerdemann and Myers, 1972). Leach, Viets, and Rowan (1984), Leach and Rowan (1985), and Leach, Rowan, and Viets (this volume) proposed that tectonism resulting from the Late Pennsylvanian and Early Permian Ouachita orogeny played a role in the northward migration of heated brines out of the thick sedimentary sections in the southern part of the Ouachita-Arkoma basin system. Gregg (1985) credited these same hot basin-derived waters moving through the Lamotte Sandstone as the most likely source of $Mg^{2+}$ needed for dolomitization of the basal Bonneterre Formation.

The purpose of this paper is to document the trace-element geochemistry of the Lamotte and Reagan Sandstones. Metal-bearing fluids migrating through these porous sandstone formations have deposited trace amounts of epigenetic minerals, primarily pyrite. Chemical analyses of the heavy-mineral concentrates of these sandstones provide information on the metal composition of the paleofluids, as well as their possible direction of migration, and on the chemistry of detrital minerals, which have a direct relationship to the origin of the sandstones.

## SAMPLING AND ANALYTICAL PROCEDURES

Basal sandstone samples were collected from the cores of 87 drill holes and from the cuttings of 13 drill holes (fig. 22). All samples were obtained from the sample libraries of the Missouri, Arkansas, and Kansas State Geological Surveys. Wherever possible, drill holes were selected that penetrated the Lamotte or Reagan Sandstone and bottomed in the Precambrian basement. Forty-eight drill holes met this criterion. The remaining 52 drill holes partially penetrate the basal sandstone formation. For each drill core hole, representative grab samples were obtained at approximately 4-ft intervals and combined into a composite sample for that hole. For drill cutting holes, a representative split was made of each 5-ft sample interval and then composited. An attempt was made to obtain fairly uniform coverage of the drill-hole sites throughout the region; however, some areas lack drill holes that reach the basal sandstone formations.

Because of the extremely low concentration of the metals in the samples, it was necessary to concentrate the heavy minerals. The samples were first disaggregated with a jaw crusher and sieved through a 0.6-mm screen. The sieved material was then panned, using standard gold-panning techniques, until dark material began to appear at the edges. The samples were then dried and the heavy minerals further concentrated by flotation in bromoform. The samples were again dried, and magnetite and any extraneous metal was removed by passing a hand magnet over the sample. The resulting heavy-mineral concentrate is a mixture of detrital minerals and hydrothermally


**Figure 22.** Drill-hole locations for study area in parts of Missouri, Arkansas, and Kansas.

introduced minerals and is considered analogous to the insoluble-residue sample used by Erickson and others in evaluating the mineral potential of the carbonate terrane of the Midcontinent (Erickson, Mosier, and Viets, 1978; Erickson, Mosier, Viets, and others, 1979; Erickson, Mosier, Odland, and Erickson, 1981; Erickson, Erickson, and others, 1985, this volume). Each concentrate sample was split, and half of the sample was hand ground and analyzed by a six-step D.C.-arc optical-emission spectrographic method (Grimes and Marranzino, 1968). The analytical results are available in a U.S. Geological Survey Open-File Report (Mosier, 1986).

## RESULTS AND INTERPRETATION

The basal sandstones generally yield less than 0.5-percent heavy-mineral concentrate having a predominant grain size on the order of 0.1–0.2 mm. Zircon is the most abundant of the detrital heavy minerals, tourmaline the second most abundant. Garnets were identified in concentrates from the northwest Missouri drill holes, and anhydrite was identified in the concentrate of drill-hole 17861 in Atchison County, Missouri (fig. 22). This drill hole is a cuttings hole, and the anhydrite may have originated from above the basal sandstone. Abundant, very angular crystals of authigenic anatase, presumably formed from alteration of iron-titanium oxide minerals, was found in drill hole NS2, Cedar County, Missouri. Other detrital minerals routinely found, but far less abundant, include glauconite, rutile, apatite, hematite, and epidote. Ojakangas (1963) also reported fluorite, hornblende, glaucophane, augite, sphene, spinel, biotite, leucoxene, ilmenite, and limonite in the detrital heavy-mineral assemblage.

Hydrothermally introduced minerals include pyrite, chalcopyrite, arsenopyrite, and galena. Galena was identified only from the heavy-mineral concentrates of drill-hole H13AK in Searcy County, Arkansas. Marcasite is almost always present but is considered to be primarily authigenic.

Table 2 shows a comparison of the trace-element chemistry of spheroidal pyrite and striated marcasite from drill-hole NS5, Dallas County, Missouri (fig. 23). The much higher metal contents of the pyritic spheroids as compared to the marcasite suggest that these minerals were formed at different times and from different fluids. The spheroids may have formed from the same metal-bearing hydrothermal fluids responsible for the formation of the Mississippi Valley-type deposits in the region. Pyritic spheroids were identified in 10 of the heavy-mineral concentrates (drill-holes 20186, 62W157, UC1, UC2, NS4, NS5, 66AK1, W1, 4MR, and 23–1). They are 0.4–0.5 mm in diameter and are almost perfect spheres. They have grown in concentric bands, each band radiating out from a core of what appears to be a very minute detrital grain. Their crystalline structure is like marcasite in appearance, but X-ray diffraction patterns show the material to be pyrite; possibly the spheroids are pseudomorphs of pyrite after marcasite.

Analytical results for the heavy-mineral concentrates show that the concentrates contain an epigenetic suite of metals consisting of Ag, As, Co, Cr, Cu, Mo, Ni, Pb, and Zn. Of this suite, Pb and Cu are the most widespread and abundant, whereas Zn, Mo, and Ag were detected only sparingly. The highest values detected for each of the elements are (in parts per million) Ag, 50; As, 2,000; Co, 300; Cr, 3,000; Cu, 20,000; Mo, 200; Ni, 300; Pb, 20,000; and Zn, 5,000. The most common mineral resident for the suite is pyrite; less common residents are arsenopyrite, chalcopyrite, and galena. Marcasite may be a minor contributor.

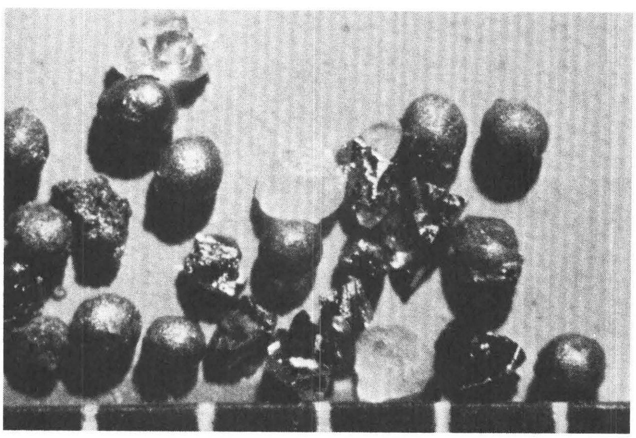

**Figure 23.** Spheroidal pyrite and striated marcasite from drill-hole NS5, Dallas County, Missouri. Millimeter scale shown.

**Table 2.** Comparison of the trace-element chemistry of framboidal pyrite and striated marcasite from drill-hole NS5, Dallas County, Missouri

[In parts per million. n.d., not detected]

| Element | Crystalline marcasite | Spheroidal pyrite |
|---|---|---|
| Mn | n.d. | 700 |
| Ag | n.d. | 7 |
| As | n.d. | 1,500 |
| Co | n.d. | 200 |
| Cr | n.d. | n.d. |
| Cu | 10 | 1,500 |
| Mo | n.d. | n.d. |
| Ni | 20 | 300 |
| Pb | 20 | 300 |
| Zn | n.d. | n.d. |

A technique called SCORESUM (Chaffee, 1983) was used to display the geochemical areal distribution pattern for the nine epigenetic elements. The SCORESUM technique allows a summation of the analytical data for the epigenetic suite of elements at each drill-hole location. The full range of reported analytical values for each of the nine elements was divided into four categories: background, weakly anomalous, moderately anomalous, and strongly anomalous. A score of 0, 1, 2, or 3 was substituted for all the analyses falling into each of the four categories. The values were then summed for each drill-hole location and the SCORESUM value plotted (fig. 24). The concentration ranges for the four categories and the number of samples represented in each category for each of the nine elements are given in table 3. SCORESUM values for each drill-hole location and the contributing score of the nine epigenetic metals are presented in table 4.

The maximum possible SCORESUM value for a drill hole is 27. In this study, values range from 0 to 23. Twenty of the drill holes have values ranging from 11 to 23 (large solid circle, fig. 24), 28 drill holes have values of 8, 9, and 10 (small solid circle, fig. 24), 22 drill holes have values of 5, 6, and 7 (small half-filled circle, fig. 24), and 30 drill holes have values of 4 or less (small open circle, fig. 24).

The highest concentrations of metals are for drill holes near the Southeast Missouri lead-zinc district in Reynolds County, Missouri. The area south of this mineralized district—that is, parts of Carter, Howell, Oregon, and Ripley Counties, Missouri—also shows a marked enrichment of metals. In general, the regional geochemical patterns support proposed models for the

**Table 3.** SCORESUM concentration ranges for trace elements in each category

[SCORESUM value for category shown in parentheses after category type. Element values in parts per million; number of samples shown in parentheses]

| Element | Background (0) | Weakly anomalous (1) | Moderately anomalous (2) | Strongly anomalous (3) |
|---|---|---|---|---|
| Ag | <1 (64) | 1-2 (15) | 3-5 (13) | 7-50 (8) |
| As | ≤100 (56) | 150 (11) | 200-300 (22) | 500-2,000 (11) |
| Co | ≤20 (48) | 30-50 (29) | 70 (12) | 100-300 (11) |
| Cr | <100 (50) | 100-150 (18) | 200 (15) | 300-3,000 (17) |
| Cu | ≤100 (46) | 150-200 (19) | 300-1,000 (18) | 1,500-20,000 (17) |
| Mo | <5 (65) | 5-7 (6) | 10-15 (17) | 20-200 (12) |
| Ni | ≤50 (43) | 70 (23) | 100 (24) | 150-300 (10) |
| Pb | ≤100 (54) | 150 (15) | 200-300 (13) | 500-20,000 (18) |
| Zn | <200 (91) | 200-500 (3) | 700-2,000 (3) | 3,000-5,000 (3) |

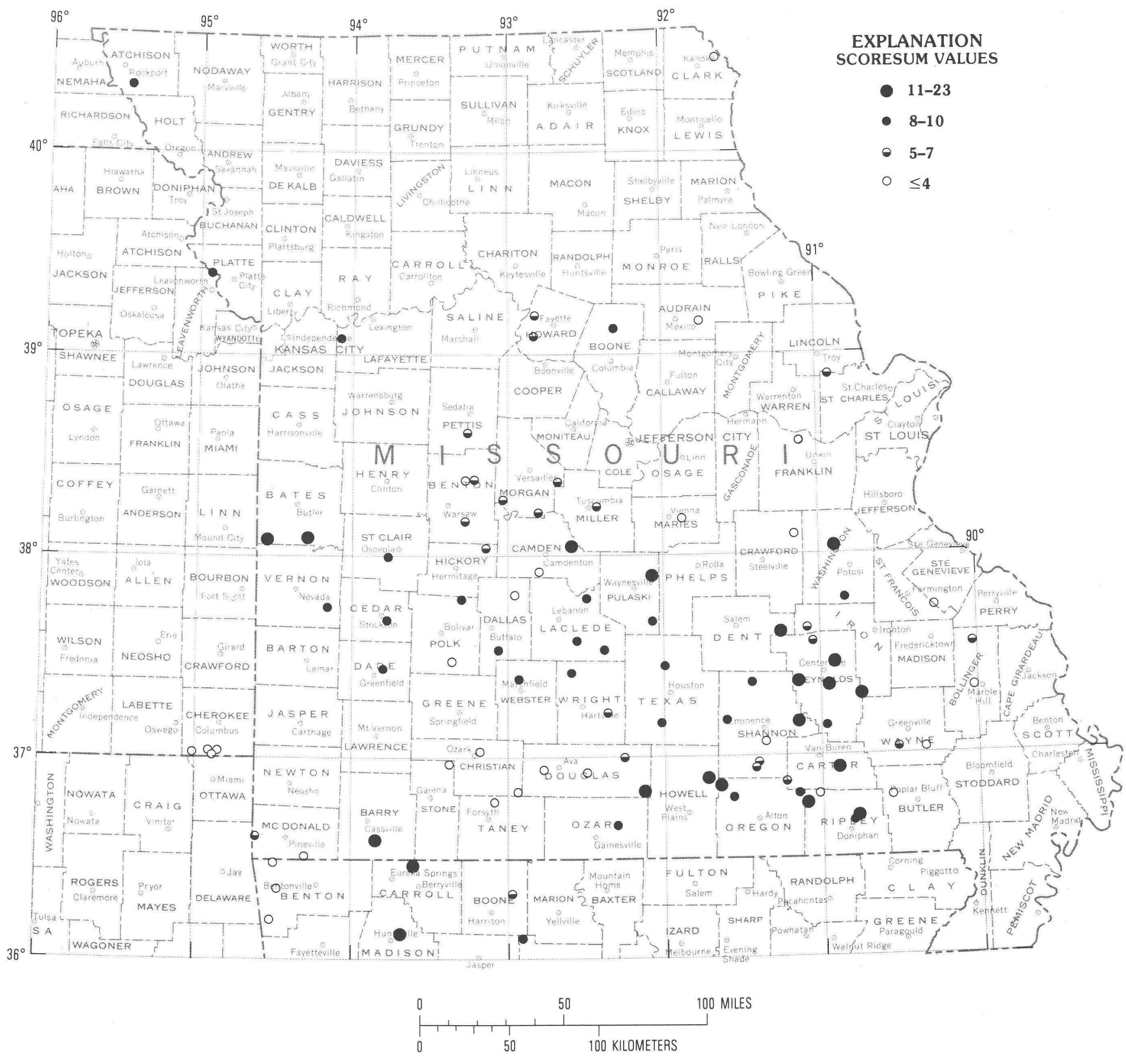


**Figure 24.** SCORESUM geochemical anomaly map based on the summation of the analytical data for Ag, As, Co, Cr, Cu, Mo, Ni, Pb, and Zn in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas. Geometric symbols indicate anomaly classes and are described in text.

migration of heated brines from the Ouachita-Arkoma basin system northward into the Midcontinent region. The basal sandstone was possibly the primary aquifer through which early solutions moved. With time, these solutions helped in the development of secondary porosity in the overlying carbonate rocks. The fluids probably migrated northward through the basal sandstone to approximately lat 38° N. At that point, conditions possibly favored a shunting of the basal solutions to the northwest. The path that solutions moved through in the basal sandstone was dependent on factors such as degree of porosity, topographic basement highs, structure, overlying aquicludes, and so forth.

The areal distribution of barium concentrations (fig. 25) is closely related to the extent of hematitic staining in the sandstones. The higher barium concentrations are associated with hematite-stained sandstone in southeastern Missouri and in a wide zone across north-central Missouri. Laboratory tests that show barium is readily soluble in relatively weak acids eliminate barite as the source of barium. One exception is drill hole 63W72 in Maries County, Missouri. This concentrate sample contains 10 percent Ba as barite in a pink epigenetic vein 1–2 mm thick. The hematitically stained sandstone beds may have originally been regional in extent and the easily solubilized barium intrinsic to the sandstone. Leaching of iron and barium from the sandstone by fluids passing through the sandstone reflects the northward extent of fluid migration in the basal sandstone.

Evidence of solution movement through the basal sandstone does not suggest that mineralizing solutions did not also move through overlying Upper Cambrian and Ordovician formations. Recent research shows that over large areas the later carbonate formations have been "pickled" by hot, highly saline brines (Leach and others, this volume). Insoluble residues derived from carbonate rocks contain a similar suite of hydrothermally introduced trace metals, and these metals are found higher in the stratigraphic sections at increasing distances west of the St. Francois Mountains (Erickson, Mosier, and others, 1981, p. 931; Erickson, Mosier, Viets, and others, 1983; Erickson, Erickson, and others, 1985). Analyses of fluid-inclusion extracts suggest that early octahedral galena of the Viburnum Trend may have been deposited from a fluid channeled primarily through the basal Lamotte Sandstone aquifer (Viets and others, 1985). Late cubic galena was deposited from a fluid containing less potassium and aluminum that perhaps had more interaction with carbonate rocks owing to development of porosity and permeability.

Tourmaline and, to a lesser extent, zircon are regarded as the minerals most useful for identifying the source of orthoquartzite sandstone (Ojakangas, 1963). Rock types exposed in the St. Francois Mountains and subsurface Precambrian rocks in Missouri and eastern Kansas are poor sources of tourmaline; this suggests that the tourmaline-rich orthoquartzite of the Lamotte Sandstone must be derived from sources outside of Missouri. Tourmaline-poor arkosic sandstone, however, was deposited in the St. Francois Mountains area from detritus derived from local granite and rhyolite and in places is overlain, interbedded, or mixed with distant quartzose sandstone (Houseknecht and Ethridge, 1978). Ojakangas (1963) described the tourmaline-deficient arkose as having dominantly subrounded and angular zircons, whereas tourmaline-abundant orthoquartzite contains basically well rounded zircons. He favored mineralogically similar Precambrian sandstone of the Lake Superior region as the source for much of the quartzose sandstone.

Boron is the most chemically diagnostic element for identifying tourmaline, and the boron content of these heavy-mineral concentrates can be directly related to the tourmaline content. Boron values are from less than 10 ppm to more than 2,000 ppm. Fifty of the 100 samples have values equal to or less than 200 ppm, 25 samples have values of 300–500 ppm, and 25 samples have values equal to or greater than 700 ppm. The areal distribution of boron is shown in figure 26. Do these boron-tourmaline concentration patterns reflect paleocurrent directions? If so, the distribution patterns favor a southward movement of the sediments across the northeastern corner of Missouri to mid-south-central Missouri. Houseknecht and Ethridge (1978) proposed that this quartzose detritus was redistributed to the east by a braided fluvial system brought on by a broadly subsiding basin and resulting in an alluvial plain extending eastward beyond the St. Francois Mountains area. Higher boron concentrations peripheral to the St. Francois Mountains suggest that this is possible. Low boron concentrations in sandstones of the Tri-State region and northwestern Missouri suggest a separate detrital origin. These low-boron sandstones constitute the Reagan Formation. They are the lithologic equivalent of the Lamotte but are regarded as closer to the Bonneterre Formation in depositional age. The zircons in the samples from the Tri-State region are predominantly subrounded prismatic to euhedral. Very few zircons are present in the samples from northwestern Missouri.

Areal distribution patterns for yttrium and thorium are similar to those for boron; however, the host mineral for these elements is zircon (figs. 22, 23). Yttrium concentrations are from 50 ppm to more than 2,000 ppm and thorium values from not detected at 100 ppm to 1,000 ppm. The thorium distribution pattern suggests that this element is associated with zircons derived from the same sources as the tourmalines. Zircons derived from the St. Francois Mountains may be thorium poor.

Tin values are anomalous in four areas (fig. 29). The largest area is centered in and around Carter County, Missouri, just south of the Southeast Missouri lead-zinc district. Sample GV1 from Carter County contains 200 ppm Sn. This sample also has the highest SCORESUM value. Another area of anomalous tin is centered in Camden

**Table 4.** SCORESUM values for each trace element in each drill hole

[SCORESUM values: 0, background; 1, weakly anomalous; 2, moderately anomalous; 3, strongly anomalous (see table 3). Drill-hole locations shown in fig. 22]

| Drill hole | Ag | As | Co | Cr | Cu | Mo | Ni | Pb | Zn | SCORESUM |
|---|---|---|---|---|---|---|---|---|---|---|
| GV1 | 3 | 3 | 1 | 3 | 1 | 3 | 3 | 3 | 3 | 23 |
| LC12 | 3 | 1 | 3 | 0 | 3 | 3 | 3 | 3 | 0 | 19 |
| 62W134 | 2 | 3 | 1 | 2 | 2 | 3 | 2 | 2 | 0 | 17 |
| 62W149 | 3 | 3 | 3 | 3 | 2 | 0 | 0 | 3 | 0 | 17 |
| RC1 | 3 | 0 | 3 | 0 | 3 | 2 | 2 | 3 | 0 | 16 |
| 20465 | 1 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 0 | 15 |
| 13-1 | 3 | 3 | 0 | 3 | 3 | 0 | 0 | 2 | 0 | 14 |
| 63W82 | 2 | 2 | 1 | 2 | 2 | 3 | 0 | 1 | 0 | 13 |
| 1HM | 0 | 0 | 1 | 2 | 3 | 3 | 3 | 1 | 0 | 13 |
| 1AN | 0 | 2 | 1 | 0 | 3 | 0 | 3 | 2 | 2 | 13 |
| CF1 | 3 | 0 | 1 | 2 | 3 | 0 | 1 | 3 | 0 | 13 |
| 319-10A | 0 | 0 | 2 | 2 | 0 | 3 | 2 | 2 | 2 | 13 |
| 65W23 | 0 | 3 | 2 | 3 | 2 | 0 | 1 | 1 | 0 | 12 |
| 1RE | 0 | 3 | 0 | 3 | 3 | 0 | 1 | 2 | 0 | 12 |
| H7 | 1 | 0 | 3 | 0 | 0 | 2 | 1 | 3 | 2 | 12 |
| L4 | 2 | 3 | 0 | 2 | 1 | 2 | 0 | 2 | 0 | 12 |
| 23821 | 0 | 3 | 0 | 3 | 0 | 3 | 2 | 0 | 0 | 11 |
| 23-1 | 2 | 2 | 3 | 0 | 3 | 0 | 0 | 1 | 0 | 11 |
| 64W73 | 1 | 2 | 0 | 2 | 2 | 2 | 1 | 1 | 0 | 11 |
| 67AK1 | 3 | 2 | 1 | 0 | 0 | 0 | 2 | 3 | 0 | 11 |
| 55W98 | 3 | 0 | 1 | 1 | 2 | 0 | 1 | 2 | 0 | 10 |
| UC1 | 1 | 0 | 2 | 0 | 0 | 3 | 2 | 2 | 0 | 10 |
| 63W113 | 2 | 2 | 0 | 0 | 3 | 3 | 0 | 0 | 0 | 10 |
| 63W29 | 1 | 1 | 3 | 1 | 1 | 1 | 2 | 0 | 0 | 10 |
| NS1 | 0 | 2 | 2 | 0 | 2 | 1 | 2 | 1 | 0 | 10 |
| 20186 | 1 | 0 | 2 | 0 | 2 | 0 | 3 | 1 | 1 | 10 |
| 4-1 | 2 | 2 | 0 | 0 | 2 | 0 | 1 | 3 | 0 | 10 |
| 63W121 | 0 | 0 | 3 | 3 | 3 | 0 | 1 | 0 | 0 | 10 |
| NS6 | 1 | 2 | 2 | 0 | 2 | 1 | 2 | 0 | 0 | 10 |
| 18139 | 0 | 2 | 1 | 3 | 3 | 0 | 1 | 0 | 0 | 10 |
| 65W32 | 0 | 0 | 2 | 1 | 2 | 0 | 2 | 2 | 0 | 9 |
| 62W161 | 0 | 0 | 3 | 0 | 2 | 1 | 2 | 1 | 0 | 9 |
| STH2 | 0 | 0 | 0 | 2 | 1 | 3 | 1 | 2 | 0 | 9 |
| SV1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 | 9 |
| H13AK | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 9 |
| 63W89 | 0 | 1 | 1 | 2 | 1 | 2 | 2 | 0 | 0 | 9 |
| NS5 | 0 | 3 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 9 |
| NS2 | 0 | 3 | 1 | 0 | 3 | 0 | 2 | 0 | 0 | 9 |
| 65W12 | 0 | 1 | 0 | 2 | 0 | 2 | 2 | 1 | 0 | 8 |
| 57M2 | 0 | 3 | 0 | 3 | 1 | 0 | 0 | 1 | 0 | 8 |
| 17861 | 0 | 2 | 1 | 0 | 0 | 0 | 2 | 0 | 3 | 8 |
| SH1 | 0 | 1 | 1 | 3 | 3 | 0 | 0 | 0 | 0 | 8 |
| MO8 | 1 | 2 | 0 | 3 | 0 | 2 | 0 | 0 | 0 | 8 |
| NS3 | 1 | 2 | 1 | 0 | 3 | 0 | 1 | 0 | 0 | 8 |
| UC2 | 0 | 1 | 1 | 2 | 0 | 2 | 2 | 0 | 0 | 8 |
| 11469 | 1 | 0 | 1 | 0 | 1 | 0 | 3 | 0 | 2 | 8 |
| IR5 | 2 | 2 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 8 |
| 319-11A | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 1 | 3 | 8 |
| 164B | 0 | 0 | 0 | 3 | 3 | 0 | 1 | 0 | 0 | 7 |
| 62W157 | 1 | 0 | 1 | 0 | 1 | 2 | 2 | 0 | 0 | 7 |

County, Missouri, just south of the Central Missouri lead-zinc-barite district and in the vicinity of the Decaturville cryptovolcanic structure. A sample from this area, 62W149, also contains 200 ppm Sn. The third area of anomalous tin, less well defined, is in northwestern Arkansas and southwestern Missouri, and the fourth area is in north-central Missouri, where one sample each from Howard, Boone, and Audrain Counties contains 15–20 ppm Sn. The

**Table 4.** Continued

| Drill hole | Ag | As | Co | Cr | Cu | Mo | Ni | Pb | Zn | SCORESUM |
|---|---|---|---|---|---|---|---|---|---|---|
| 62W126 | 0 | 0 | 1 | 0 | 2 | 0 | 3 | 1 | 0 | 7 |
| 62W141 | 0 | 0 | 3 | 0 | 1 | 0 | 3 | 0 | 0 | 7 |
| BT3 | 0 | 2 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 7 |
| 62W135 | 1 | 0 | 1 | 0 | 0 | 2 | 0 | 3 | 0 | 7 |
| GT5A | 0 | 0 | 0 | 3 | 2 | 0 | 2 | 0 | 0 | 7 |
| GT1 | 0 | 0 | 3 | 2 | 1 | 0 | 1 | 0 | 0 | 7 |
| 62W145 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 7 |
| 61W48 | 2 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 0 | 6 |
| 62W153 | 0 | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 6 |
| BT1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 3 | 0 | 6 |
| 424 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 6 |
| 64W94 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 3 | 0 | 6 |
| 62W159 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | 2 | 0 | 6 |
| 64W133 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 0 | 0 | 6 |
| W1 | 2 | 2 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 6 |
| 4MR | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 5 |
| H44AK | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 5 |
| 21765 | 0 | 0 | 2 | 0 | 1 | 0 | 2 | 0 | 0 | 5 |
| XT1 | 0 | 0 | 0 | 3 | 1 | 0 | 1 | 0 | 0 | 5 |
| DC1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 5 |
| 317A | 0 | 0 | 0 | 1 | 1 | 2 | 0 | 0 | 0 | 4 |
| 63W5 | 0 | 1 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 4 |
| 64W58 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 4 |
| TD1 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 4 |
| 63W72 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 4 |
| L05 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 4 |
| 63W25 | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 4 |
| NS4 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| KB | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 3 |
| 66AK3 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 3 |
| 66AK2 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 3 |
| 64W30 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 3 |
| H13M0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 3 |
| 12328 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 3 |
| 58W49 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 |
| 59M1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 |
| HF1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 2 |
| WIL | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 |
| GA1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 66AX1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| J3 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 331-2A | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 1EW | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 57M1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 66W84 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| H12 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| CO9 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 64W86 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 64W49 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| KX | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

host mineral for tin has not been determined and the relationship between tin and the sandstones is an open question. Do the tin values reflect detritus derived from local Precambrian highs? For the most part, analyses of subsurface Precambrian igneous rocks from the St. Francois Mountains igneous province reveal low tin contents (Viets and others, 1978). The tin anomalies could possibly be representative of cryptovolcanic activity.

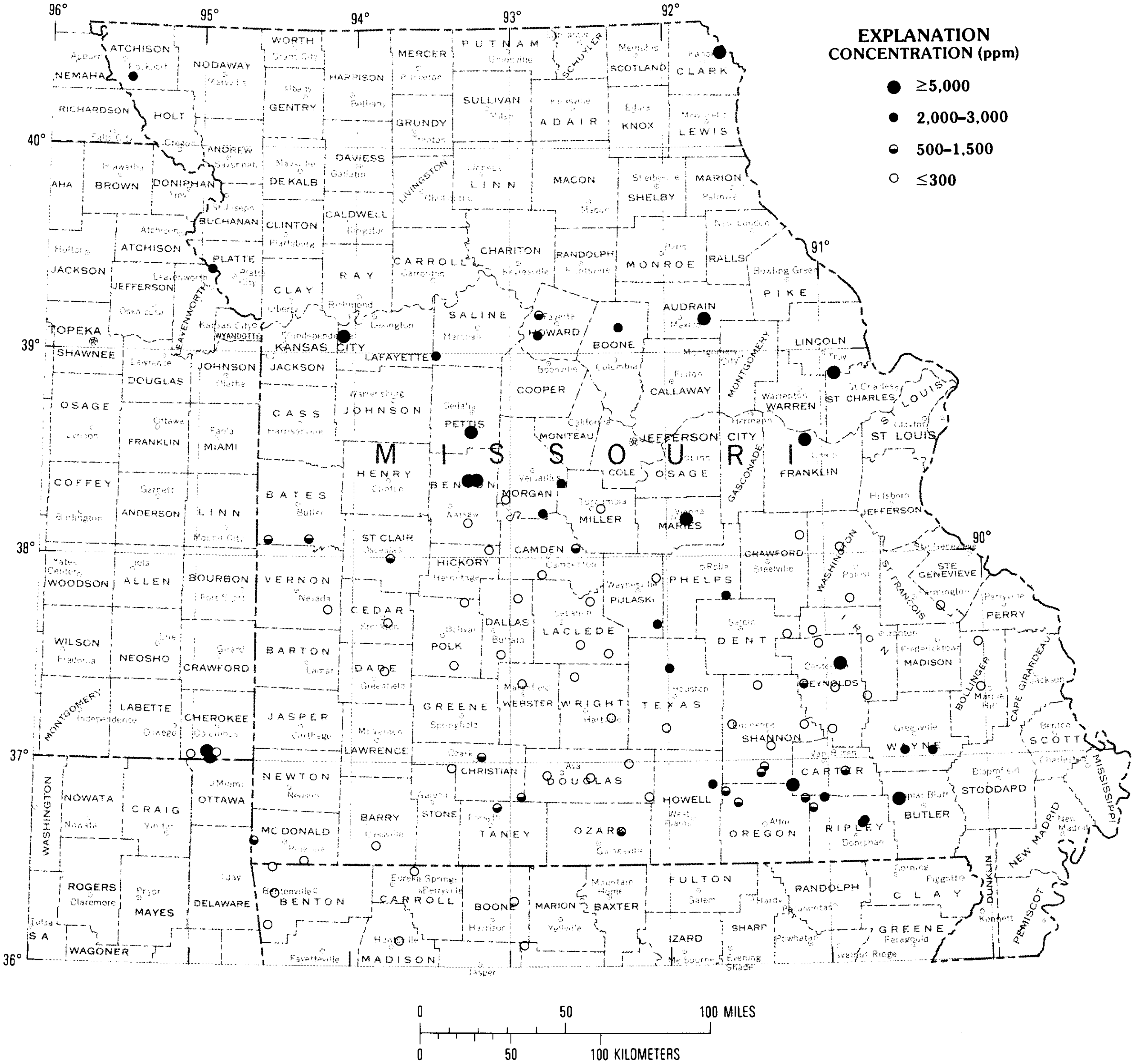


**Figure 25.** Barium concentrations in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas.

## SUMMARY

Trace-element analyses of heavy-mineral concentrates derived from Midcontinent basal sandstones provide information on the characteristics of the depositional detritus and the chemistry of migrating mineralizing fluids. One suite of closely associated epigenetic elements (Ag, As, Co, Cr, Cu, Mo, Ni, Pb, and Zn) mainly is present as trace elements in pyrite that was precipitated from hydrothermal fluids moving through the sandstone. The areal distribution of these trace elements suggests that the metal-bearing solutions migrated generally from south to north and probably originated in the Ouachita-Arkoma basin. Barium is probably intrinsic to the sandstone and closely related to hematitic staining. The solutions have leached barium and iron from the sandstone leaving a clean white orthoquartzite. Barium contents of heavy-mineral concentrates from hematitically stained sandstone that are orders of magnitude higher than in clean orthoquartzite show the extent of fluid migration through the sandstone.

Boron, yttrium, and thorium are directly related to detrital minerals: boron to tourmaline, and yttrium and thorium to zircon. Their distribution patterns confirm a southward movement of the paleocurrents that deposited the basal sandstones. Zircons associated with the tourmaline-rich source sandstones from the north have higher yttrium

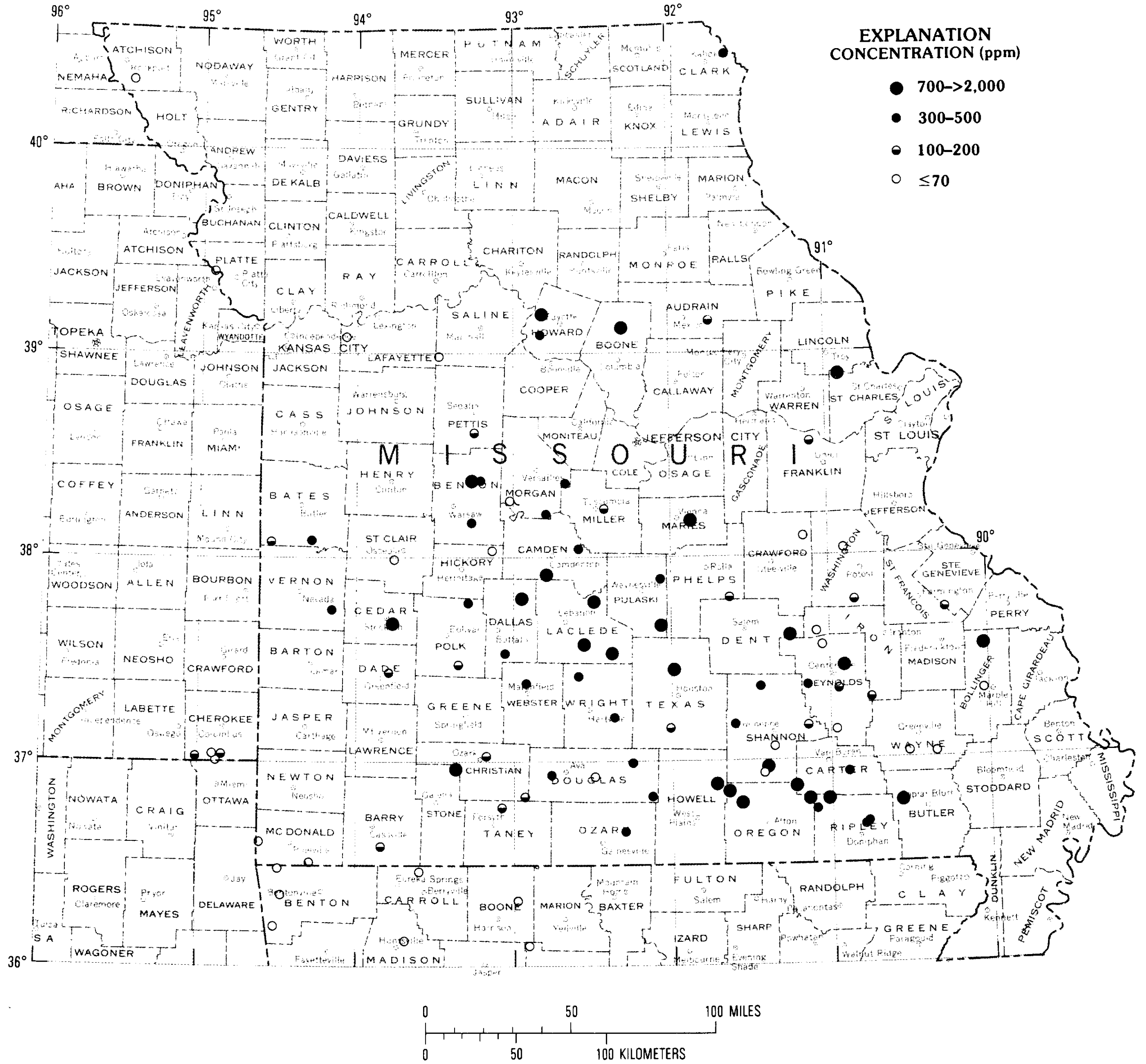


**Figure 26.** Boron concentrations in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas.

and thorium contents than zircons derived locally from the St. Francois Mountains region.

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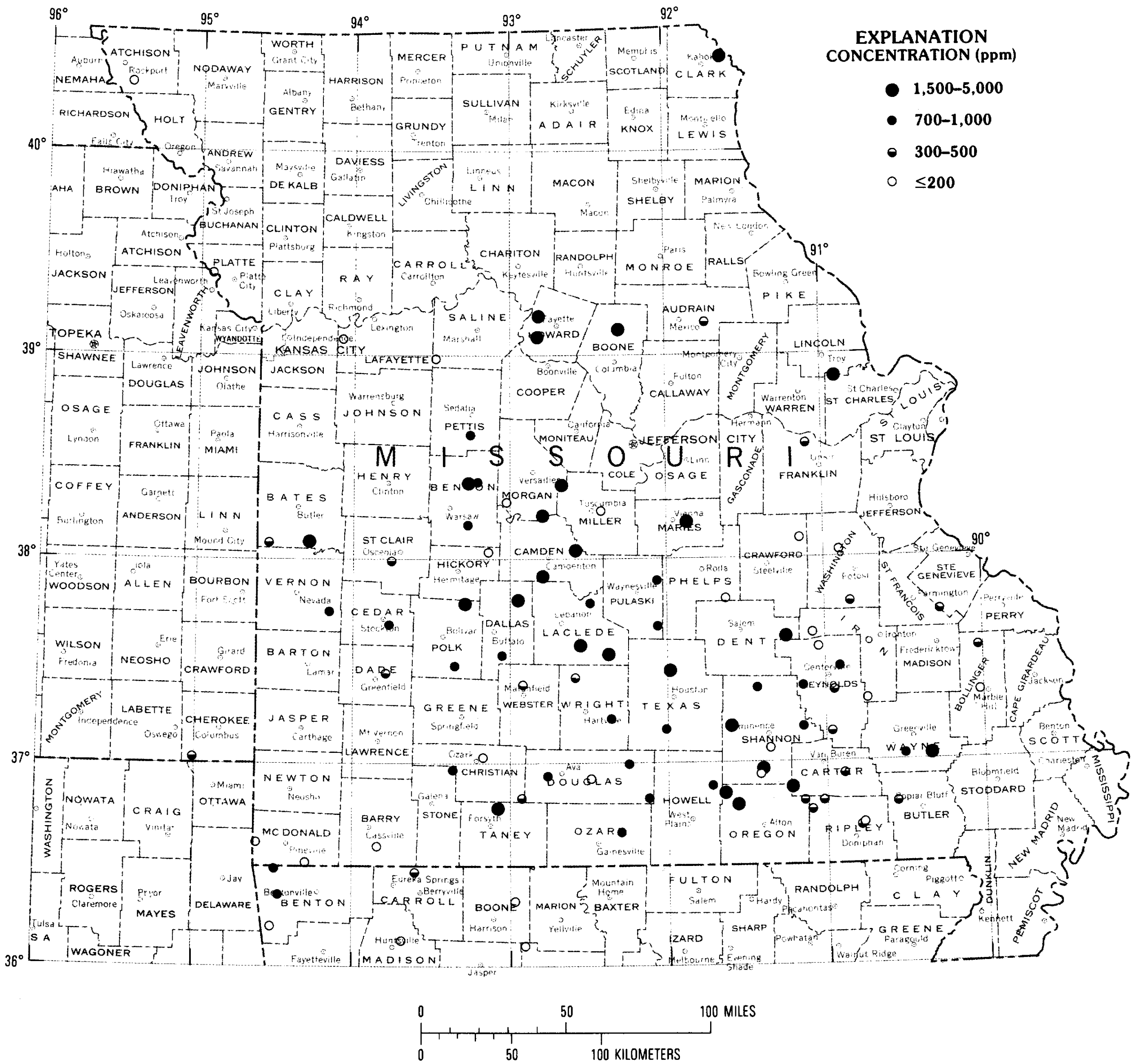


**Figure 27.** Yttrium concentrations in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas.

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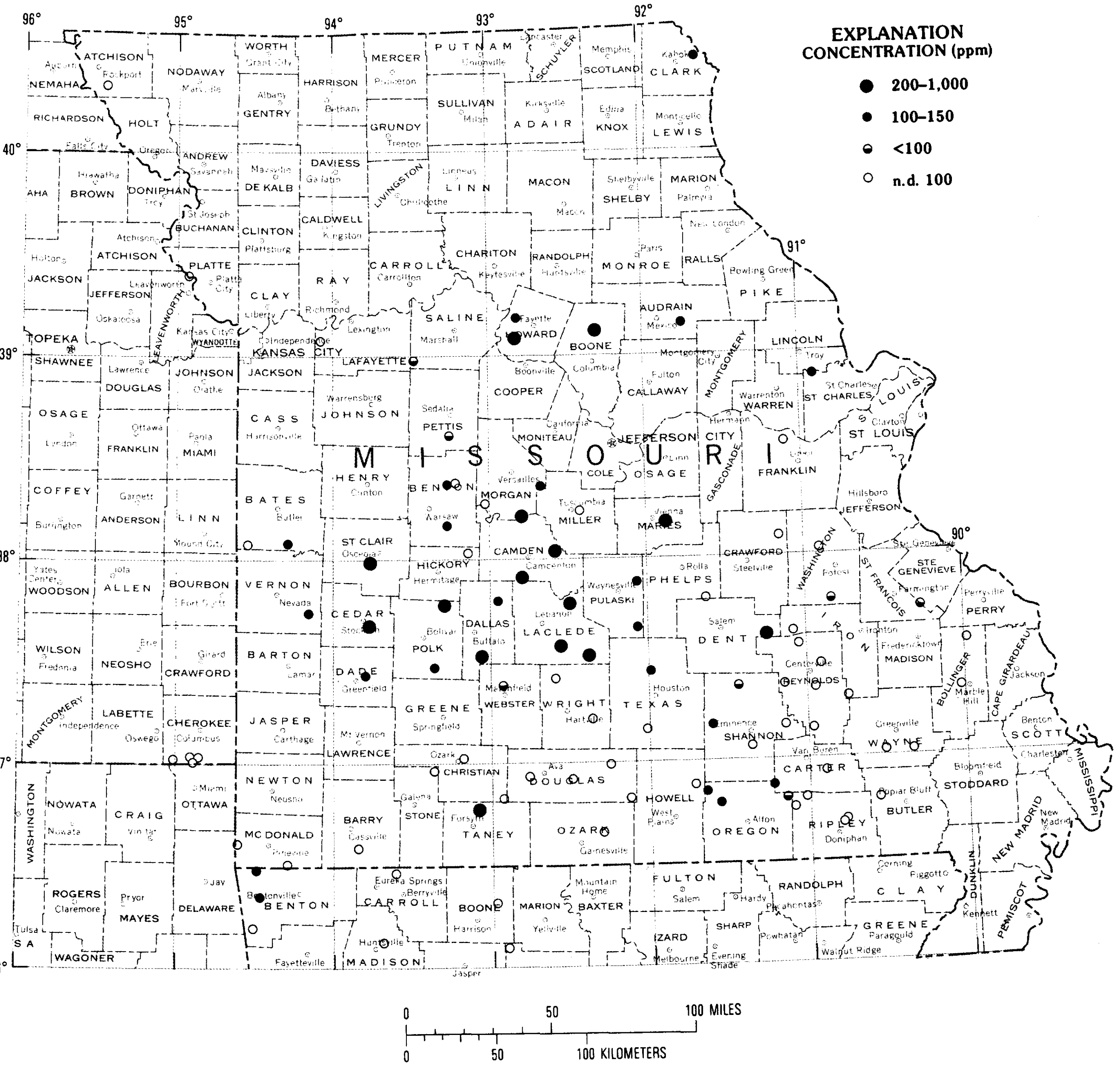


**Figure 28.** Thorium concentrations in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas.

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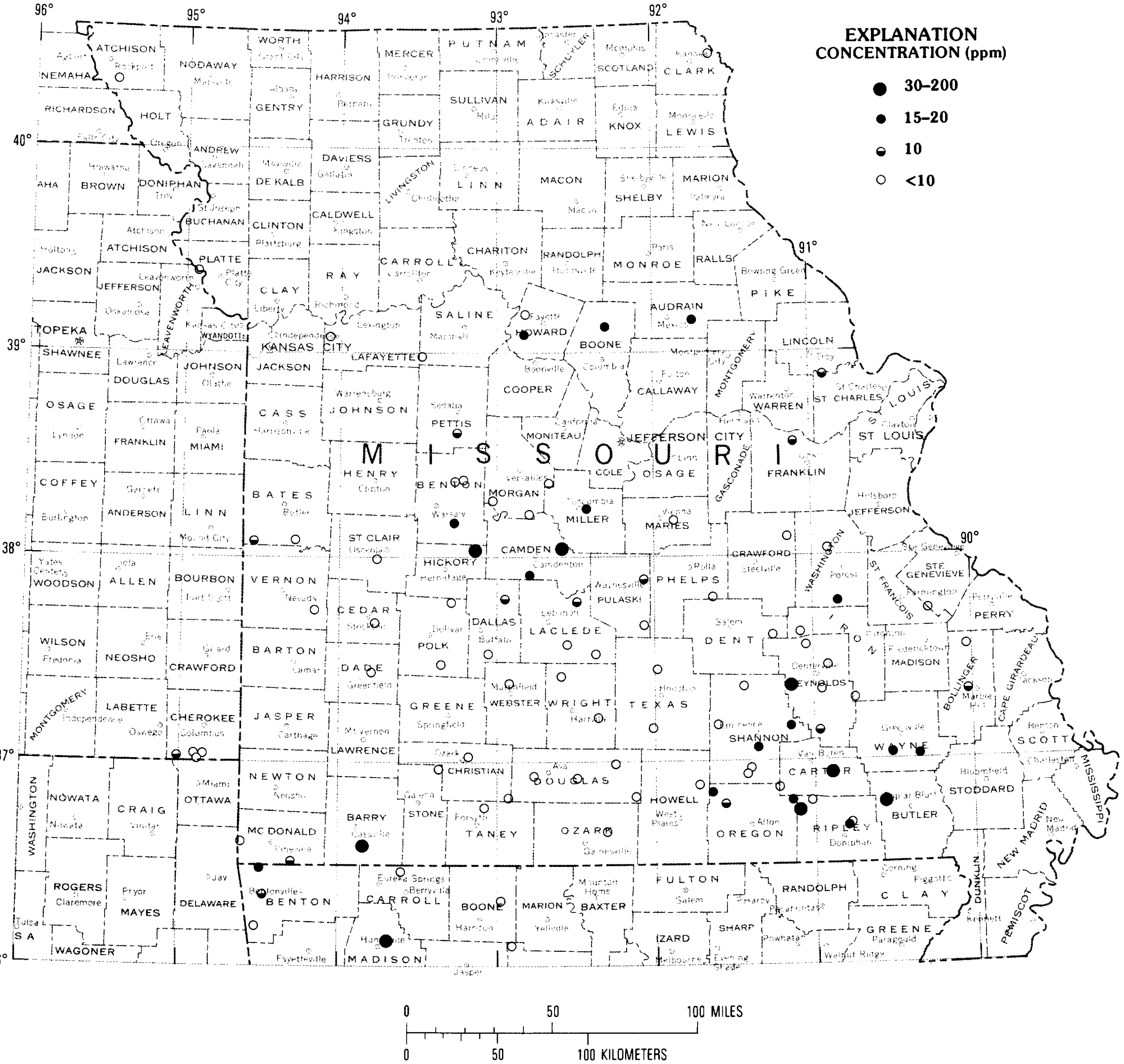


**Figure 29.** Tin concentrations in heavy-mineral concentrates of Cambrian basal sandstone from parts of Missouri, Arkansas, and Kansas.

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# Aeromagnetic and Gravity Studies of Buried Basement Rocks

*By* Lindrith Cordell

## INTRODUCTION

Aeromagnetic and gravity data enable one to figuratively see through sedimentary-rock cover (which comprises 100 percent of the Springfield 1°×2° quadrangle) into the Precambrian crystalline basement and to test whether the stratabound mineral deposits of the region are associated with basement features. The per-area cost of the geophysical surveys is small, and, if a relationship between mineralization and the basement can be established, then a large area can be investigated inexpensively by this indirect means. No economically important stratabound mineral deposits are known in the Springfield quadrangle from which we can determine the relationship (if any) between basement and mineralization. Erickson and others (this volume) believe that large volumes of metal-bearing fluid have passed through the Paleozoic strata, but they point out that lithofacies and geochemical data points are sparsely distributed and that no large block of ground favorable for metal *deposition* has been identified. Apart from mineral-resource considerations, however, the geophysical data show exceptionally coherent expression of basement features. Some of these basement features are large, and only tantalizing fragments were sampled by the geophysical survey of the Springfield quadrangle.

Little is known of basement rocks in the Springfield quadrangle from direct evidence. Data from 26 drill holes (reviewed by Kisvarsanyi, this volume) indicate three major rock types: foliated metamorphic rocks, unmetamorphosed granite, and gabbro (fig. 30). The gabbro bodies are of only local, topical, and economic interest, the principal division of regional significance being that between an orogenic metamorphic terrane and an anorogenic granite terrane. Locations of drill holes and a locality index are shown in figure 30. From drill-hole data, Kisvarsanyi (this volume) infers a northwest-trending terrane of metamorphic rocks flanked by younger, unmetamorphosed granites on both sides. The boundary between these terranes is interpolated from sparse drill-hole data and is not apparent in either the gravity or the aeromagnetic data.

*Acknowledgments.*—I am grateful to Eva Kisvarsanyi, Missouri Geological Survey, for sharing her data and interpretations with me throughout this and preceding and current projects. I am also grateful to Walden Pratt, Ralph Erickson, and David Williams, U.S. Geological Survey, for review and enthusiastic discussion.

## GRAVITY DATA

Gravity data (fig. 31) reflect variations in rock density. Phanerozoic rocks of the region probably have densities of 2.4–2.9 g/cm$^3$, but inasmuch as individual stratigraphic units are only on the order of 100 m thick, gravity anomalies related to Phanerozoic sedimentary rocks are probably only a few milligals. Lack of correspondence between gravity and lithofacies trends (Palmer, 1985) and general correspondence between gravity and magnetic trends further suggest that the gravity anomalies primarily reflect density variations in the basement, where one to two orders of magnitude larger volumes of rock are available. Some of the gravity features, we can assume, *are* caused by unsuspected density variation within the sedimentary rock cover.

Line segments on figure 31 delineate inferred rock density boundaries, as determined by an objective analytic process that uses the trace of maxima of the amplitude of (the horizontal component of) the gravity gradient (Cordell and Grauch, 1985). Inspection of figure 31 shows that these lines track inflection points (contour lines closest together), which tend to occur over density boundaries, as intuition would suggest.

The principal basement density boundaries are indicated by heavy lines on figure 31. Many of these boundaries are straight, northwest-trending segments more than 30 km long. A slight, but probably not significant, tendency is for bottom-hole granite to be associated with gravity lows and for metamorphic rocks to be associated with gravity highs. Certain other gravity lows and highs can be confidently interpreted, by using supporting magnetic and drill-hole data, as granitic or mafic intrusive bodies, as will be discussed later.

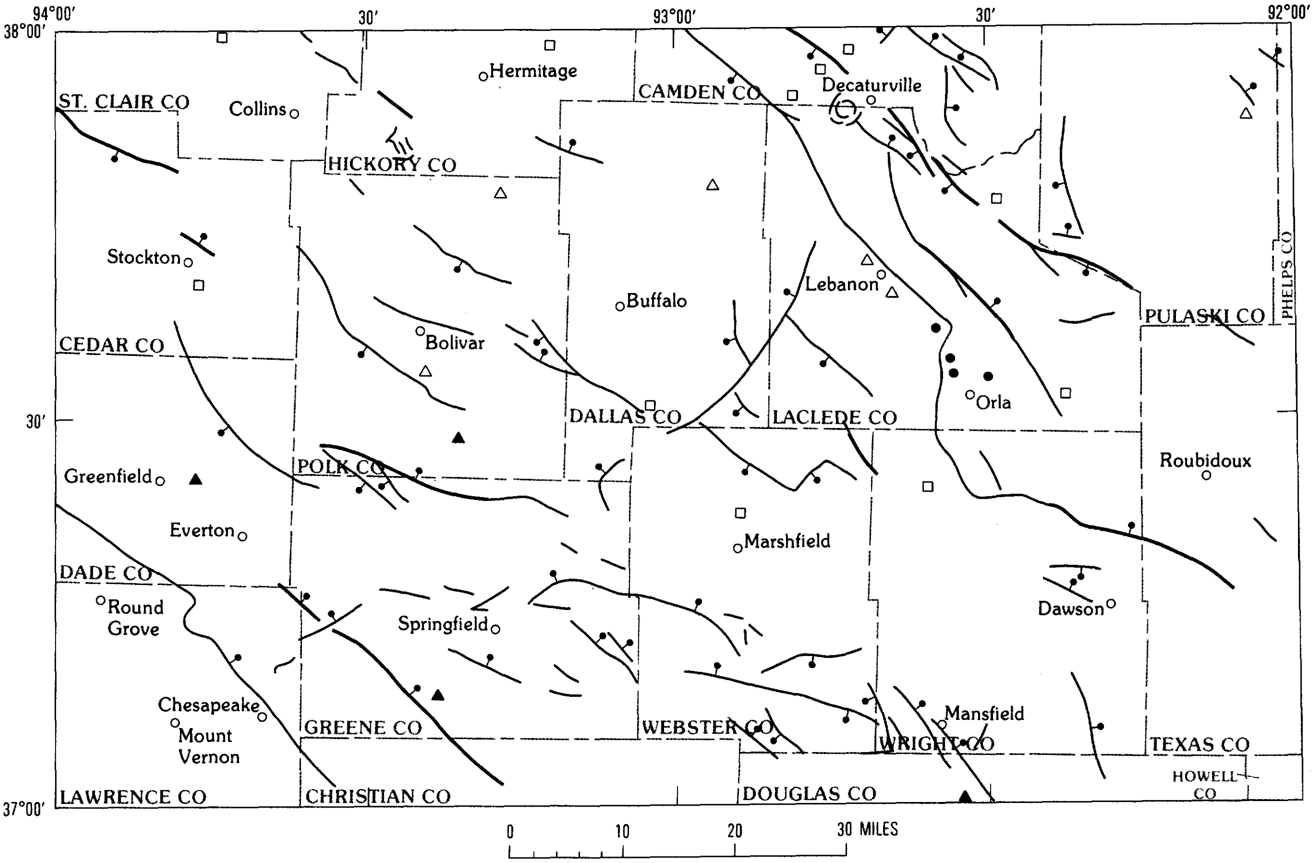



**Figure 30.** Locations of drill holes to basement (rock types generalized from Kisvarsanyi, this volume) and geologically mapped faults (Middendorf, 1985), Springfield 1°×2° quadrangle. Heavy lines indicate geologically mapped faults coincident with major basement density or magnetization boundaries identified in the geophysical data; light lines indicate geologically mapped faults; bar and ball on downthrown side, where known. Drill-hole symbols: open triangle, unmetamorphosed granite; open square, foliated metamorphic rocks; solid circle, gabbro and other mafic rocks. Solid triangles indicate drill holes that are within Cambrian geochemical anomaly of Erickson and others (1985).

## Central Missouri Gravity Low

The prominent 125-km-long gravity gradient that trends northwest through Roubidoux and Decaturville (figs. 30, 31) in the northeastern corner of the gravity map is a segment of the southern boundary of the regional "Missouri gravity low" of Guinness and others (1982) (*see also* Arvidson and others, 1984). The amplitude of the anomaly along this trend is 15–20 mGal. As an illustrative example, such an anomaly could be modeled as a vertical step more than 2,000 m high and having a density contrast of 0.2 gm/cm$^3$ (higher, if the density contrast is less).

So large a feature must lie within the basement (at least within pre-Upper Cambrian rocks), but at what depth? By analogy with nearby buried rifts (Hildenbrand, 1985, for example), low-density arkose filling an Eocambrian graben could give rise to the observed gravity low. Foliated metamorphic rocks in all six of the basement drill holes within the gravity low in the Springfield quadrangle (fig. 30) (Kisvarsanyi, 1979), however, seem to make the hypothesis of an arkose-filled graben untenable.

The minimum thickness of the anomalously low density body can be estimated from reasonable density bounds and the anomaly amplitude. These in turn permit an estimate of maximum possible source depth, constrained by the steepness of the gravity gradient. The gravity effect $g(x)$ of a vertical step with density contrast ρ at depth ζ and depth extent $\zeta + t$ can be expressed as

$$g(x) = 2\pi\gamma\rho \int_{\zeta}^{\zeta+t} \left[\frac{1}{2} + \frac{1}{\pi} \arctan \frac{x}{\zeta}\right] d\zeta \, ,$$

($\gamma = 6.67$ for length units in km and density in g/cm$^3$), from which the scalar horizontal gradient $\vartheta g / / \vartheta x$, evaluated over the edge of the step ($x = 0$) is

$$g_x(0) = 2\gamma\rho \log \frac{\zeta + t}{\zeta} \, ,$$

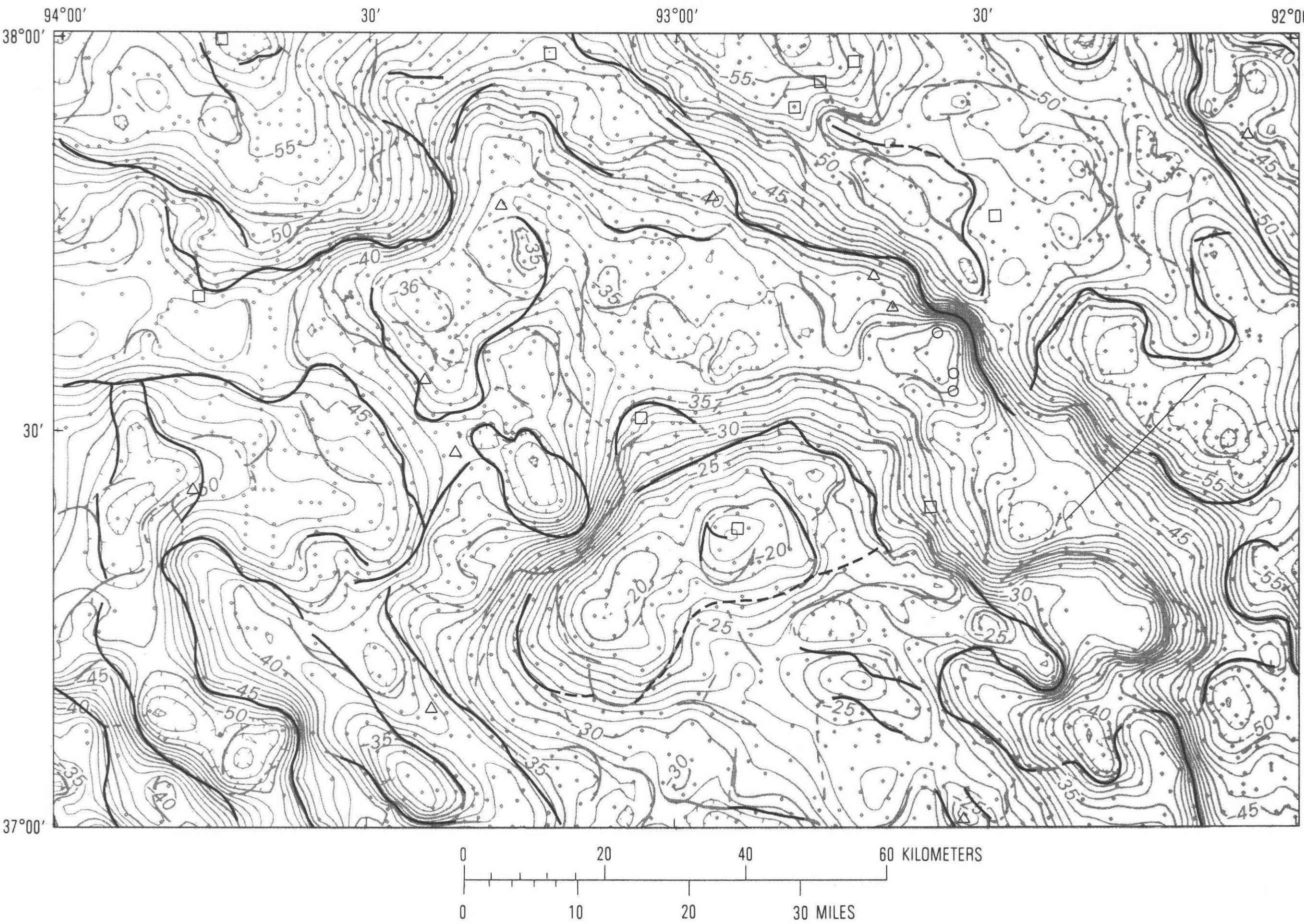



**Figure 31.** Bouguer gravity anomaly map of the Springfield 1°×2° quadrangle. Gravity stations indicated by dots. Reduction density is 2.67 g/cm$^3$; contour interval is 1 mGal. Line segments show trace of inflection points and inferred density boundaries; the more important of these are shown by heavy lines. Basement drill-hole symbols as in data from figure 30. Line of gravity profile (fig. 32) also shown. Modified from Grauch and Cordell (1983).

giving a solution for maximum (because the step is vertical) depth of

$$\zeta_{\max} = \frac{t}{\exp\ [g_x\ (0)\ /2\gamma\rho] - 1} \ . \qquad (1)$$

A profile (fig. 32*A*) across the gravity anomaly shows a gravity amplitude of 19 mGal and a gradient at the inflection point of 1.4 mGal/km. If the upper bound density contrast is 0.2 g/cm$^3$, then the minimum thickness, $t$, is 2.3 km, giving, with the help of the preceding equation, a maximum depth to the top of the step of 3.3 km. A nonlinear matrix-based computer inversion (Webring, 1985) shown in figure 32*B* gives a slightly greater depth (4 km) and thickness (3 km); however, the calculated gravity effect of the model gives a slightly gentler gravity gradient than is observed, showing that the model is at or below the maximum depth.

The steeper the gradient, the shallower must be the source. I avoided the steepest part of the anomaly, some 20 km northwest of the profile of figure 32, because here the gradient is oversteepened because of mafic intrusive rocks at Orla, as discussed later. Possibly the gradient at the computed profile is also oversteepened due to adjacent

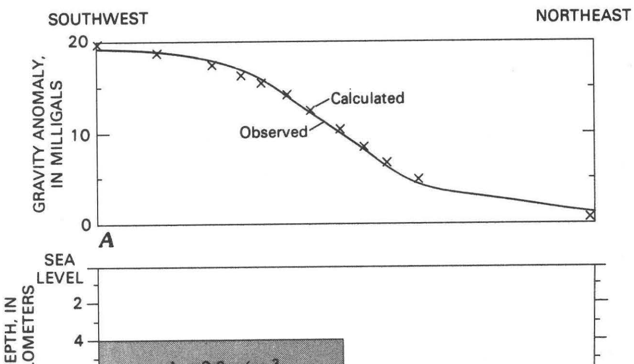



**Figure 32.** Gravity profile and model across border of Central Missouri gravity low (fig. 31). *A*, Gravity profile showing observed gravity anomaly (solid line) and gravity effect calculated from model (indicated by x's). *B*, Gravity model, horizontal and vertical scales are the same.

sources and gives a too shallow depth to source. Evaluation of equation (1) for other locations along the gradient trend northwest of Lebanon (fig. 30), however, gives similarly shallow maximum depths.

To review: if a vertical step and single-density contrast are valid assumptions, then reasonable density bounds require the central Missouri anomaly edge to reflect a 2,000- to 3,000-m-thick step, and the gravity gradients observed require that the step be no deeper than about 4 km. Limited drill-hole data do not suggest a low-density source immediately at the basement surface and cannot easily accommodate a hypothesis of Late Proterozoic rifting. Aeromagnetic data raise even more questions concerning this gravity low.

## Marshfield and Other Gravity Anomalies

Near the center of the gravity map, near Marshfield (figs. 30, 31), is a prominent 50 by 20 km gravity high. It is particularly prominent because it trends northeast, athwart the regional northwesterly grain. The amplitude of this anomaly is difficult to extract from background but is probably more than about 15 mGal, again indicating a thickness of more than 2,000 m of, in this case, relatively high density rock. A complicated magnetic pattern is associated with this anomaly.

Certain other prominent gravity anomalies, some associated with magnetic features, are a large low centered at Collins in the northwestern corner of the map, a sharp, sinuous low between Mount Vernon and Greenfield in the southwestern quadrant, and highs adjacent to the Mount Vernon anomaly and at Dawson and Lebanon.

# AEROMAGNETIC DATA

About half the Springfield quadrangle was previously covered by aeromagnetic data flown at 0.5- and 0.25-mi line-spacings; aeromagnetic surveys of the remainder of the quadrangle were flown by the U.S. Geological Survey, at 0.5-mi line-spacing, for the CUSMAP study (Missouri Geological Survey, 1981; U.S. Geological Survey, 1984). These data are shown and discussed here in image format, which brings out, far better than either color or contour maps, the high-frequency signature zonation upon which most of the interpretation depends.

Image analysis of aeromagnetic data has been reviewed by Cordell and Knepper (1987). For the Springfield image, a low-order surface (fig. 33) obtained from a band-pass filter, tapered in the frequency domain, was removed from the data. The upper and lower 2 percentiles of the filtered data were skimmed (assigned white or black tones, respectively), and the rest of the data was scaled linearly into 256 gray-tone levels—darker for low, lighter for high. The resulting image is shown in figure 34. Figure 34 includes data from the adjacent Rolla quadrangle (Cordell and Knepper, 1987) to show continuity of the central Missouri feature, but otherwise only the Springfield data will be discussed here.

For even greater dynamic range, another higher order regional surface (fig. 35, obtained by using the strip-filter method of Cordell, 1985) was removed from the data, yielding the aeromagnetic data image shown in figure 36. Although certain trends are enhanced in figure 36, figure 34 is generally more representative of the data.

The inclined polarization of the Earth's magnetic field causes induced magnetic anomalies to be skewed toward the south side of the causative body; thus, features are mislocated when the data are interpreted by inspection. To avoid this problem, Cordell and Grauch (1985) developed a spiking function for delineating magnetization boundaries automatically, similar to the method of delineating density boundaries used in making figure 31. Results of application of the spiking-function operator to the original Springfield total-field residual aeromagnetic data are shown in figure 37. Lines drawn by inspection along highs (light tones) delineate magnetization boundaries.

The boundary lines from figure 32 were transferred to the original aeromagnetic image (fig. 34), the more significant boundaries were selected subjectively, and probable boundaries missed by the automatic method were completed by inspection.

The result (fig. 38) is an annotated image providing a remarkable picture of the buried basement of the Springfield quadrangle. I emphasize that the solid lines on the figure are determined by objective, reproducible methods and that these lines are generally displaced slightly northward, as they should be, from their associated magnetic anomalies.

The background pattern is flowing and lineated and likely reflects the foliation trend (west to west-northwest, *not* northwest) of the metamorphic basement. Subcircular knots 5–30 km in diameter are in this matrix; some of these have the low-with-high-border magnetic signature associated with epizonal granite in the adjacent Rolla 1°×2° quadrangle (compare with fig. 34). Extreme highs (white spots) delimit drilled gabbro bodies in the Orla area and perhaps elsewhere (Kisvarsanyi, this volume).

Otherwise, a less coherent relationship between the drill-hole and aeromagnetic data sets (fig. 38) would be hard to imagine. Drawing a simple boundary line separating the anorogenic from the orogenic terranes seems to have little merit, and such a simple boundary may not, in fact, exist. The lineated pattern in the aeromagnetic data, however, can only reflect either metamorphic grain or a pattern of imbricated faulting in otherwise unlineated anorogenic granite.

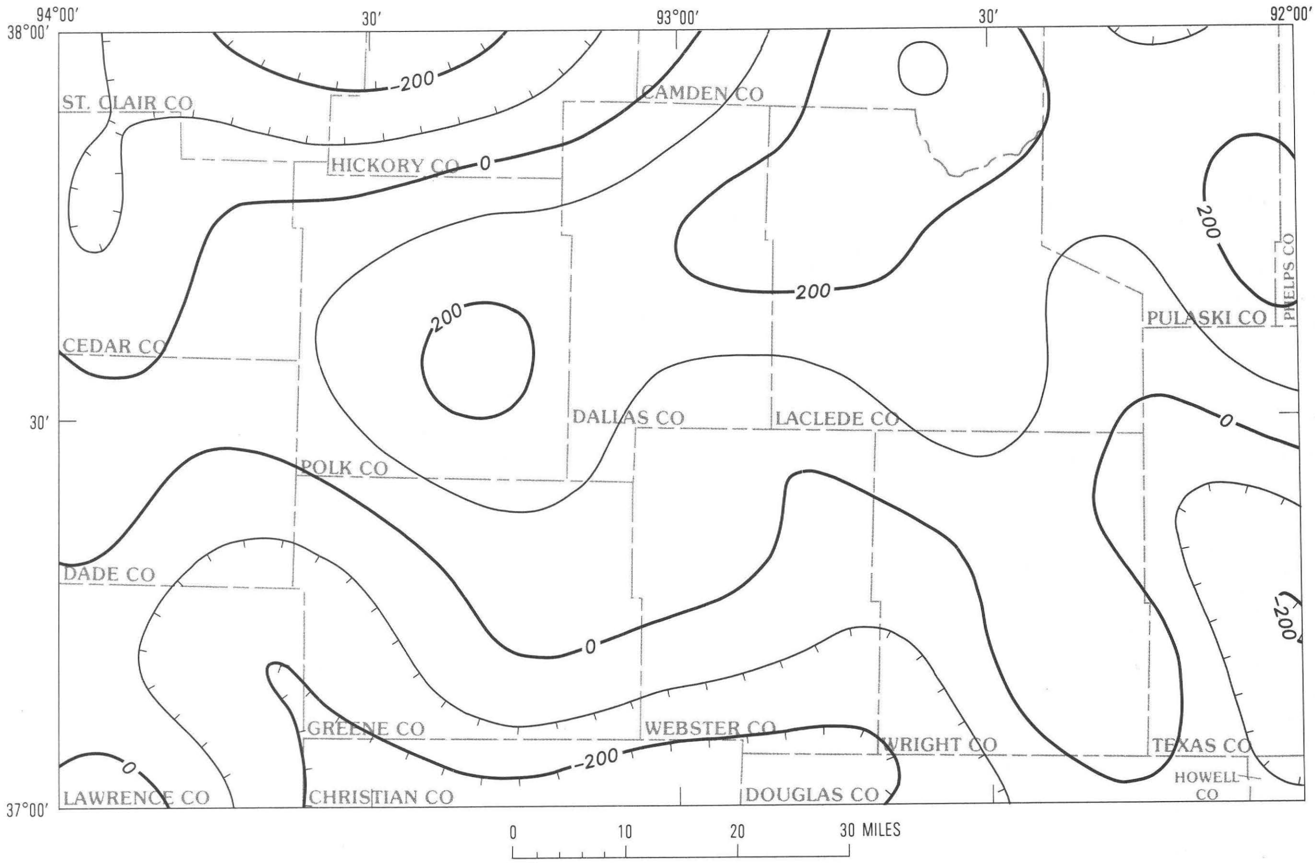



**Figure 33.** Low-order surface removed from residual aeromagnetic intensity data, Springfield 1°×2° quadrangle. Contour interval 100 gammas. Zero contour shown by heavy line; hachures indicate lows.

## The Central Missouri Gravity-Magnetic-Tectonic Zone

The most eye-catching feature in the aeromagnetic image (figs. 34, 38) is the northwest-trending, magnetically low swath across the quadrangle in the area of the Missouri gravity low defined by Guinness and others (1982) and Arvidson and others (1984) (fig. 31). The feature can be tracked across a corner of the adjacent Rolla quadrangle (fig. 34) and has an overall length of at least 160 km. The magnetic low is fairly uniformly 20 km wide. Its southern side is exactly coincident with the gravity boundary (compare gradient lines delineating physical property boundaries in figs. 31, 38) but is not represented by surficial faults (although a major fault zone is present in the general vicinity of the southern edge of the magnetic anomaly, fig. 30). The northern edge of the magnetic anomaly is only subtly expressed in the gravity data but coincides exactly with mapped surficial faults (compare figs. 30, 31, 38). Sharp magnetic highs over inferred mafic intrusive rocks are present preferentially along the edges of the magnetic anomaly, and the magnetic high near Decaturville gives the impression of being truncated by the northwest-trending border of the magnetic low.

Kisvarsanyi (1984, this volume) defined a tectonic zone coincident with the southern border of the Missouri gravity low and named it the Central Missouri "tectonic zone." As defined by her, this is a statewide feature. In light of the complications encountered when gravity, magnetic, drill, and fault data are considered together, this seems justified. Kisvarsanyi's "Central Missouri tectonic zone" in the Springfield quadrangle (1984; figs. 47, 48, this volume) approximately coincides with the northern edge of the magnetic low (fig. 38). Both the presence of foliated metamorphic rocks and the lack of attenuation of magnetic anomalies within the gravity low indicate that the anomaly source is probably not a graben in which the metamorphic basement is buried by thick, low-density, detrital fill. A zone of strike-slip faulting is an alternative hypothesis. There is no real evidence for such faulting except that local magnetic features do seem to be truncated at the edge of the northwest-trending magnetic low. On straining, one can imagine 50 km of right-lateral displacement of the material straddling the Springfield-Rolla quadrangle boundary relative to similar-patterned material in the central part of the Springfield quadrangle (figs. 34, 36). I emphasize that the only real evidence from the geophysical data is for a sharply defined northwest-trending tectonic zone involving

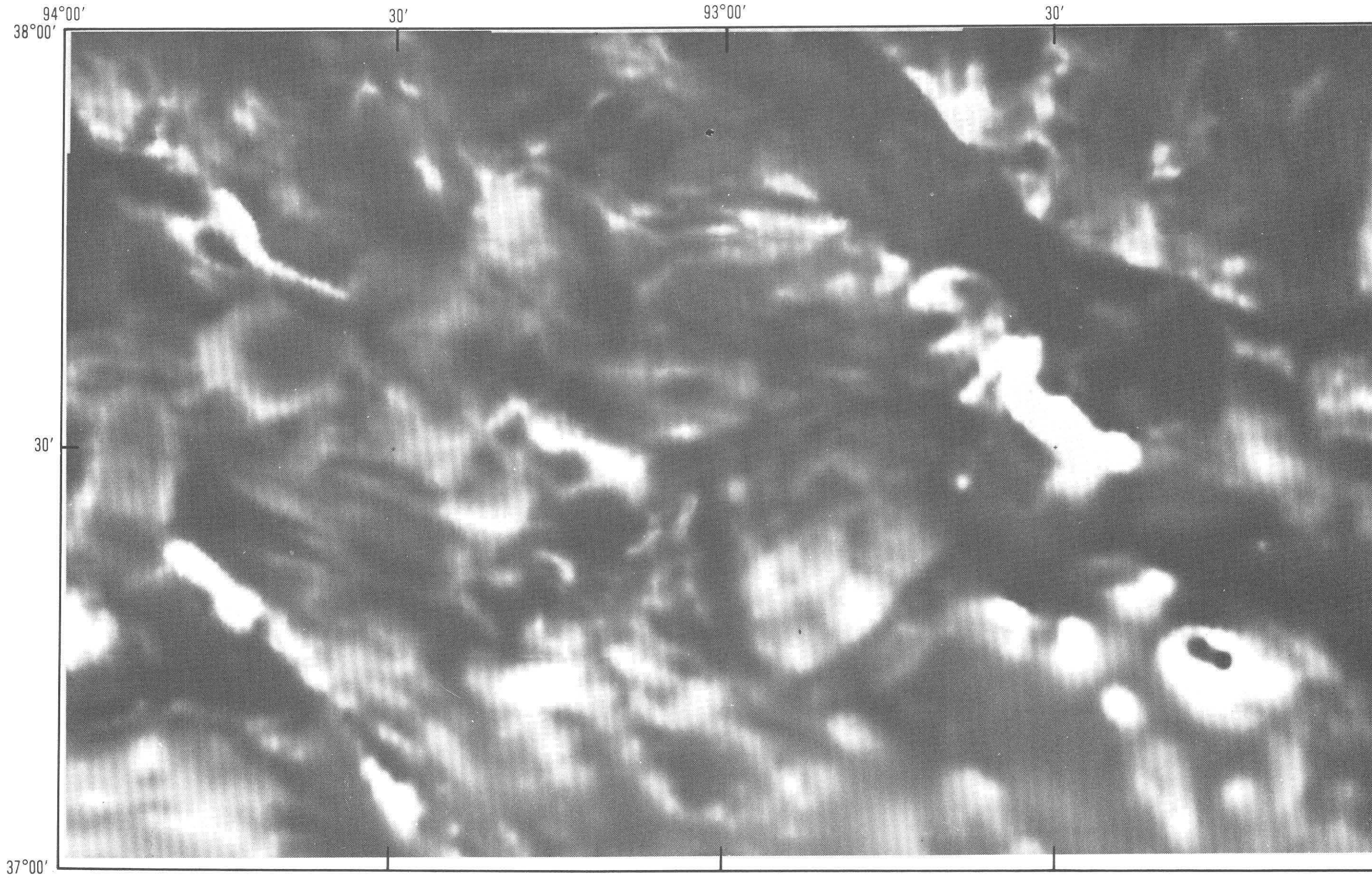



**Figure 34** (above and facing page). Gray-scale image of high-pass aeromagnetic data, Springfield and Rolla 1°×2° quadrangles. Dark is low; light is high. See text and Cordell and Knepper (1987) for technical details.

major abrupt linear density and magnetization contrasts within the basement.

## Mafic Plutons

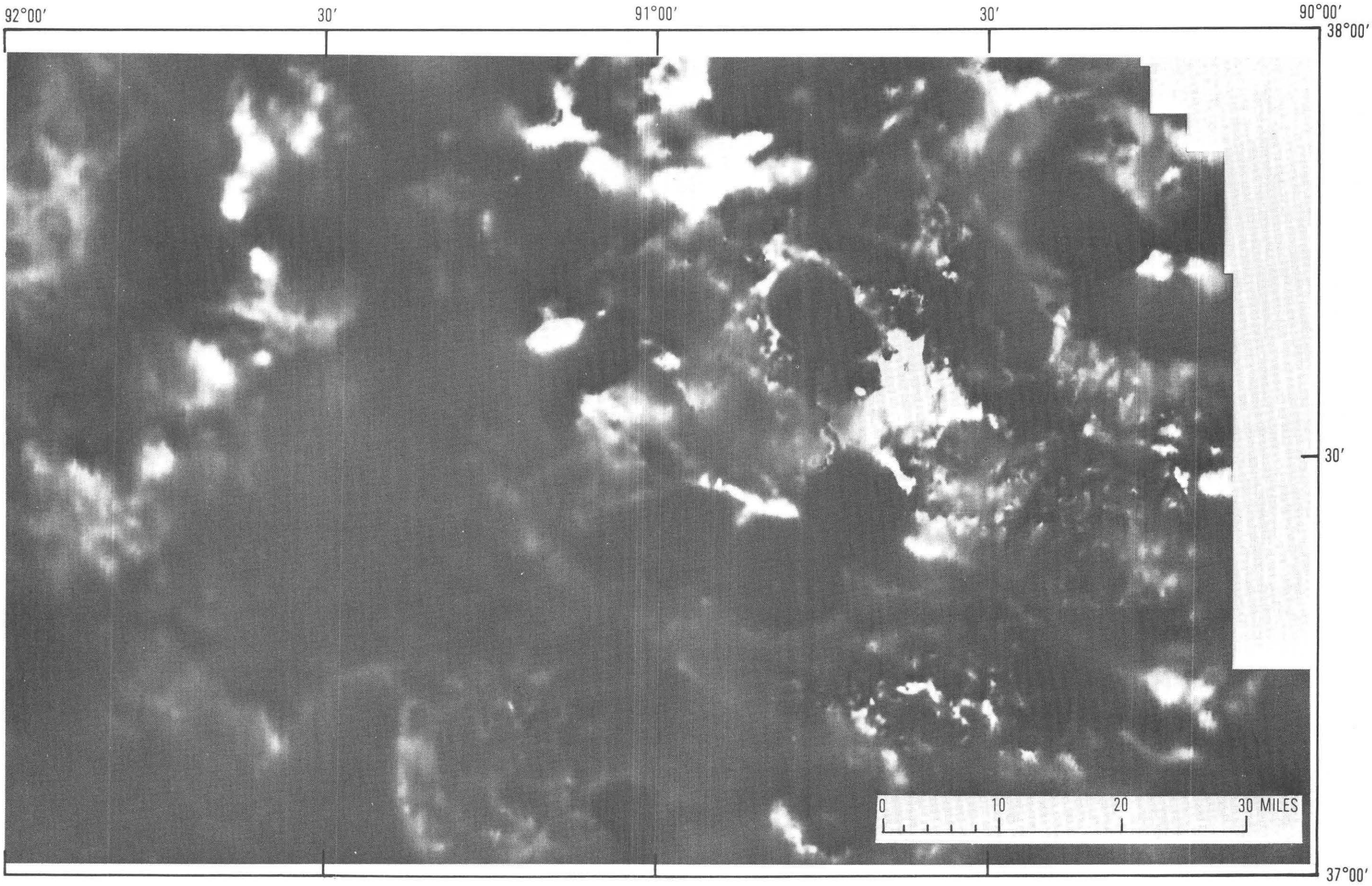
Drilling on the magnetic high near Orla encountered a layered gabbro pluton described by Kisvarsanyi (this volume). Similar anomalies elsewhere in the quadrangle probably also indicate mafic dikes and plutons. Although the magnetic data provide the location of these, the associated gravity anomalies give a better estimate of their relative size. The biggest of these is near Dawson in the southeastern quadrant of the quadrangle, where both a subcircular feature and a dikelike magnetic feature are associated with very prominent gravity highs. A similar dikelike gravity and magnetic high is at Everton in the southwestern quadrant. Amplitudes of the Dawson and Everton gravity anomalies are difficult to extract from complicated background fields but are probably about 5–10 mGal. Prominent magnetic highs near Stockton, Springfield, and southeast of Bolivar, as at Orla, are associated with gravity anomalies of only a few milligals. Gravity data are insufficient to characterize the large magnetic high at Round Grove.

## Marshfield Anomaly

The prominent gravity anomaly at Marshfield, discussed previously, can be seen on close inspection to be constricted by a low-gravity belt across its middle, forming an eastern half and a western half (fig. 31). The eastern half has a coherent magnetic expression; the western half does not. The lone drill hole (in the eastern half) intersected a granoblastic orthogneiss of moderately high metamorphic grade (Kisvarsanyi, this volume). Magnetic patterns within the eastern half, however, show a subcircular, cobblestone-like pattern thought to be characteristic of plutons in the anorogenic terrane (Cordell and Knepper, 1987).

## Other Circular Features

Circular magnetic lows in various places on figure 38 are reminiscent of similar lows associated with gravity lows and known granite plutons in the Rolla quadrangle (fig. 34)




(Cordell and Knepper, 1987). Here, however, the interpretation is less straightforward. The ringed magnetic low at Greenfield near the western edge of figure 38 is associated with a gravity low, but the gravity low continues to the south for 40 km, to the southern edge of the map area (fig. 31). A similar magnetic low nearby (southeast of Stockton) has no gravity expression. Magnetic lows 5–10 km in diameter, east of Hermitage and elsewhere in the northern part of the map, are too small to show up in the gravity data. There is no obvious alignment of the magnetic lows.

## STRUCTURAL GRAIN

The geophysical data show two distinct structural trends in the basement: a west-northwest trend throughout the central part of the quadrangle and a northwest trend common to most individual large features. I believe that the west-northwest trend may represent the foliation trend of the older orogenic metamorphic terrane. The northwest trend is shared by the various gravity and magnetic lines defining the Central Missouri tectonic zone and by the dikelike trend of the inferred mafic bodies at Orla, Everton, and west of Dawson. Both of these trends permissively suggest a brittle, fracture-dominated regime.

Similar northwest and west-northwest grain can be seen in the bedrock (fig. 30). Quite a few of the geologically mapped faults (Middendorf, 1985) are exactly coincident with basement density and magnetization features (see fig. 30). The surface faults show only dip-slip-normal displacement of generally much less than 100 m and would be too small to cause anomalies. The observed gravity and magnetic anomalies reflect much thicker and larger volume lithologic discontinuities in the underlying basement by which the coincident post-early Paleozoic faulting has been passively controlled. A particularly good case for this seems to be along the Central Missouri tectonic zone.

Inherited structural control is a plausible and popular notion and always a principal concern of buried-basement geophysical studies. It is difficult to establish because of the problem of mapping in three dimensions and is actually established only rather infrequently. In my experience, the amount of *exact* correspondence (loose correspondence is always easily found) between faults and basement geophysical trends in the Springfield data is exceptional and indicates that the west-northwest and northwest basement fabric was favorably aligned with whatever post-early Paleozoic stress regime caused the mapped faults. Young structures *cut* old structures, otherwise. A northeast

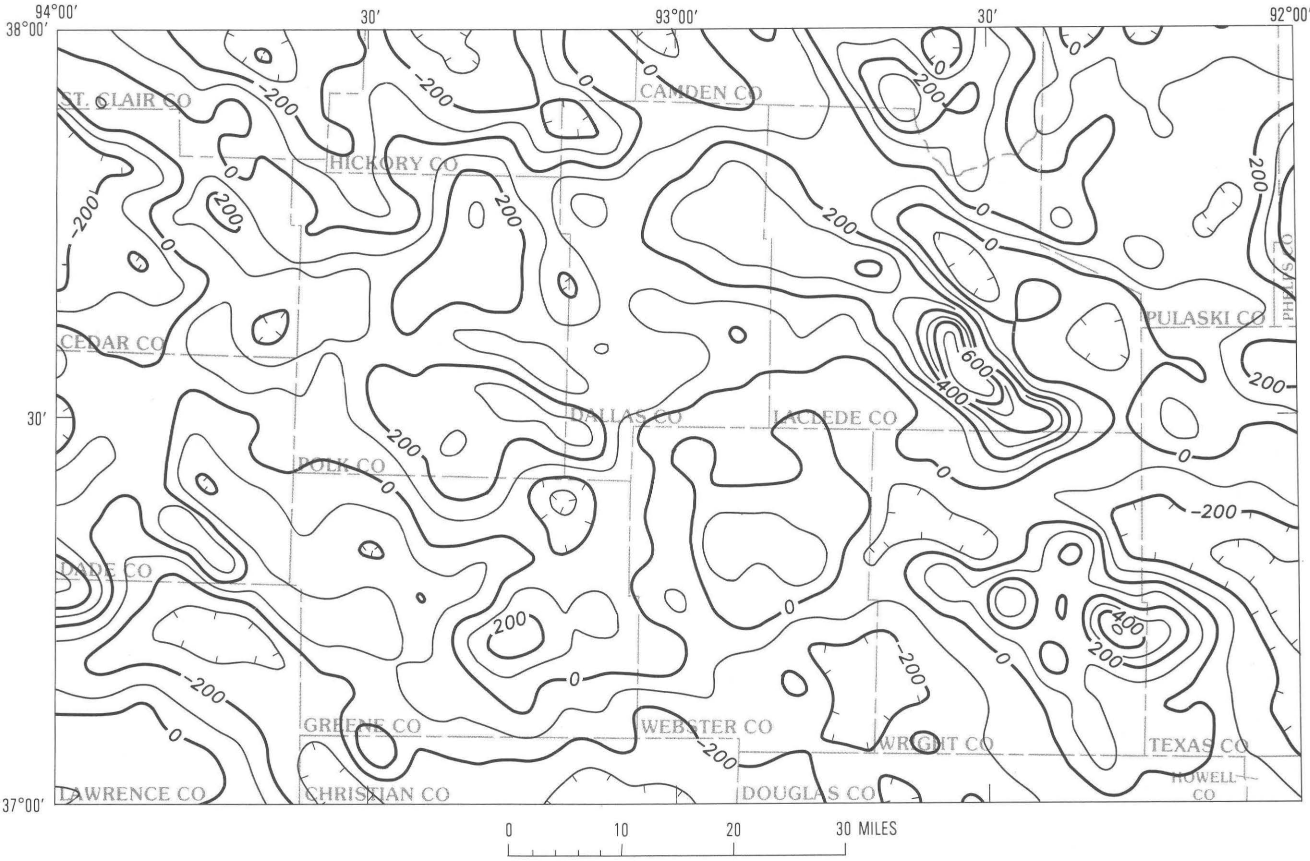



**Figure 35.** Alternative, higher order, low-pass surface removed from the aeromagnetic data, yielding image shown in figure 34. Contour interval 100 gammas.

diagonal line from corner to corner across the fault map of Middendorf (1985) (fig. 30) crosses only northwest-trending "dip-slip-normal" faults (11 of these) that indicate a stress regime of modest but significant southwest-directed extension. This seems an unexpected result in light of regional tectonics. Sense of displacement in the basement structures, if they are faults, is unknown.

Kisvarsanyi (1984) identified, in combined subsurface, structural, remote-sensing, and other regional data, two other tectonic zones, the Bolivar-Mansfield and the Chesapeake, that trend northwest across the western part of the map area (fig. 38). No clear aeromagnetic expression of these exists either in the high-resolution digital data depicted in figures 34 and 38 or in the colored magnetic map of Zietz and others (1984), nor is there evidence for these tectonic zones in the gravity data (fig. 31).

Lithofacies boundaries, critical to discussion of possible habitat of stratabound base-metal deposits, trend generally north-south across the map area (Erickson and others, 1985, this volume, plate 1; Palmer, 1985, this volume, figs. 4, 7, and 11), seemingly uninfluenced by west-northwest and northwest Precambrian structural grain.

## CONSIDERATION OF THE BASEMENT IN TERMS OF MINERAL RESOURCES

In terms of mineral resources, we need to consider the basement in two aspects: (1) possible mineral deposits within basement rocks and (2) the possible role of basement rocks and structures in the origin of stratabound base-metal deposits within overlying sedimentary strata. Kisvarsanyi (this volume) reviews some of the mineral-deposit types characteristic of the granitic and regionally metamorphosed terranes in the Springfield quadrangle. To judge from industry interest as evidenced by drilling, the most interesting prospect is the mafic complex at Orla, which has anomalous amounts of Cr, Ni, Ti, and Cu. If the complex at Orla is interesting, then the magnetic anomalies over inferred mafic plutons and dikelike bodies at Dawson and Everton would be the more so because of the relatively larger volumes of mafic rocks indicated by the associated gravity anomalies.

In the consensus of the papers in this volume, the principal mineral-resource target is stratabound base-metal deposits. In this regard, the Springfield quadrangle can be

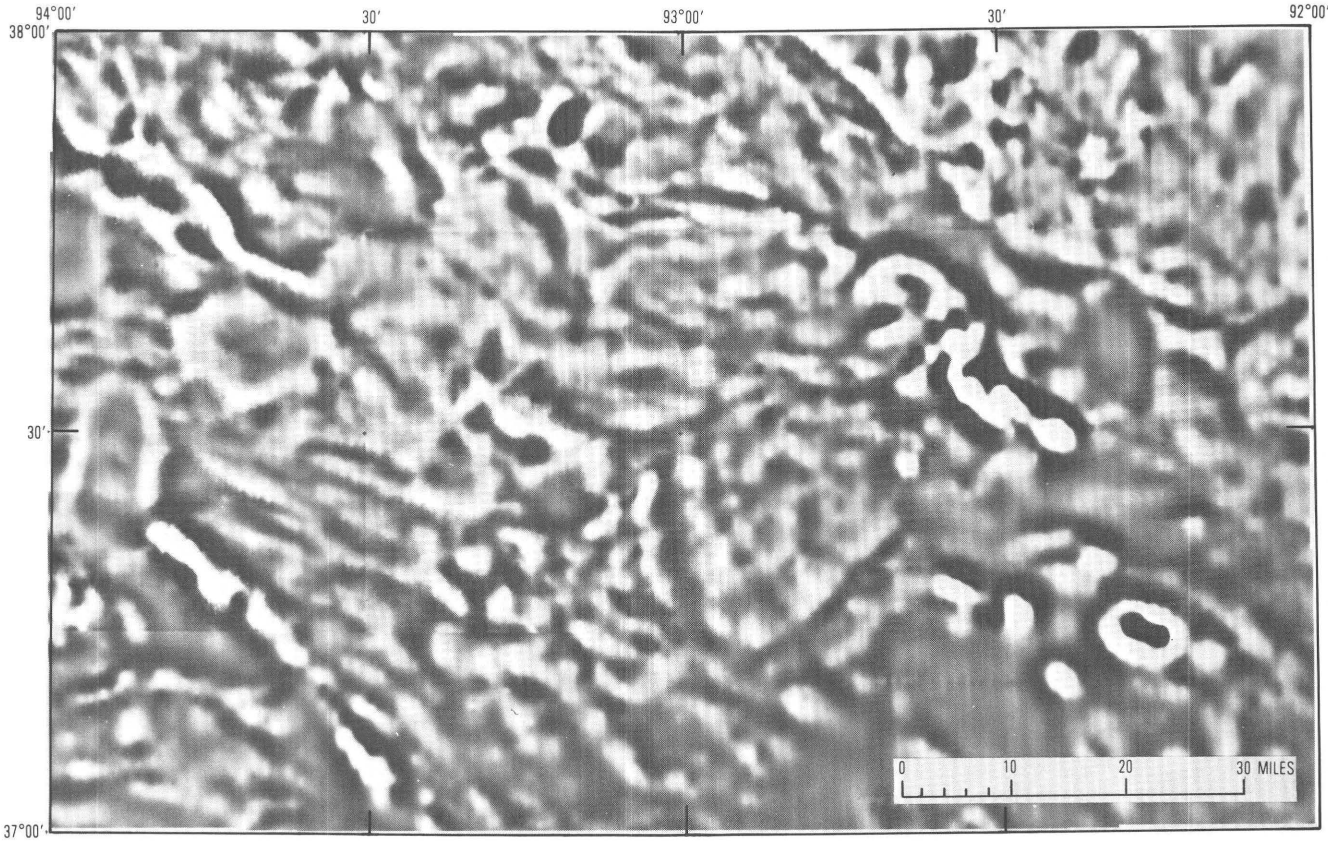



**Figure 36.** Gray-scale image of higher pass aeromagnetic data, Springfield 1°×2° quadrangle.

characterized as a tract of barren ground flanked by important stratabound deposits in the Tri-State, Central Missouri, and Viburnum Trend districts. A particular affinity with the Tri-State zinc-lead district is suggested by Wharton (this volume).

Erickson and others (1985, this volume) described a northwest-trending swath of anomalous metal content in insoluble residues in "post-Bonneterre Cambrian" rocks (fig. 30). Erickson and Chazin (this volume) describe the anomalous metal zone as being bounded by the Cheaspeake and Bolivar-Mansfield "tectonic zones," and they infer that the area between these zones is the major plumbing system for ore fluids in the Springfield quadrangle.

If a relationship between the geochemically anomalous drill-hole samples in the western part of the quadrangle and faults is perceived, then there is a surely better relationship between barren holes and the better developed fault system in the eastern part of the quadrangle (fig. 30). The Central Missouri tectonic zone is a major feature involving large, abrupt physical-property discontinuities in basement rocks, igneous (mafic?) intrusions, and demonstrable superposition of structural trends in overlying strata. The barrenness of such a zone suggests that a favorable host rock, geochemical environment, or other "elusive unique factor" (Erickson and Chazin, this volume) necessary to cause precipitation of metal was not present.

All four of the geochemically anomalous holes drilled to basement bottomed in anorogenic granite. By contrast, all of the holes that bottomed in the foliated metamorphic terrane were barren (fig. 30). This could mean simply that both metals and granite increase westward from the central part of the quadrangle, without causal relationship. The inability of the geophysical data to define a boundary between the granite and metamorphic terranes in the Springfield area is puzzling but could indicate that the boundary is either gradational (hybridization, for example) or one of gentle onlap.

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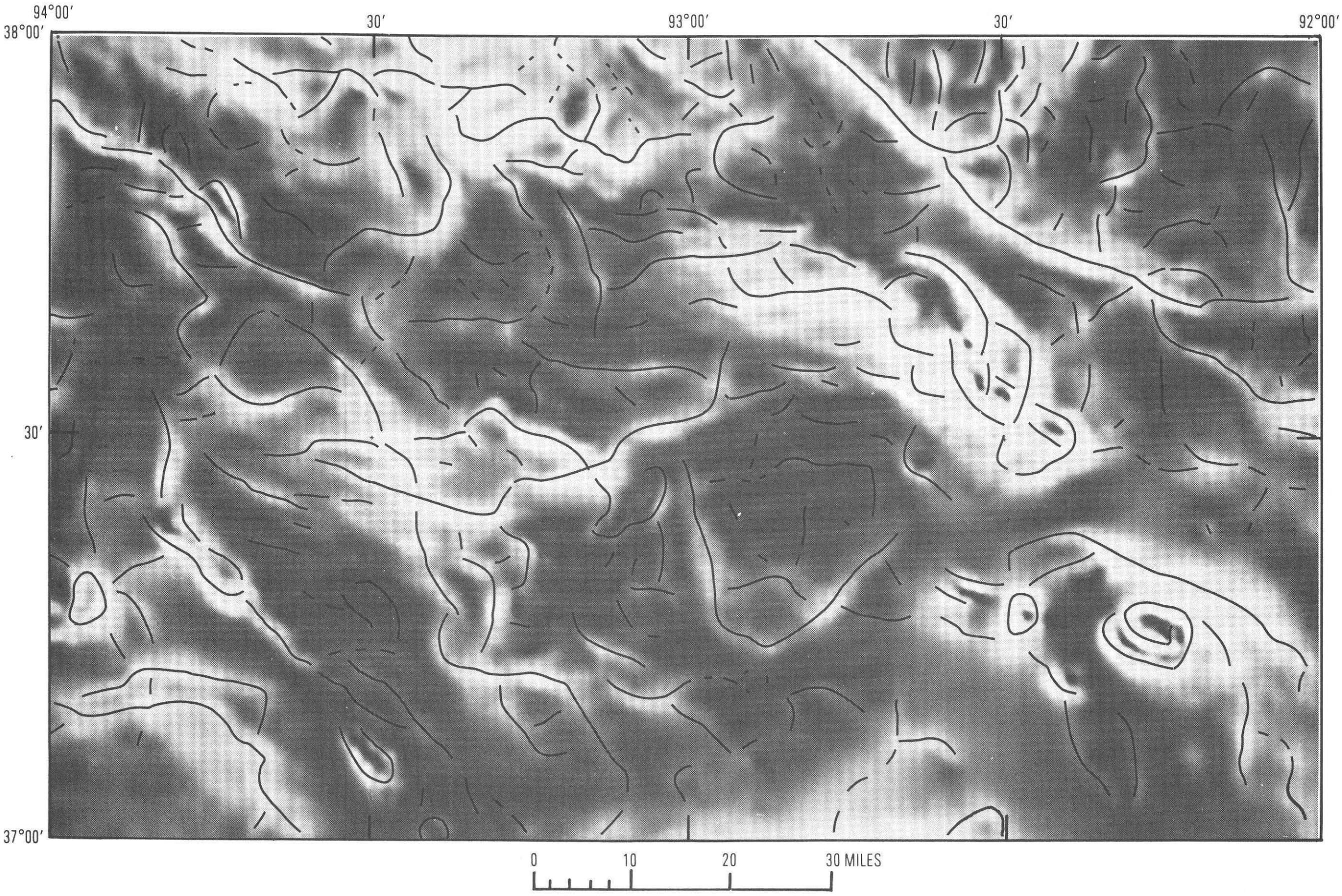


**Figure 37.** Magnetization boundaries, as determined by trace of maxima (light tones) of amplitude of horizontal component of pseudogravity gradient, Springfield 1°×2° quadrangle. Calculated using methods of Cordell and Grauch (1985).


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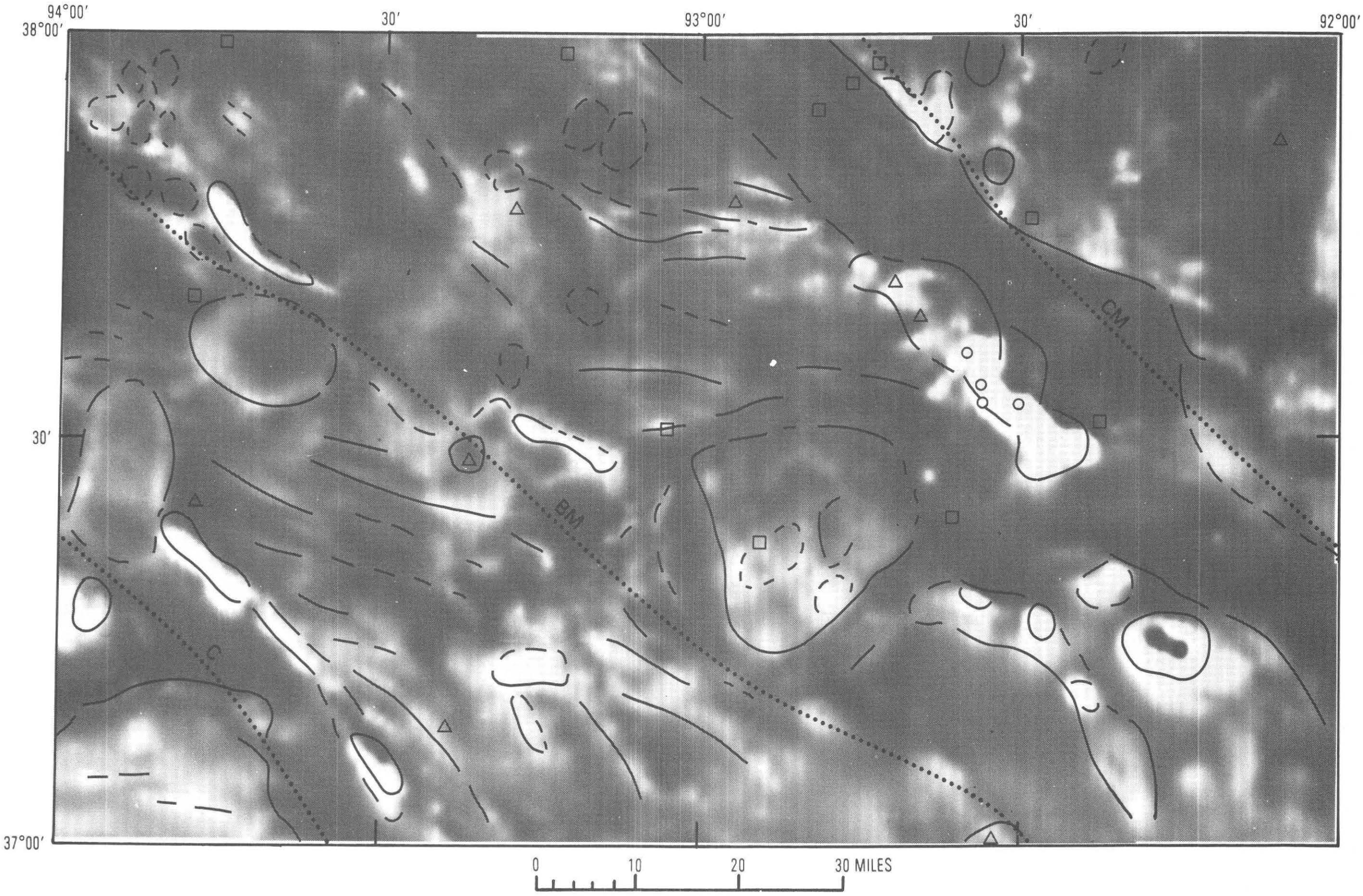


**Figure 38.** Aeromagnetic image (Springfield data from figure 34) showing principal magnetization boundaries and drill-hole data, Springfield 1°×2° quadrangle. Solid line boundaries traced from figure 37; dashed line boundaries determined by inspection; drill-hole data from figure 30. Dotted lines show Central Missouri (CM), Bolivar-Mansfield (BM), and Chesapeake (C) tectonic zones of Kisvarsanyi (this volume).

# Industrial Mineral Resources

*By* Ardel W. Rueff[1]

## INTRODUCTION

The industrial mineral resources of the Springfield 1°×2° quadrangle are crushed stone, dimension stone, industrial sand, construction sand and gravel, and clay and shale. Of these, only stone and construction sand and gravel are currently of economic importance; industrial sand and clay and shale are judged to be hypothetical resources. Lime, a product manufactured from high-purity limestone, is produced in the quadrangle but is considered together with other crushed stone products. Barite in the quadrangle is considered in a separate report (Wharton, this volume) because of its association with lead and zinc resources. All current mineral production in the Springfield quadrangle is from industrial minerals; the value of this production during 1983 was approximately $16 million. Figure 39 shows production values for the period 1952 through 1983. Table 5 is a generalized stratigraphic table of units cited in the text.

[1]Missouri Geological Survey, P.O. Box 250, Rolla, Missouri 65401.

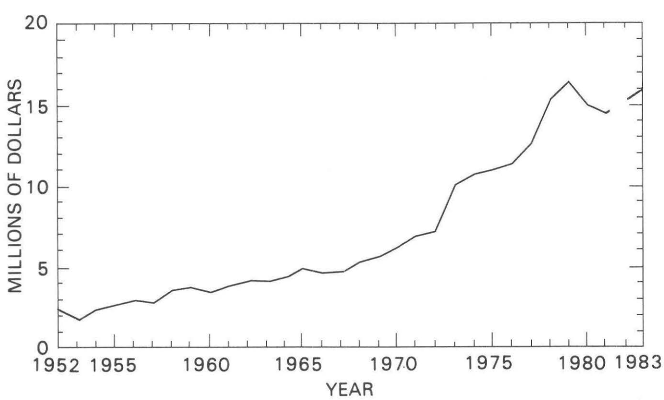


**Figure 39.** Annual value of industrial mineral production in the Springfield 1°×2° quadrangle, 1952–1983.

**Table 5.** Generalized stratigraphic table of units cited in text

| |
|---|
| PENNSYLVANIAN SYSTEM |
| Undifferentiated channel sandstones |
| Desmoinesian Series |
| Cherokee Group |
| Rowe Formation |
| Warner Formation |
| Atokan Series |
| Riverton Formation |
| MISSISSIPPIAN SYSTEM |
| Meramecian Series |
| Warsaw Formation |
| Osagean Series |
| Burlington and Keokuk Limestones |
| Elsey Formation |
| Reeds Spring Formation |
| Pierson Limestone |
| Kinderhookian Series |
| Northview Formation |
| Sedalia Formation |
| Compton Limestone |
| Bachelor Formation |
| ORDOVICIAN SYSTEM |
| Canadian (Ibexian) Series |
| Jefferson City and Cotter Dolomites |
| Swan Creek sandstone (an unranked unit of the Cotter Dolomite) |
| Roubidoux Formation |
| Gasconade Dolomite |
| Gunter Sandstone Member |
| CAMBRIAN SYSTEM |
| Upper Cambrian Series |
| Eminence Dolomite |

This report is taken from a more detailed report and series of maps published in the Springfield CUSMAP folio (Rueff, 1987).

## CRUSHED STONE

Crushed stone is the most valuable mineral commodity produced in the quadrangle. In 1983, the latest year for which complete data are available, 2.8 million tons was produced; production was reported from 20 sites representing every county in the quadrangle. The major use during that period was for aggregate; other uses included lime manufacture, aglime, and specialty limestone products. Figure 40 shows annual stone production in the quadrangle from 1952 through 1983; figure 41 shows stone production by use during 1983.

In order to evaluate the stone resource potential of the quadrangle, samples were collected from 42 localities. Major-element chemical analyses and common aggregate tests were run on each sample (Rueff and Hayes, 1985). These data, combined with knowledge of past and present usage, provide a basis for classifying the stone resources of the quadrangle into the five categories listed below. Figure 42 shows the general distribution of these resources.

1 Known resources of *high-purity limestone*. For the purposes of this report, high-purity limestone consists of formations that contain mineable sections of limestone having a minimum $CaCO_3$ content of 95 percent ($CaO \geq 53$ percent). Resources meeting this criterion are in the Warsaw Formation and Burlington and Keokuk Limestones.

2. Known resources of *high-specification aggregate*. This is an arbitrary category that designates stone meeting standard specifications of the Missouri Highway and Transportation Department and other agencies, for aggregate used in portland cement. Resources meeting this criterion are in the Warsaw Formation and Burlington and Keokuk Limestones.

3. Known resources of *commercial limestone and dolomite*. This category includes rock units in the high-purity limestone and high-specification aggregate categories and those suitable for less stringent aggregate and aglime use. Resources are in the Warsaw and Sedalia Formations; Burlington, Keokuk, Pierson, and Compton Limestones; and Jefferson City, Cotter, and Gasconade Dolomites. Resources of commercial limestone and dolomite are large and widespread in the quadrangle.

4. Known resources of *high-purity dolomite*. Resources in this category consist of those dolomite formations that contain mineable sections of dolomite having a $MgCO_3$ content of 40 percent or greater ($MgO \geq 19$ percent). Resources are in the upper unit of the Gasconade Dolomite and in the Eminence Dolomite.

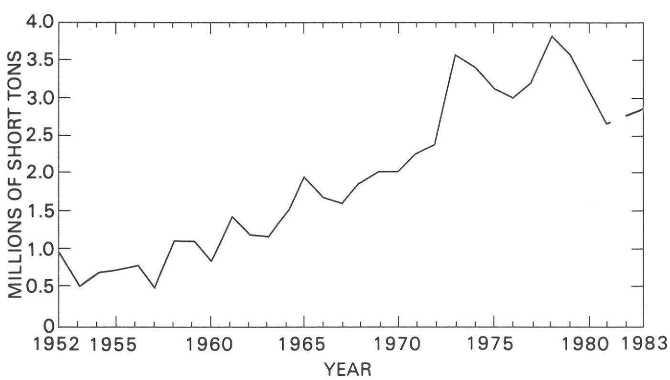


**Figure 40.** Annual stone production in the Springfield 1°×2° quadrangle, 1952–1983.

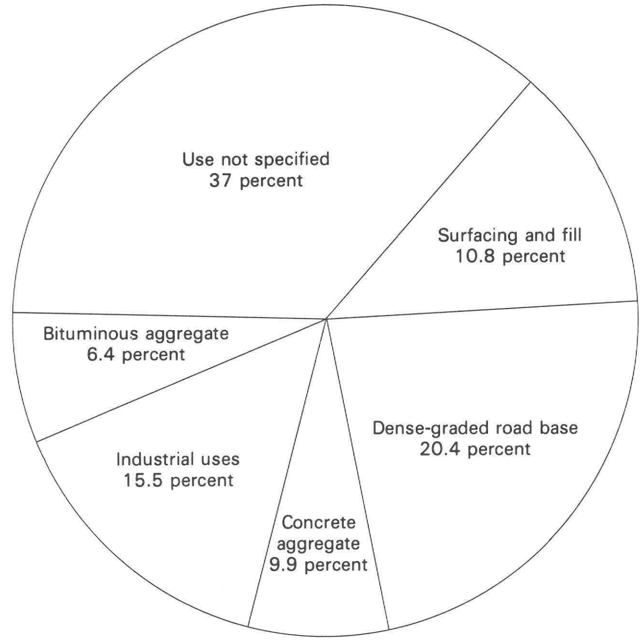


**Figure 41.** Stone production by use during 1983 in the Springfield 1°×2° quadrangle.

5. Hypothetical resources of *high-specification aggregate*. This category consists of formations that may contain sections of stone meeting the specifications for high-specification aggregate as defined earlier. The upper unit of the Gasconade Dolomite is the only unit in this category.

Large areas of the Springfield quadrangle are underlain by formations having little or no commercial value as crushed stone; they are left blank on figure 42. Areas in this category are those underlain by the Pennsylvanian formations and the Elsey, Reeds Spring, and Roubidoux Formations and those near complex structural features.

For detailed information on the structure, lithology, and distribution of geologic units mapped in the quadrangle refer to Middendorf (this volume) and Middendorf and others (1987).

## DIMENSION STONE

Dimension-stone resources are considered separately from crushed stone resources, though they include many of the same formations. Although these resources are large and diverse, they have little economic value. Dimension-stone resources in the quadrangle can be divided into the following categories.

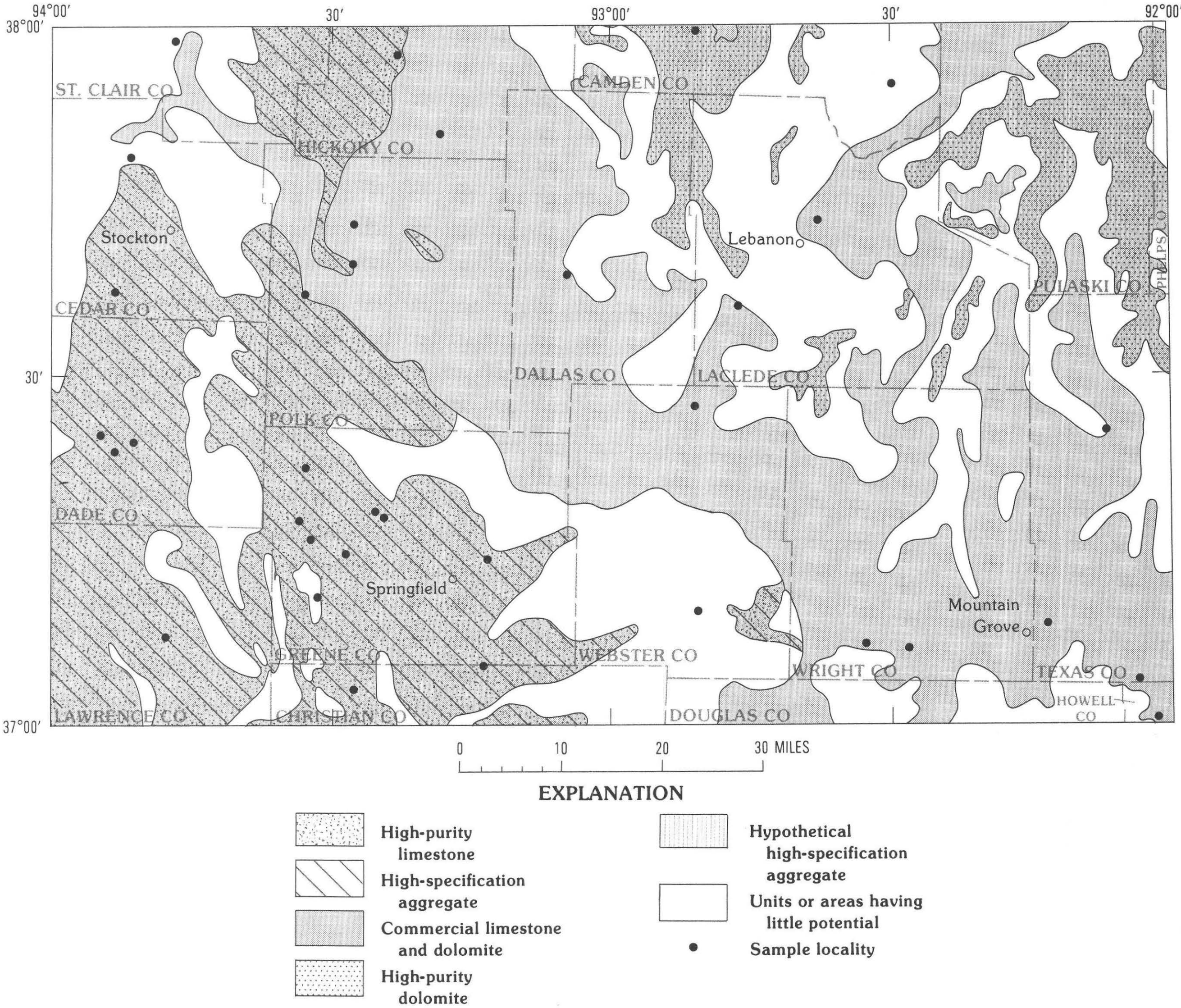


**Figure 42.** Stone resources of the Springfield 1°×2° quadrangle.

1. Known resources of *marble*. For purposes of this report and by commercial definition, marble is any carbonate rock that can be polished. Resources are in the Warsaw Formation and the Burlington and Keokuk Limestones. A quarry that produced rough blocks of Warsaw limestone for finishing outside the area of the quadrangle has been closed since the early 1960's.

2. Known resources of *siltstone*. Resources are in the Northview Formation where that unit is a durable, calcite-cemented siltstone. Siltstone from the Northview is commonly used in construction of fireplaces and for decorative purposes where an earthy, dark-colored stone is desired. It is commonly used with dark or black mortar.

3. Known resources of *carbonate building stone*. This category includes carbonate rock units that have past or present use as building, rubble, or flagging stone. The rock is commonly used as roughly shaped blocks. Resources having extensive past production are in the Warsaw Formation, Burlington and Keokuk Limestones, and Jefferson City, Cotter, and Gasconade Dolomites. Minor resources are in the Pierson Limestone, Sedalia Formation, and Compton Limestone.

4. Known resources of *sandstone building stone*. This category includes those units having past or present use as building, rubble, or flagging stone. Resources are in the Roubidoux Formation and in the Gunter Sandstone Member of the Gasconade Dolomite. These sandstones have been extensively used in southern Missouri for houses, fireplaces, patios, and decorative trim.

Units having little potential for commercial dimension-stone production include the Pennsylvanian formations, the Elsey and Reeds Spring Formations, and the Eminence Dolomite.

## INDUSTRIAL SAND

The resource potential for industrial sand (silica) in the Springfield quadrangle is hypothetical. Units considered as possible sources of industrial sand are the Warner Formation, undifferentiated channel sandstones in the Pennsylvanian Cherokee Group, the informal Swan Creek Sandstone of the Cotter Dolomite, the Roubidoux Formation, and the Gunter Sandstone Member of the Gasconade Dolomite. These sandstones are believed suitable for no more than the lowest industrial-use specification without extensive beneficiation; no past or present use for any industrial purpose is known. Major drawbacks are chemical impurities, improper grain size, irregular shape, and a high degree of cementation.

## CONSTRUCTION SAND AND GRAVEL

Construction sand and gravel resources, although not widespread in the Springfield quadrangle, are locally important as aggregate for ready-mix concrete. During 1984, the latest year for which complete data are available, production of almost 200,000 short tons was reported. Samples were collected from 31 sites and evaluated for size gradation.

The best resources are in the northeastern part of the quadrangle, along the Big Piney River, Roubidoux Creek, and the Osage Fork and Gasconade Rivers. Lesser resources are available along the Niangua River and in small streams at the southern margin of the quadrangle. Streams in the western part of the quadrangle contain mostly chert gravel and very little sand of suitable quality.

## CLAY AND SHALE

The Springfield quadrangle contains no known high-quality structural clay and shale resources. Firing tests to determine ceramic potential were made by the U.S. Bureau of Mines on 13 samples from the Rowe, Riverton, and Northview Formations (Rueff, 1986). None of the tested samples was suitable as sole-source material for the manufacture of structural clay products. Samples from shale of the Rowe may have some potential; those from the Northview are mostly unsuitable. Even samples classified as suitable had short firing ranges, followed by abrupt vitrification. If blended with other materials, however, some of this shale might may be usable. Because of these inadequacies, resources of clay and shale in the Springfield quadrangle are considered hypothetical.

## SUMMARY

The production of industrial minerals is the only mineral industry currently active in the Springfield quadrangle and the only aspect active within the last 20 years.

Of the industrial minerals present, only crushed stone and one of its products, manufactured lime, are currently of major economic importance. Limestone units in the Warsaw Formation and Burlington and Keokuk Limestones contain thick sections of stone suitable for the manufacture of cement, lime, and specialty limestone products. Future development of these resources will depend on demand and prospective investment. Construction sand and gravel are produced from streams in the northeastern part of the quadrangle; however, they are of lesser economic importance.

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# Mines, Prospects, and Occurrences of Metallic Minerals and Barite

*By* Heyward M. Wharton[1]

## INTRODUCTION

An important element in the mineral-resource assessment of the Springfield 1°×2° quadrangle was determining the types of deposits known to be present and their location, character, and significance. The basic information was compiled from records at the Missouri Geological Survey and has been published in the form of a map and catalog (Wharton, 1987) in which the mode of occurrence, host rock, period of mining activity, and production information are summarized as far as possible for each known or reported mine, prospect, and occurrence. A realistic basis was thereupon established for determining the type and size of possible undiscovered mineral deposits in the area. The purpose of this report is to briefly summarize the earlier findings and, where possible, to include comments that directly address the mineral-resource appraisal.

The relationship of the Springfield quadrangle to the Rolla 1°×2° quadrangle and to the several nearby mining districts is shown in figure 43. The Springfield quadrangle is about 50 mi west of the Southeast Missouri lead-zinc and barite districts but only about 25 mi east of the once major Duenweg-Webb City-Oronogo mining areas of the Tri-State zinc-lead district. In fact, the U.S. Bureau of Mines, U.S. Geological Survey, and some other authorities extend the outline of the Tri-State district eastward to include even the Pierson Creek mines southeast of the City of Springfield. In effect, any significant zinc and lead deposits hosted by Mississippian rocks were included in the district. Small sections of the Central Missouri district (mostly barite deposits) and the Steelville filled-sink iron district also are within the quadrangle. All of the Springfield iron district and fringe areas of the Osage River and West Plains iron districts are also included.

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## MINERAL-DEPOSIT TYPES

The following mineral deposit types have been identified in the Springfield quadrangle.

1. Mississippi Valley–type (stratabound, carbonate-hosted) zinc and lead deposits in Mississippian rocks.
2. Mississippi Valley–type lead and zinc deposits in Cambrian (?) and Ordovician rocks.
3. Residual brown iron ore deposits.
4. Hematite and marcasite-pyrite deposits in filled sinks.
5. Barite and lead-barite deposits in sedimentary rocks.
6. Base-metal minerals in the Decaturville structure.
7. Copper minerals in sedimentary rocks.
8. Manganese deposits in sedimentary rocks.

Mine production of barite, iron ore, iron pyrites, lead, and zinc is known from deposits of the first six types but not from the copper and manganese occurrences. The listing is in order of past economic importance because there is no mining of these mineral types in the quadrangle at the present time. Zinc-lead deposits in Mississippian rocks are by far the most important. The Upper Cambrian Bonneterre Formation, host rock of the major lead-zinc deposits of southeastern Missouri, is found only in the subsurface in the quadrangle. It has been the target for considerable prospect drilling in the area, but I know of no important discoveries to date. Lead and zinc minerals and minor ore production have been reported from Cambrian formations exposed at the Decaturville structure in Camden and Laclede Counties. A separate listing is given for these occurrences as type 6 because their genesis is in question.

Zinc and lead were last mined in the quadrangle about 1950, but exploration drilling for these metals (and copper) has occurred sporadically up to and including the 1980's. Barite was last mined in the 1960's, but some leasing activity occurred as recently as 1982. No shipments of pyrites are known since 1918 or of hematite after 1934. Last reported mining of brown iron ore in the area was in 1958.

Table 6 summarizes the numbers of mines, prospects, and reported occurrences in the quadrangle, by commodity. A total of 275 deposits is indicated. Some 190, or 70 percent, contained lead, zinc, or zinc and lead combined.

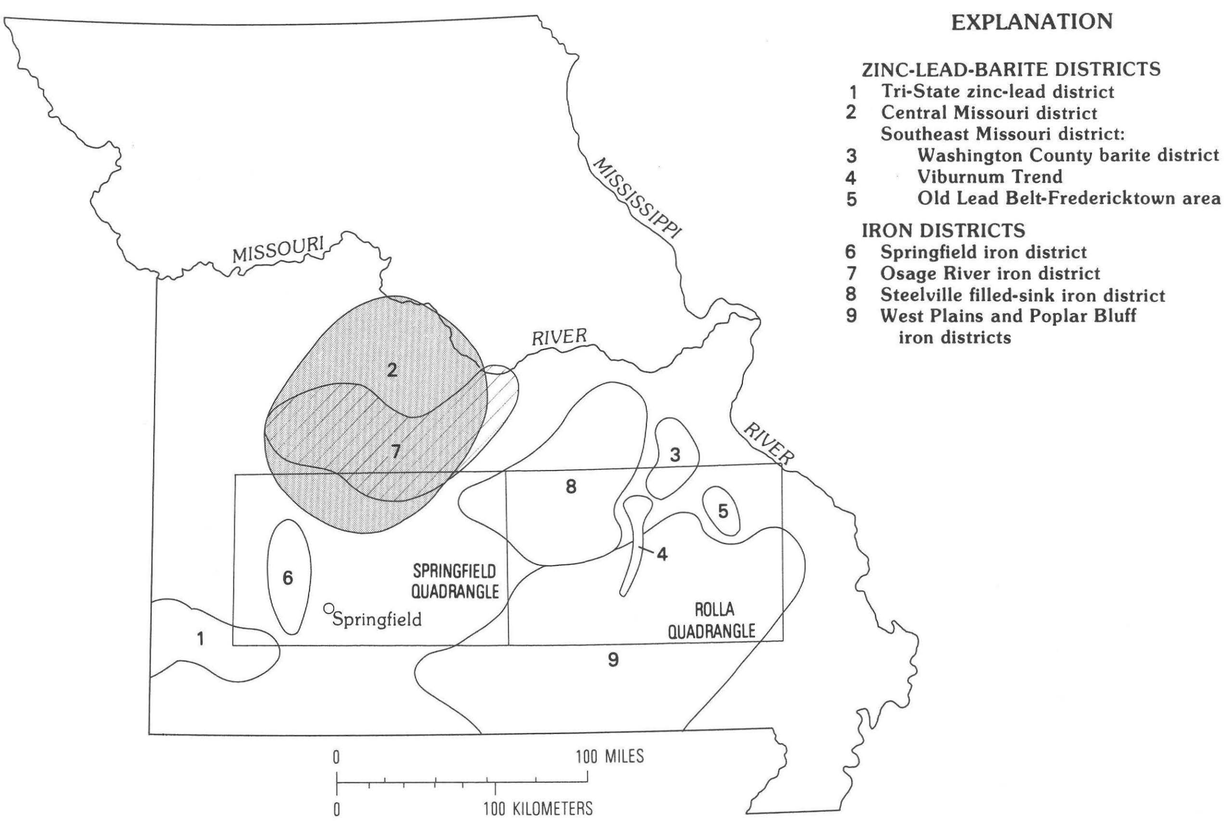


**Figure 43.** Missouri mining districts related to the Springfield 1°×2° quadrangle.

Among the known mines, 90 of the 116 (almost 80 percent) contained lead or zinc or both metals. Zinc-lead mines in Mississippian rocks (Tri-State model) were the most abundant and by far the most important ore producers. Only about one-third of the quadrangle in the western part is underlain by Mississippian rocks. In the following sections, the principal mines and prospects in each commodity group are briefly described and evaluated.

**Table 6.** Number of mines and prospects in the Springfield quadrangle, by type of ore

| Commodity | Mines with reported production | Prospects and reported occurrences | Total |
|---|---|---|---|
| Barite | 5 | 0 | 5 |
| Copper | 0 | 4 | 4 |
| Iron ore–hematite (magnetite) | 2 | 1 | 3 |
| Iron ore–brown | 18 | 48 | 66 |
| Lead | 19 | 48 | 67 |
| Lead-barite | 1 | 1 | 2 |
| Lead-zinc | 26 | 11 | 37 |
| Manganese | 0 | 1 | 1 |
| Pyrites | 1 | 2 | 3 |
| Zinc | 12 | 19 | 31 |
| Zinc-barite | 0 | 1 | 1 |
| Zinc-lead | 32 | 23 | 55 |
| TOTAL | 116 | 159 | 275 |

## PRINCIPAL MINES OF LEAD AND ZINC

The lead and zinc mines in the quadrangle are treated separately here because of their past importance and the special interest attached to the possibility of new ore discoveries in the general area. Each of the distinct commodity groupings is described separately.

### Zinc-Lead Mines

Zinc-lead mines are by far the most important and numerous type in the area. There were 32 known mines in the quadrangle. The six foremost mining areas will be reviewed. Mineralization was in Mississippian rocks (Tri-State model) in the first five and in Ordovician rocks in the sixth area, the Mansfield district. The Red Wasp–Arrow mines, part of the important Aurora district, are listed third only because most of the mine workings are just outside the Springfield quadrangle. Aurora ranks with Granby as an outstanding ore producer, and it is usually considered an integral part of the Tri-State zinc-lead district. Information about the Aurora district as a whole will be given because it is not unreasonable to expect that undiscovered zinc-lead deposits of this size could be present in the Springfield quadrangle, as well as in the bordering Harrison 1°×2° quadrangle to the south.

1. The Stotts City deposits in Lawrence County were mined at intervals from 1888 until 1945 and yielded about 31,000 tons of zinc ore concentrates and 1,000 tons of lead ore concentrates. Crude ore production may have been as high as 500,000 tons. The principal output was from two parallel, linear ore runs striking north-northwest, the main run being about 3,000 ft long. The runs probably are fracture zones having little or no vertical displacement. The main ore horizon was near the top of the Mississippian Reeds Spring Formation. Drilling by the U.S. Bureau of Mines in 1943 and 1944 failed to find additional ore.

2. The Pierson Creek mines are in Greene County near the southeastern edge of the City of Springfield. Mineralization along the James River was reported by Schoolcraft in 1819, and mining for lead began in a small way in 1844, possibly the first instance in southwestern Missouri. Ore was in a series of parallel faults and fractures striking north-northwest, mainly in the Mississippian Northview Formation and Compton Limestone, and some ore extended downward into the Ordovician Cotter Dolomite. Production from 1875 through 1916 was estimated to be about 29,000 tons of zinc ore concentrates and 3,000 tons of lead ore concentrates. Total crude ore production may have exceeded 400,000 tons. Exploration drilling was done in the area by Eagle-Picher in the 1960's and by Gulf Oil in the 1970's. Mineralization in Ordovician rocks was of particular interest in the later exploration efforts.

3. The Red Wasp and Arrow mines are in Lawrence County at the northern edge of the Aurora district. Mineralized rock is in a north-south fracture zone, and the main ore horizon is in the Mississippian Reeds Spring and Elsey Formations. Production between 1916 and 1940 may have exceeded 10,000 tons of combined zinc and lead ore concentrates, but no production data are available after 1918. Output reported for 1916–1918 was about 4,500 tons.

Two strong trends are apparent in the main mining area of the Aurora district: one about east-west and a less prominent one almost north-south. These may be related to the east-west Richey fault about 2 mi to the south. All the Mississippian formations were mineralized, but mineralization was strongest in beds of the Reeds Spring and Elsey. Ore was also found at the top of the Ordovician Cotter Dolomite in some of the mines. The district was active from 1886 until 1951, a span of more than 60 years. Production records are incomplete, but it is estimated that about 404,000 tons of zinc concentrates and 35,000 tons of lead concentrates with a combined value of almost $13 million were produced from 4–5 million tons of crude ores. Mining covered an area of about 2 mi$^2$.

4. The Ash Grove–Everton mines in Greene and Dade Counties and the Corry mines not far to the northwest in Dade County were groups of small surface mines and shallow shafts in Mississippian bedrock. Both areas were discovered in the 1870's, and there was some minor production as late as the 1940's. Estimated production from the Ash Grove–Everton area is about 5,500 tons of zinc concentrates and 800 tons of lead concentrates and from the Corry mines 5,000 tons and 2,500 tons, respectively.

5. The Mansfield district, near the southwestern corner of Wright County, included many small mines developed on narrow fissure-vein deposits in the Ordovician Jefferson City and Cotter Dolomites. Most mining was from the 1850's until 1900, and an estimated 3,000 tons of zinc and 500 tons of lead ore concentrates were produced. This type of deposit is of no importance today.

## Lead Mines

Typical lead mines in the area are small, shallow diggings in the residual clays developed on both Ordovician and Mississippian bedrock. Workings sometimes extended downward into fractures, crevices, and joints containing galena in the bedrock itself. Five mining areas were singled out as the most important. The Pickerel Creek mines in southwestern Greene County and the "Webster County mines" near Fordland were each reported to have produced at least 4,000 tons of lead ore, mostly before 1880. Hundreds of pits and shallow shafts were used to extract ore in the clays and underlying bedrock of Mississippian and, in some cases, Ordovician ages.

The Rex Consolidated and Rambo mines are considered the next largest producers. They are at the southern edge of the Central Missouri district in Hickory and Dallas Counties, respectively; both are associated with Ordovician rocks. There is no record of the output from the Rex Consolidated mine, but there was reported to be a 500-ton-per-day jig mill in operation when it was last worked in 1908. The Rambo mine was a clay-filled circle deposit 60 ft in diameter and initially was mined from 1868 to 1870. About 500 ton of galena was recovered, and the deposit was later mined from time to time as an open pit, perhaps as recently as the 1930's.

The Brazelton mines near Mountain Grove in Wright County round out the more important lead mines. Several hundred tons of galena were probably mined from residual clays above Ordovician bedrock before 1900.

Surficial lead deposits in the quadrangle are similar to the better known ones in Washington County, Missouri. They could be easily and cheaply exploited by hand-mining methods for many years in the past but have no importance in terms of today's mining industry.

## Lead-Barite Prospects

Some barite was probably recovered along with galena at the Rex Consolidated mine in Hickory County, described in the previous section. There is no record of successful operations here after 1908. The nearby Tatum lead-barite prospect was not large enough to warrant mining. The lead-barite occurrences have the same economic shortcomings as the lead mines described previously.

## Lead-Zinc Mines

Three lead-zinc mines were selected as the most important past producers in the quadrangle. The Teague Creek mines in Webster County are reported to have produced more than 500 tons of lead ore and some zinc ore from residual clays above Ordovician rocks during the 1870's. The Lawrenceburg mines near the northeastern corner of Lawrence County were shallow pits opened for lead in 1894. By 1905, there were shafts into the Mississippian bedrock that yielded some zinc silicate ore in addition to galena. Recorded output was only about 250 tons of lead ore and lesser amounts of zinc ore. The Brookline camp in Greene County southwest of Springfield was discovered in 1873. Mining was by shafts in clays and decomposed Mississippian bedrock. Only about 200 tons each of lead and zinc silicate ores had reportedly been recovered through 1893. These surficial occurrences are obviously of no economic importance today.

The Decaturville area attracted attention as early as the 1870's because of lead-zinc mineralization in outcrops of deformed Cambrian rocks. Ozarks Exploration Co. was formed in 1954, and considerable drilling was done during the following years. Although mineralization is widespread, it was reported to be low grade. Nonetheless, an open-cut mine was started and a jig mill constructed. It is doubtful that any lead-zinc ore concentrates were ever produced in the mill. The area was mapped and studied in the 1970's by T.W. Offield and H.A. Pohn of the U.S. Geological Survey, and they concluded (Offield and Pohn, 1979) that the disturbed area is probably caused by a meteor impact. There was drilling for lead and zinc in the vicinity as recently as the 1970's. The mineral potential of this area will remain in doubt until a more systematic study is undertaken.

## Zinc Mines

Five former zinc producers were selected as the most important zinc mines in the quadrangle. The Robertson Mining Company mines in Christian County were active from 1916 to 1918. Initially, zinc carbonate ore was mined by shallow shafts in Mississippian bedrock. Later, these shafts were deepened to mine zinc sulfide ore discovered by drilling. Construction of a 150-ton-per-day mill was started in 1916. There is no record of production, but likely more than 1,000 tons of zinc ore was mined. The Star (Porter) mine and mill in Webster County were operated for a year during 1927 and 1928, but no record of production is available. Two shafts were used to mine ore in Ordovician rocks. Mostly oxidized zinc ore was mined from the "Old and New Mines" in Dade County in the Corry Mines area. More than 2,000 tons of ore was mined at the former site and lesser amounts at the latter from residual material above Mississippian bedrock. All reported activity was in the 1870's. The Pittsburg mines in Hickory County also yielded mostly oxidized zinc ore in and above Ordovician bedrock. Activity was around the turn of the century.

The near-surface zinc deposits exploited in these mines are much too small to be of economic importance today, and it is unlikely that many undiscovered deposits of this type remain in the area.

# PRINCIPAL MINES AND PROSPECTS OF OTHER MINERALS

## Barite Mines

Only five small barite mines were identified in the quadrangle. The McCanless (Murphy) mine near Houston in Texas County was the most important, yielding about 1,300 tons of barite concentrates over many years. The deposit is unusual in that it is about 60 mi away from the Washington County and Central Missouri barite districts. The barite itself is semitransparent and has a distinctive blue color. It was present in a solution-collapse structure similar to the karst-related "circle" deposits in the Central Missouri district. Deposits of this type were described in detail by Mather (1947).

The other four mines were at the southern edge of the Central Missouri district. The Crystal (Harmon) deposit at Vista in St. Clair County was unique in that it is in the fractures of a sandstone of probable Pennsylvanian age, a short distance west of the Weaubleau structure. The barite is glassy, and some crystals are as much as 6 in. on a side. There is some evidence the deposit is in a filled-sink structure. It was thoroughly prospected in the 1960's, but only a few hundred tons of barite was mined. The three other mines were a few miles to the east in Hickory County. Most of their output was from residual clays developed on Ordovician bedrock, and tonnages were small.

Typical barite deposits in Central Missouri are related to karst features in carbonate rocks, and some evidence of their presence is common at the ground surface. Some of the circle deposits were significant producers; a few yielded in excess of 10,000 tons of barite; however, given the small size of the deposits known in the Springfield quadrangle and the long history of prospecting and mining in the general area, there seems little chance for discovering larger deposits.

## Copper Prospects

Only four minor copper occurrences were identified in the quadrangle, and they are of no importance. There has, however, been some recent interest in Olympic Dam–type deposits in this part of Missouri. The Olympic Dam deposit in South Australia contains copper, uranium, and gold in rocks of about the same age (1.4–1.5 billion years) as those in the Precambrian basement of Missouri. Union Carbide drilled two holes to basement in 1982 in the Springfield quadrangle, in Polk and Webster Counties, to test for this occurrence model. Results were negative. This topic is discussed in more detail by Kisvarsanyi (this volume).

## Iron Ore—Hematite and Magnetite

The G.W. Lane and Moccasin Bend mines in Pulaski County, at the edge of the Steelville filled-sink iron district, were the only noteworthy hematite mines in the quadrangle. About 3,000 tons of hematite ore was shipped from the former around 1930 and one carload from the latter in 1934. Several of the important mines in the Steelville district produced between 100,000 and 1 million tons of ore, but there has been no mining of these near-surface sedimentary hematites since the 1950's. Chances for discovering important new deposits of this type in the Springfield quadrangle are considered small.

Five deep holes were drilled at the prominent Orla magnetic anomaly near Lebanon in Laclede County. Results were negative for Kiruna-type deposits of magnetite or copper-iron–mineralized rocks similar to those known in southeastern Missouri at Pea Ridge, Pilot Knob, and Boss. The two holes drilled at the center of the anomaly in 1957 and 1968 cut diorite and gabbro containing disseminated magnetite but no ore. The three holes drilled in 1966 were also testing for lead and zinc on the flanks of possible basement knobs in the area. They were unsuccessful for both targets. These topics also are discussed further by Kisvarsanyi (this volume).

## Brown Iron Ore

The five most productive brown iron ore mines in the quadrangle were in the Springfield Iron district in Christian and Greene Counties. All were small and were operated before 1910. The Frisco mine, near the northwestern corner of Christian County, produced 23,000 tons of ore between 1904 and 1907. The four other mines yielded between 1,100 and 8,000 tons. Last known production (1,2000 tons) was from a small mine near Republic, Greene County, in 1957–1958. By 1968, the market for this type of material was practically nil. Because good surface exposures of iron ore rubble are common at these sites, it seems unlikely that any sizeable deposits remain to be discovered in the Springfield quadrangle.

## Iron Pyrites

Only one iron pyrites mine and two prospects are known in the quadrangle. According to Grawe (1945), a carload of ore was shipped from the Hinote mine in Wright County in 1918, but the mine had little potential. The two prospects are in Pulaski County, near the western border of the Steelville filled-sink iron district. It is doubtful that any large deposits are in the Springfield quadrangle.

## Manganese

The single manganese prospect identified in the quadrangle is in Howell County. It was explored by two shafts and was then abandoned as being too small for further development. A very minor occurrence was also reported nearby in Texas County. The potential for discovering economic deposits of manganese in the Springfield quadrangle is almost nil.

## SUMMARY

The zinc-lead deposits at Aurora and Stotts City are believed to be large enough to be economically mineable today. Those at Pierson Creek were smaller and scattered, as were those at Ash Grove–Everton and the Corry mines. Because the general area probably has been carefully prospected over the years, it is unlikely that any large zinc-lead deposits remain to be discovered in areas where Mississippian rocks are exposed. Residual lead and oxidized zinc deposits were generally found at the surface above important bedrock deposits. It is concluded that the best chances for significant ore discoveries in Mississippian rocks in the Springfield quadrangle are in areas where they are overlapped and masked by Pennsylvanian formations. Perhaps a tenth of the quadrangle in the western part is underlain by the younger rocks.

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# Fluid-Inclusion Evidence for the Source of Ore Fluids for Mississippi Valley–Type Deposits in Missouri, Arkansas, Kansas, and Oklahoma

*By* David L. Leach, E. Lanier Rowan, *and* John G. Viets

It is generally accepted that Mississippi Valley–type (MVT) deposits formed from basinal brines, as proposed by White (1958) and popularized by the classic papers of Hall and Friedman (1963) and Beales and Jackson (1966). There is much less agreement, however, on the specific sources of the fluids, the flow paths and timing of fluid migration, and virtually every other aspect of ore genesis. Although a simple, comprehensive genetic model for all MVT deposits is probably not attainable, Leach and others (1984), Rowan and others (1984), and Viets and others (1984) presented evidence that many MVT occurrences in the Ozark region of the Midcontinent (Missouri, Arkansas, Kansas, and Oklahoma) (fig. 44) share a genetic link with Ouachita foldbelt tectonism. In this report, we summarize the fluid-inclusion evidence that implicates the Arkoma-Ouachita basin as the source of the ore-forming fluids.

The Ozark region hosts the world-class Viburnum Trend, Old Lead Belt, and Tri-State MVT districts, as well as the lesser known Northern Arkansas, Central Missouri, and Southeast Missouri barite districts. Mineralization is in Upper Cambrian rocks in the Viburnum Trend and the Southeast Missouri barite district and in Ordovician through Pennsylvanian rocks in the Central Missouri, Tri-State, and Northern Arkansas districts. Trace and minor occurrences of sphalerite are also common in coal mines, rock quarries, drill cores, and outcrops throughout the stratigraphic section over a wide area in the Ozarks.

Fluid-inclusion studies of the minerals in MVT occurrences in the Ozarks show that the ore fluid was a brine of greater than 15 weight percent NaCl-equivalent salinity. Modes of homogenization temperature distributions not corrected for pressure are 90–150 °C. The ore districts generally have been assumed to have been thermal anomalies during ore deposition (Cathles and Smith, 1983); however, studies of fluid inclusions in dolomite and calcite in barren country rocks near the Viburnum Trend (Leach and others, 1983) indicate no evidence of a thermal gradient within 20 km of the deposits. Furthermore, widespread minor and trace occurrences of

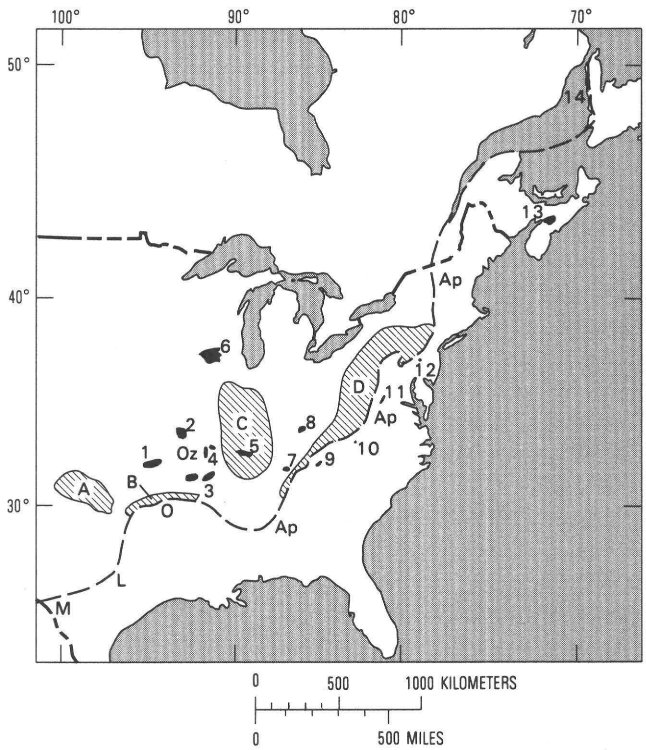


**Figure 44.** Appalachian and Ouachita foldbelts, Mississippi Valley–type lead-zinc districts, and basins discussed in text. Dashed line represents foreland edges of Ouachita and Appalachian foldbelts. Districts (black areas): 1, Tri-State; 2, Central Missouri; 3, Northern Arkansas, 4, Viburnum Trend, Old Lead Belt, and Southeast Missouri barite; 5, Southern Illinois; 6, Upper Mississippi Valley; 7, Central Tennessee; 8, Central Kentucky; 9, East Tennessee; 10, Austinville; 11, Timberville; 12, Friedensville; 13, Gays River; 14, Daniel's Harbour. Basins (crosshatched and undelineated areas): A, Anadarko-Ardmore; B, Arkoma; C, Illinois; D, Appalachian. Uplifts: M, Marathon; L, Llano; O, Ouachita; Oz, Ozark; Ap, Appalachian.

sphalerite in the Ozarks yield fluid inclusion homogenization temperatures and salinities essentially identical to those in adjacent mining districts (Leach, 1979;

Cobb, 1981; Coveney and Goebel, 1983). The absence of thermal gradients away from the deposits and the ubiquitous presence of "hot" (90–150 °C) fluid inclusions in the widespread trace occurrences of sphalerite and hydrothermal dolomite require that the mineralizing fluid be in thermal equilibrium with an enormous volume of rock.

Based on a reconstruction of the stratigraphic section, the estimated maximum possible cover is about 1 km for Ordovician- and Mississippian-hosted deposits and as much as 2.5 km for Cambrian-hosted deposits. If the ore fluids were heated by conduction from the basement, geothermal gradients of 60–100 °C/km would be required to account for the temperatures recorded by fluid inclusions. Such a gradient implies exceptionally high and unrealistic temperatures at shallow depths in the crust. A more reasonable explanation for the regional heating of the stratigraphic section is migration of large volumes of hot brines out of a deep sedimentary basin such as the Arkoma-Ouachita Basin.

Despite the absence of thermal gradients away from the ore deposits, there is an apparent broad regional trend of increasing fluid-inclusion homogenization temperature values to the south. Homogenization temperatures for sphalerite in Ordovician and Mississippian rocks in the central Missouri region are predominantly between 80 and 105 °C (Leach, 1979; Cobb, 1981; Coveney and Goebel, 1983) and as a group are the lowest recorded homogenization temperatures in the Ozark region. South of the central Missouri region, the Tri-State ore deposits, which are hosted principally by Mississippian rocks, yielded homogenization temperatures for sphalerite in the 80–120 °C range (Schmidt, 1962). Ordovician and Mississippian formations in the Northern Arkansas district host the southernmost MVT occurrences; homogenization temperatures are predominantly 95–130 °C but are as high as 170 °C (Nelson, 1974; Leach and others, 1975).

Cambrian-hosted hydrothermal dolomite and sphalerite of the Viburnum Trend typically have homogenization temperatures of 95–135 °C, 10–20 °C hotter than those in nearby Ordovician and Mississippian-hosted occurrences (Roedder, 1977; Leach and others, 1983; Rowan and others, 1984); this difference suggests a small vertical or stratigraphic thermal gradient.

The final melting temperatures of inclusion fluids from which NaCl-equivalent salinities are calculated are remarkably uniform among the deposits and trace occurrences of sphalerite and dolomite; however, Viets, Rowan, and Leach (1984) and Viets, Leach, and others (1985) reported regional variations in the cation ratios of the inclusion fluids. The most striking variation is a sytematic shift from high Na/K in northern Arkansas to lower values in southern and central Missouri. This ratio varies linearly with distance from the Arkoma basin. In the Viburnum Trend, fluids in the earliest ore stages depart from this trend although the later ore fluids fall on it. Viets (Viets, Leach, and others, 1985) interpreted this regional trend in Na/K ratios as progressive interaction between mineralizing fluids from a single principal source and the carbonate rocks along their flow path.

We believe that these fluid-inclusion data record the effects of an enormous hydrothermal event that affected much of the region north of the Ouachita foldbelt. Ages obtained from radiometric and paleomagnetic dating of a hydrothermal event coincide with the closing stages of the Ouachita orogeny in Late Pennsylvanian and Early Permian time (Bass and Ferrara, 1969; Beales and others, 1980; Wu and Beales, 1981; Aronson reported *in* Rothbard, 1983; Wisnioweki and others, 1983; Desborough and others, 1985). We believe that this regional hydrothermal system responsible for the MVT deposits may have been driven by topographic relief (that is, it was gravity driven in a sedimentary terrane) in which pre-flysch carbonate rocks and sandstones served as aquifers. Fluids could have entered such a system at a recharge area in the Ouachita foldbelt at the uplifted southern margin of the Arkoma basin. Economic concentrations of MVT minerals are along the length of the southern flank of the North American craton in regions where fluid flow was focused by basement topography and (or) zones of high permeability.

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# Resource Assessment for Mississippi Valley–Type Base-Metal Deposits

*By* R.L. Erickson *and* Barbara Chazin

## INTRODUCTION

Economically important stratabound deposits of base-metal sulfides in carbonate host rocks, commonly referred to as Mississippi Valley-type deposits, are not known in the Springfield 1°×2° quadrangle. The Central Missouri barite-lead-zinc district is just north of the quadrangle, and the Mississippian-hosted Tri-State zinc district is centered about 50 km west of the southwestern corner of the quadrangle. The Aurora, Stotts City, and Pierson Creek districts and numerous other small zinc-lead mines and prospects in Mississippian and Ordovician carbonate rocks are in the western half of the quadrangle, particularly in the southern part (Wharton, 1987, this volume). None of the districts in or adjacent to the quadrangle and none of the small mines or prospects within the quadrangle is currently active.

## DESCRIPTIVE MODELS

The resource appraisal for Mississippi Valley–type deposits in the Springfield quadrangle is based on two descriptive models: (1) the Bonneterre-Lamotte model developed for the Southeast Missouri lead district (Viburnum Trend and Old Lead Belt) in the Rolla 1°×2° quadrangle to the east (Pratt, 1981), and (2) a much more generalized model developed here for the entire carbonate section above the Cambrian Bonneterre Formation (post-Bonneterre through Mississippian rocks).

### Bonneterre-Hosted Deposits

The Bonneterre Formation is in the subsurface in the Springfield quadrangle at depths of 1,100–1,500 ft. Thus, our appraisal must consider the potential for undiscovered Bonneterre-hosted deposits similar to the Southeast Missouri lead-zinc deposits. At present, no Bonneterre-hosted deposits are known in the Springfield quadrangle. Five diagnostic and seven permissive recognition criteria, derived from the descriptive model, were used in making the resource appraisal in the Rolla quadrangle (Pratt, 1981). Only the five diagnostic criteria are considered here.

1. Deposits are in dolomite, near limestone-dolomite interface.
2. Deposits are in brown rock, near interface with white rock.
3. Deposits are near areas of faults and fractures in enclosing or underlying rocks.
4. Deposits are near or within favorably situated digitate reef-complex facies.
5. Deposits are near areas of anomalously high amounts of base metals in insoluble residues of megascopically barren Bonneterre Formation.

### Deposits in Post-Bonneterre Formations

Because there are no known economically significant post-Bonneterre deposits in the quadrangle from which we could derive specific or detailed characteristics, our post-Bonneterre model necessarily is generalized and includes only those characteristics common to most Mississippi Valley-type deposits in the Midcontinent region.

1. Deposits in pre-Mississippian rocks are in shallow-water, dolomitized carbonate rocks; deposits in Mississippian rocks are chiefly in cherty limestone that is only very locally dolomitized and silicified.
2. Deposits are in or near areas of faults, fractures, and joints. These structures are important because they facilitate fluid movement and, hence, development of solution collapse breccias. Some of the best ore in all known Mississippi Valley-type districts is in solution collapse breccia.
3. Deposits are in or near areas of anomalously high amounts of base metals in insoluble residues of barren carbonate rocks.
4. Deposits commonly are below an impermeable lithology such as shale and (or) siltstone that acted as a confining cap rock to fluid movement.

## Distribution of Favorable Criteria

### Lithofacies

The first step in making the resource appraisal for pre-Mississippian carbonate-hosted Mississippi Valley–type deposits in the Springfield quadrangle, for both models (Bonneterre and post-Bonneterre), is to eliminate areas where dolomite is *not* present. This was done for the Cambrian section by using the series of lithofacies maps (7 levels in the Bonneterre Formation and 8 levels in post-Bonneterre Cambrian rocks) prepared for this project by Palmer (1985). [Note: These lithofacies were subsequently revised somewhat (*see* Palmer, this volume).—Editors] Areas of limestone, areas of basin or deep ramp facies composed chiefly of shale and thin interbedded limestone and quartz siltstone, and areas of shelf facies composed of arkose, quartz sandstone, siltstone, or limey or dolomite glauconitic quartz sandstone were eliminated from further consideration. Most of the Cambrian facies boundaries trend north-south, and they define a broad gentle platform across the central part of the quadrangle flanked by ramp and basin facies to the east and to the west. Elimination of non-dolomite areas resulted in a derivative map showing areas of dolomite in the Bonneterre Formation and the lower half of the post-Bonneterre Cambrian section (pl. 1). The upper half of the post-Bonneterre and the Ordovician rocks are chiefly dolomite everywhere in the Springfield quadrangle. Mississippian carbonate rocks, present only in the western part of the quadrangle, are chiefly cherty limestone and are only very locally dolomitized.

### Structure

The second step of the resource appraisal was to overlay the structure map of the quadrangle (Middendorf, 1985) and the two major Precambrian tectonic zones (Kisvarsanyi, 1982) on the lithofacies map in order to define areas where structurally complex zones are present in dolomite areas (pl. 1). Faults are common throughout the quadrangle, and all dolomite areas contain faults; however, the principal fault orientation is northwest, cutting across all lithofacies boundaries. In our opinion, growth faults parallel with and near lithofacies boundaries would be more favorable for ore occurrence because such faults would be conducive to algal reef buildups on the upthrown side of the faults.

### Geochemistry

The third step in the resource appraisal was to overlay the subsurface geochemical maps (Erickson and others, 1985) on the lithofacies and structure maps in order to define areas where dolomite, faults, and anomalously high amounts of metals (>3,000 anomalous metal feet (AMF)) in insoluble residues of barren dolomite samples from drill holes are all present (pl. 1). (The concept of anomalous metal feet as a measure of the intensity of trace mineralization is explained in Erickson and others, this volume.)

### Caprocks

Impermeable caprocks that could confine fluid movement are not present in areas of the Springfield quadrangle where the other three criteria are present (dolomite, faults, and favorable geochemistry). Although the Bonneterre Formation is chiefly dolomite in the central one-third of the quadrangle, the overlying Cambrian Davis Formation also is chiefly dolomite in this area—not an impervious shale facies as is common in the Southeast Missouri lead district.

The post-Bonneterre Cambrian dolomites, within which we believe most metal-bearing fluid movement took place, are overlain by the Ordovician Gunter Sandstone Member of the Gasconade Dolomite—clearly not an impermeable caprock.

The Chattanooga Shale of Devonian age, a possible caprock for Ordovician dolomites, is not present in the quadrangle. The Northview Formation of Mississippian age (5–80 ft thick) overlies Ordovician dolomite in the western part of the quadrangle (Middendorf and others, 1987).

Mississippian carbonate rocks undoubtedly were capped by thick shales of the Cherokee Group of Pennsylvanian age in the southwestern part of the quadrangle.

## DISCUSSION

An examination of the subsurface geochemistry (Erickson and others, 1985) and subsurface carbonate petrology (Palmer, 1985) clearly shows that most of the anomalously high metal values in the Springfield quadrangle are in dolomitized, shallow-water carbonate rocks of post-Bonneterre Cambrian age, *not* in the Bonneterre Formation. Restricted platform flats and shoals where dolomite formed as crystalline carbonate rocks and mudstone to grainstone are the favored lithofacies. Basin and deep-ramp facies do not have high AMF contents. These observations make good sense because much of the shallow-water facies is recrystallized, porous, and permeable, factors that facilitate the passage of metal-bearing fluids; however, rock types that are favorable for fluid movement are not necessarily also favorable for metal deposition. Thus, rock units that have high AMF values may not have high mineral-resource potential. We do say, with confidence, that large volumes of metal-bearing fluids have migrated through post-Bonneterre Cambrian dolomites in much of the Springfield quadrangle. Equally important, we recognize that dolomitized shallow-water carbonate facies do not everywhere contain high AMF values. In fact, no lithofacies contain high AMF values in the eastern half of the quadrangle.

The presence of two criteria that seem to be important for significant metal accumulation in the Bonneterre Formation in the Southeast Missouri lead district have not been demonstrated in either Bonneterre or post-Bonneterre Cambrian units in the Springfield quadrangle: (1) an overlying impermeable shale-siltstone caprock to restrict fluid flow (the Davis Formation is the caprock in southeast Missouri), and (2) some localized unique factor in potential host rocks favorable for the precipitation of metal sulfides such as organic material or abundant diagenetic iron sulfide. In the Southeast Missouri district, ore is in brown rock near the interface with white rock. Brown rock contains three to five times more organic carbon than white rock (Viets and others, 1983). There is little doubt that enormous volumes of metal-bearing fluid have moved through the post-Bonneterre dolomites in the Springfield quadrangle, but, on the basis of subsurface data available to us, no block of ground containing that elusive unique factor that causes metal deposition has been identified. Admittedly, our data points are sparsely distributed, and large blocks of favorable ground could easily be accommodated between data points. Nevertheless, it is also possible that metal-bearing fluids flushed their way through the Springfield quadrangle, never encountering an environment that would cause significant metal deposition.

From a more optimistic view, there is a remarkably good correlation of the northwest-trending geochemical high (Erickson and others, 1985) with the major Precambrian tectonic zones, the Bolivar-Mansfield and Chesapeake. These tectonic zones appear to form the boundaries of the geochemical high, and perhaps the area between these zones is the major plumbing system for ore fluids in the Springfield quadrangle. Cordell (this volume), however, is unable to identify any geophysical expression of these zones and finds no correlation between basement features and geochemically anomalous zones and no geophysical evidence that geochemical anomalies are structurally controlled. (These observations remind us that there is no aeromagnetic or gravity expression of the ore trends in the Southeast Missouri lead district.) Nevertheless, a northwest-trending geochemical pattern is indicated whether or not the pattern is structurally controlled or bounded. All investigators, however, do recognize a regional northwest structural grain across the quadrangle. Our data and our prejudices dictate that structure, *not* lithofacies, is the primary control of the distribution and abundance of anomalously high amounts of metals in the Springfield quadrangle for the following reasons.

1. The northwest-trending geochemical pattern transects north-trending lithofacies. In contrast, geochemical patterns coincide with lithofacies boundaries in the Southeast Missouri lead district in the Rolla 1°×2° quadrangle.
2. Highest metal values in our data set are in breccia zones. The most anomalous drill holes are in or along the projection of the Bolivar-Mansfield fault system.
3. There is a regional northwest structural grain across the Springfield quadrangle.
4. Known mining districts outside of but near the quadrangle (Tri-State zinc-lead, Northern Arkansas zinc, and Central Missouri barite-lead-zinc districts) exhibit strong structural control. Although major faults in these districts are rarely mineralized, minor faults and numerous fractures subsidiary to the major faults play an important role in localizing ore within the stratiform deposits (Snyder, 1968, p. 279).

In summary, favorable ground for subsurface mineral-deposit occurrences can be defined as areas where high AMF values are in appropriate lithofacies (dolomitized shallow-water carbonate rocks) in and near fault zones. Faulting could produce channelways to sites of ore deposition or could form dams of fault gouge that impede ore-fluid movement and cause metal deposition. Available data suggest that the latter circumstance is the best possibility for the presence of significant mineral-resource potential in the quadrangle—in contrast to the world-class lead-zinc deposits of the Southeast Missouri district where brown rock probably is the favored site of metal deposition. From the existing data, we are unable to demonstrate the presence of appreciable areas of brown rock or something akin to it, in either Bonneterre or post-Bonneterre dolomites, that could cause metal sulfide deposition in the tonnage and grade class characteristic of the Southeast Missouri deposits.

It is interesting to note that many of the diagnostic and permissive criteria for the Bonneterre-hosted deposit model of the Southeast Missouri district (Pratt, 1981) are present in the subsurface of the Springfield quadrangle. Our data bases show several limestone-dolomite interfaces (probably the single most important criterion in southeast Missouri) in the Bonneterre and Davis Formations (Palmer, 1985). Faults and fractures appear to be as prevalent in the Springfield quadrangle as in southeast Missouri (Middendorf, 1985). Precambrian topographic highs are present (Kisvarsanyi, 1982). Small patches of reef facies and of brown rock are known, but they are not of large areal extent (Palmer, 1985). Occurrences of base-metal minerals are known in post-Bonneterre Cambrian rocks and in overlying formations (Searcy, 1981, 1982; Wharton, 1987); however, in areas where most or all of these criteria are present, we have *not* found favorable geochemical trends (also a *diagnostic* criterion for Southeast Missouri deposits), and mineral deposits are not known, by us, to be present. Part of the problem may be that dolomite adjacent to the limestone-dolomite interface is white rock or dolomitic mudstone with interbedded shale and grainstone, or dolomitic siltstone. To our knowledge, reef complexes or brown rock at or near the interfaces are not present in the Springfield quadrangle.

These observations concerning both Bonneterre and post-Bonneterre Cambrian rocks suggest to us that depositional facies, or transitions between them, are not as important as what has happened to each facies since deposition—except that shaly basin and clastic deep ramp facies, by definition, are not favorable host rocks for Mississippi Valley–type deposits. A potential ore-host facies must possess four characteristics: (1) it must be dolomitized; (2) it must have good porosity and permeability, commonly secondarily developed (abundant stylolites, vugs, solution collapse breccia, and so forth); (3) it must have some unique property that will cause metal sulfide deposition (organic material, abundant syngenetic or diagenetic iron sulfide); and (4) it must have an abrupt transition to other facies. We conclude that the favorable characteristics for formation of Mississippi Valley–type deposits are postdepositional, secondary processes. The original depositional lithofacies is important insofar as how that facies reacts or responds to secondary processes.

As noted earlier, economically important stratabound Mississippi Valley–type deposits are not known in the Springfield quadrangle. We recognized that development of a detailed descriptive model, such as that developed in the Rolla quadrangle for Bonneterre-hosted deposits, was not feasible in the Springfield quadrangle because the available data are much less dense in areal coverage (that is, fewer drill holes) than in the Rolla quadrangle. Further, in the Rolla quadrangle, there is a wealth of literature and more than 100 years of exploration experience to draw upon. Neverthless, we believe that the available data do reasonably permit us to divide the quadrangle into areas of high, moderate, and low mineral-resource potential. The data do *not* permit us to make probability estimates of number of undiscovered deposits or size and grade of undiscovered deposits.

## RESOURCE ASSESSMENT

The quadrangle is divided into 23 areas of high, moderate, or low resource potential (pl. 2), having a moderate level of certainty (see following section), based upon the areal distribution of the three diagnostic criteria shown on plate 1. Because some faults are present in all areas, each area boundary is defined by lithofacies change and (or) AMF values.

The largest area of high resource potential indicated by our data is a northwest-trending zone in post-Bonneterre Cambrian rocks that extends from the Missouri-Arkansas border across the Springfield quadrangle. This possible new mineral trend, bounded by major tectonic zones, was suggested by Erickson and others (1981) and has since been expanded by acquisition of lithologic, structural, and geochemical data from additional drill holes (Erickson and others, 1983). The zone contains 17 of the 19 areas in the Springfield quadrangle considered to have high or moderate resource potential. Undoubtedly, drilling of closer spaced holes would reveal many barren areas within the postulated trend. Nevertheless, on the basis of the areal distribution of the criteria discussed above, we consider this zone to have moderate to high mineral-resource potential. Many of the small inactive surface zinc and (or) lead mines and prospects in Ordovician and Mississippian rocks also are in this trend; however, none of these occurrences is considered to have high potential for large tonnage zinc-lead deposits.

### Level of Certainty

We believe that the terms "high, moderate, and low potential" used in this report might be more useful to the reader if accompanied by assignment of a "level of certainty" to the assessment. In doing this we are borrowing the concept of level of certainty of regional mineral-resource assessments discussed by Taylor and others in their recent assessment of the mineral-resource potential of the San Isabel National Forest in Colorado (Taylor and others, 1984, p. 41–42). The authors of that report defined four levels of certainty of a resource assessment, ranging from level A (minimum) to level D (maximum), based on the extent of available data regarding the geologic environment, the level of mineral-resource potential, the likelihood of resource occurrence, the activity of resource-forming processes, and the adequacy of available occurrence and (or) genetic models for predictive applications.

We believe that for the areas in the Springfield quadrangle to which we have assigned a high, moderate, or low resource potential, the available data support what we would call a *moderate level of certainty*, corresponding to level C of Taylor and others (1984), which they define as follows: "The available data give a good indication of the geologic environment and the level of mineral resource potential, but additional evidence is needed to establish precisely the likelihood of resource occurrence, the activity of resource-forming processes, or available occurrence and (or) genetic models are minimal for predictive applications."

We have described area C–3 in the Springfield quadrangle (pl. 2) as having unknown resource potential. This assessment automatically places area C–3 in degree of certainty level A of Taylor and others (1984), which is defined as follows: "The available data are not adequate to determine the level of mineral resource potential. Level A is used with an assignment of unknown mineral potential."

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# A Model for Genesis of Red-Bed–Evaporite-Associated Stratabound Copper Deposits and Potential in the Springfield 1°×2° Quadrangle and Surrounding Areas

*By* Timothy S. Hayes

## INTRODUCTION

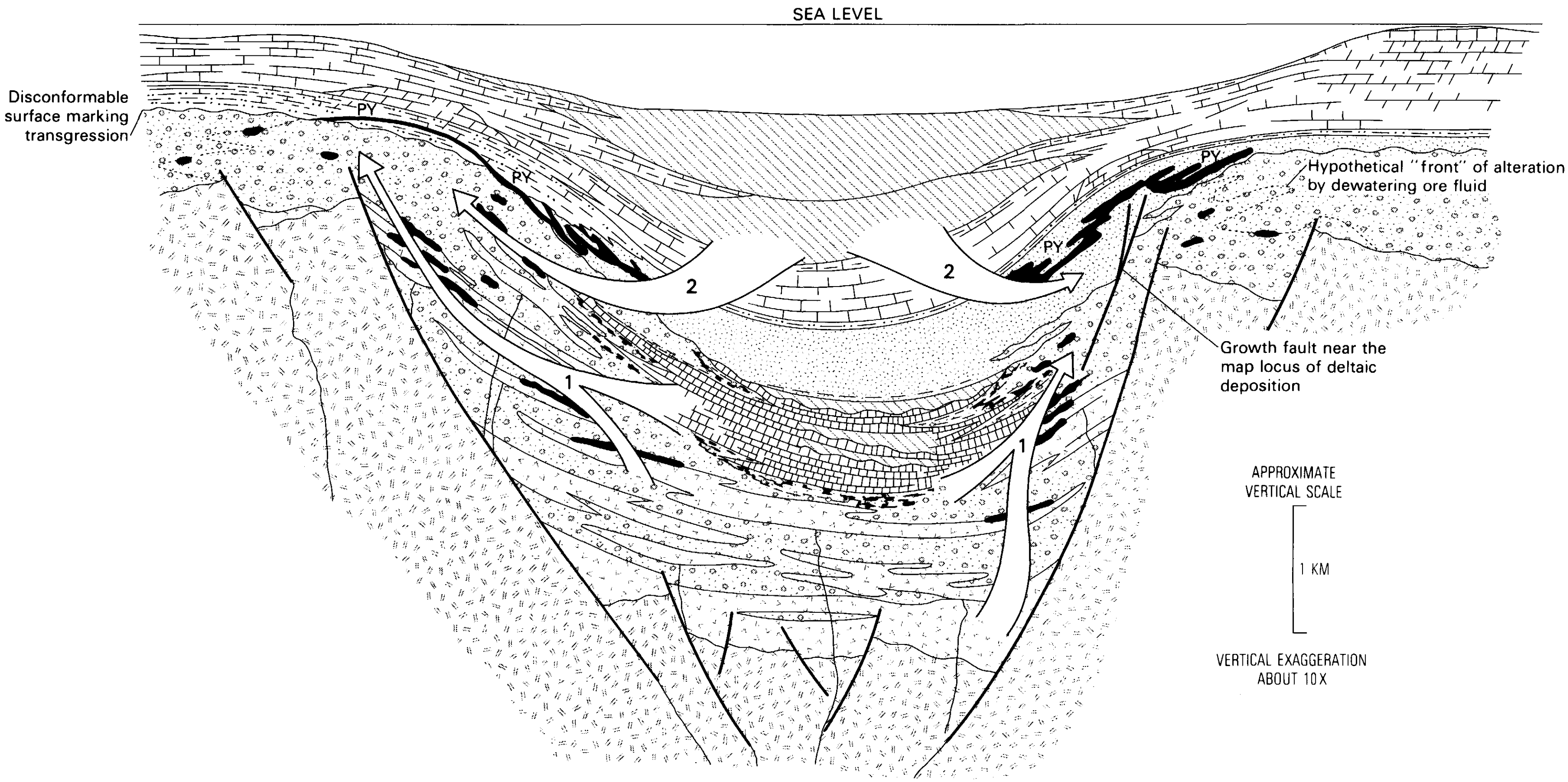
In simplest description, most red-bed–evaporite-associated (RBEA) stratabound copper deposits are blanket-like zones of disseminated chalcocite and other copper sulfide minerals near the contact between an underlying siliciclastic red-bed section and the host beds of carbonaceous, pyritic shale or siltstone (fig. 45). In some districts the host rock is a carbonaceous algal dolomite. Familiar examples are the deposits within the Kupferschiefer in central Europe (Rentzsch, 1974; Jung and Knitzschke, 1976), deposits of the Copperbelt in Zambia and Zaire (Bartholomé, and others, 1973; Fleischer and others, 1976), the White Pine deposit in Michigan (Ensign and others, 1968; Brown, 1971), and the Redstone deposits in Northwest Territories, Canada (Chartrand and Brown, 1985).

The second major variant of RBEA stratabound copper deposits is the group of large-tonnage deposits in sandstone. Sandstone-hosted RBEA deposits are zones of disseminated chalcocite and other copper sulfide minerals at the contact between red (or formerly red) rocks and gray or green pyritic rocks, within a particular sandstone interval (fig. 45). Examples of sandstone-hosted deposits include some of the deposits associated with the Kupferschiefer at Lubin, Poland (Banas, and others, 1982), Mufulira and Chibuluma in Zambia (Fleischer and others, 1976; Annels, 1979), the huge Udokansk and Dzezhkazkan ore fields in Russia (Bakun and others, 1966; Gablina, 1981), and Spar Lake, Montana (Hayes, 1983). Large orebodies in sandstone hosts tend to be shaped like flattened tongues. Small-tonnage lenses of chalcocite-rich rock entirely within red-bed sections (red-bed copper deposits) should also be considered together with this deposit type because their genesis is similar to the RBEA stratabound copper deposits (Davidson, 1965; Rose, 1976; Hayes, 1982). Small red-bed copper deposits and small RBEA shale-hosted deposits are known in Permian and Triassic host rocks in several areas west of the study area (Johnson and Croy, 1976; LaPoint, 1979), the nearest being in central Kansas (Ripley and others, 1980). Another ore deposit type that shows common spatial association with the RBEA stratabound copper deposits consists of native copper in basalt flow tops, typically found downsection from the sediment-hosted ores (White, 1968; Anhaeusser and Button, 1973), of which the Michigan or Keweenawan native copper district is a good example.

The genesis of RBEA stratabound copper deposits is not well understood. Nevertheless, a model for these deposits based on analogy with known examples identifies potential host beds in a given stratigraphic section and thereby focuses the search for such deposits to that part of the section. The purpose of this chapter is to present such an occurrence model and apply it to assess potential for RBEA stratabound copper deposits in the Springfield 1°×2° quadrangle.

## DEPOSIT HOST ROCKS: THE TECTONO-SEDIMENTARY SETTING OF LARGE DEPOSITS

Host rocks for large RBEA stratabound copper deposits are distinct rock types at a distinct position within a regular stratigraphic sequence. They are typically carbonaceous marine sandstone, shale, or algal dolostone. These host rocks immediately overlie thick (>1 km) sections of continental red beds, lacustrine to locally marine evaporites, and basalt-rhyolite sequences, or are laterally adjacent to areas where such pre-host continental sequences are thick (fig. 45). They are overlain by platform carbonate-evaporite sequences or by marine clastic rocks. The host beds thus mark a major marine transgression—the first major transgression in a sedimentary sequence floored by nonmarine rocks. A well-studied example of such stratigraphy is the upward sequence of Permian rocks in central Europe: Rotliegendes (nonmarine and lacustrine to restricted-marine evaporites with intercalated basalt-rhyolite); Kupferschiefer (restricted marine, carbonaceous, dolomitic mudstone host rock that forms the base of the carbonate-evaporite sequence); and Zechstein (platform carbonate-evaporites). The Rotliegendes probably overlie a graben and horst




## EXPLANATION

**Marine evaporite**

**Marine platform limestone and dolomite**

**Marine, carbonaceous mudstone, siltstone, and dolostone**

**Coastal sandstone**

**Lacustrine evaporite**

**Fluvial red beds**

**Tholeiitic to alkalic, bimodal volcanic rocks, mostly flood basalts**

**Basement rocks**

**Alternative hypothetical ore fluid paths**

1 **Ore fluid moves through water-escape structures from the thick, rift-set package of red beds, basalts, and lacustrine evaporites, possibly thermal driven**

2 **Ore fluid moves through water-escape structures from laterally contiguous marine evaporites, driven by differential compaction**

**Large, blanketlike RBEA stratabound copper deposit in marine, carbonaceous mud to siltstone**

**Large, tonguelike RBEA stratabound copper deposit in coastal sandstone**

**Red-bed copper deposit in fluvial host**

**Native copper deposit in top of basalt flow**

PY **Early diagenetic, disseminated and framboidal pyrite**

**Figure 45.** An occurrence model for red-bed–evaporite-associated (RBEA) stratabound copper deposits showing stratigraphic position of potential host rocks, spatial relations to basement rifts, and alternative hypotheses for ore fluid sources and paths.

terrane composed of upper Paleozoic metamorphic rocks (Jowett and Jarvis, 1984). Kupferschiefer ore deposits are above the margins of basement grabens, adjacent to areas of thick Rotliegendes graben-fill sedimentation (Jung and Knitzschke, 1976).

The vertical sequence—bimodal volcanic rocks, fluviolacustrine clastic rocks, marine siliciclastic host rocks, platform carbonate-evaporites—is easily identified as the stratigraphic sequence beginning in proto-oceanic rift settings that precede opening of oceans and continental breakup and progressing upward to open-ocean stages (Hoffman and others, 1974). Time distribution of RBEA stratabound copper deposits worldwide corroborates the association of such deposits and rift tectonism. RBEA deposits are most abundant in rocks of two ages: Middle Proterozoic and Permian and Triassic (Meyer, 1981). Both ages are well-known times of continental breakup (Briden, 1976; Habicht, 1979). The presence of this deposit type within evaporite-bearing sections suggests an additional correlation with arid paleoclimates and perhaps suggests a location within or at the margins of aulacogens that allows the restricted marine circulation conducive to evaporite deposition.

These characteristics of the host rocks of RBEA stratabound copper deposits, remarkably consistent for every large deposit of this type, identify potential host rocks within any given stratigraphic section. The potential host is the first extensive, reduced, marine unit upsection within the rift to open ocean sequence; that is, it is a transgressional marine unit overlying a continental red-bed sequence (Gustafson and Williams, 1981).

## DEPOSIT ZONATION AND PARAGENESIS

RBEA stratbound copper deposits, whether hosted by sandstone, shale, or dolostone, exhibit (1) a characteristic sulfide zonation and (2) a consistent sulfide paragenesis. Small red-bed deposits exhibit the same sulfide paragenesis as large deposits, and that similarity demonstrates the likelihood that they have similar genetic histories.

The mineral zones that constitute the large deposits cross the bedding at very low angles (fig. 45) (Brown, 1978, 1980). From laterally outside the deposit to its center and, for most cases, from above the deposit to its center, authigenic sulfide and oxide minerals are as follows (read the > symbol as "gives way to"): pyrite+leucoxene> (trace) galena, (trace) sphalerite, chalcopyrite, pyrite+ leucoxene>chalcopyrite, (trace) pyrite, (possible) carrollite+ leucoxene>bornite, digenite+hematite>digenite, chalcocite+ hematite.These changes are across horizontal distances of kilometers and across vertical distances of a few meters or less. Economic zones of most deposits are the bornite-, digenite-, and chalcocite-bearing zones, though grades are rich enough in the chalcopyrite-carrollite zones in Zambia and Zaire to mine copper and cobalt.

Sulfide paragenesis is interpreted to indicate a single advance of ore fluids into chemically reactive host rocks (Brown, 1978, 1980). All studies of unmetamorphosed orebodies indicate the following paragenesis (read the → symbol as "is/are replaced by"): pyrite→galena-sphalerite; pyrite→chalcopyrite, carrollite; remnant pyrite and chalcopyrite→bornite→digenite→chalcocite.

This zonation and paragenesis indicates continuous addition of copper-rich solutions from sources nearer the chalcocite side of the asymmetric sulfide zonation. Authigenic mineralogy in rocks even closer to the source of fluids than the chalcocite zone is poorly described but includes a chlorite–native copper zone at White Pine and an albite-chlorite–ankerite-(trace)-chalcopyrite zone at Spar Lake. Because rocks at greater distances from ore deposits in the same direction are invariably hematitic and hematite is present within chalcocite zones, it is generally assumed that ore solutions were in equilibrium with hematite (oxidized) and invaded a reduced (pyrite-carbon-leucoxene bearing) host (Rose, 1976). This may be an erroneous assumption. Both the chlorite–native copper zone at White Pine and the albite-chlorite–ankerite-chalcopyrite zone at Spar Lake overprinted and replaced hematitic red beds (Hamilton, 1967; Hayes, 1984).

## TIMING OF ORE DEPOSITION

The most recent studies of RBEA stratabound copper deposits contribute to understanding the timing of ore deposition. Before about 1970, the dominant genetic theory was that sulfide minerals were deposited from supersaturated, anoxic bottom waters at the same time as clastic sedimentation (Garlick, 1963). The theory explained the blanketlike form of deposits, the near conformity of ore with a single sedimentary lithofacies, and the small-scale conformity of sulfide concentrations with primary sedimentary structures. Since 1970, however, petrographic studies of such deposits have shown that ore sulfide minerals formed after a first diagenetic stage in the host rocks. The metals were introduced after the host rock was deposited, and the ore stage was a cementation and lithification event (Brown, 1971; Bartholomé and others, 1973; Rentzsch, 1974; Annels, 1979; Gablina, 1981; Hayes, 1984; Chartrand and Brown, 1985). RBEA stratabound copper deposits are synlithification, in contrast to Mississippi Valley–type deposits, which are postlithification (Heyl, 1983). Metals introduced from without into already existing host rocks define the RBEA stratabound copper deposits as epigenetic.

The absolute age of RBEA stratabound copper deposits is not well known. The ore and gangue minerals of these deposits are difficult to date isotopically. The age of the White Pine deposits is the best constrained, but even they are dated only relatively. Disseminated ore at White Pine was emplaced less than 100 million years after deposition of the Middle Proterozoic host rock, as determined by dating of pre-ore Keweenawan rhyolite and post-ore calcite veinlets (Ruiz and others, 1984).

## ORE FLUIDS

Attention to the theory of syngenesis (Garlick, 1963) delayed studies aimed at characterizing and clearly identifying the ore fluids for RBEA stratabound copper deposits. As a result, very little is known about ore fluids.

Temperatures of ore-forming fluids were probably only mildly elevated above surface conditions. Post-ore veinlets at White Pine formed from fluids at 70–80 °C, and earlier disseminated mineralization presumably occurred at even lower temperatures (Kelly and Nishioka, 1985). In Zaire, silicification that accompanied mineralization probably took place at 125–140 °C, and even temperatures of maximum burial did not exceed 250 °C (my interpretations of the data of Pirmolin, 1971). Studies of Kupferschiefer vitrinites (Rentzsch, 1974) indicate that the temperature of those rocks never exceeded 175 °C. Isotope geothermometry studies of the Spar Lake deposit are now in progress. At Spar Lake, the introduced ore fluid was probably warm relative to the host rocks, and ore deposition probably occurred across a spatial temperature gradient from as much as 150 °C on the side toward the ore fluid source to around 50 °C on the pyritic side.

No studies of fluid-inclusion chemistry have been reported, and only theoretical data are available on salinity of ore fluids. Ore solutions must have been very saline because only minor copper could have been transported in dilute solutions at low temperatures. High chlorinity and intermediate (cuprous-copper-stable) oxygen fugacity are best guesses at the ore solution character (Rose, 1976). Chlorinity greater than 1 molar is probable and suggests a possible link to marine evaporitic brines.

## METAL SOURCES

Metal sources available to hypothetical ore fluids include only (1) the downsection sedimentary-volcanic pile and basement rocks, (2) the laterally contiguous sedimentary rocks, and (3) some hypothetical buried intrusion for which no clear evidence exists at any deposit. Sedimentary dewatering brines (Brown, 1984) or fluids expelled upward in load metamorphism of the basalts (Jolly, 1974; Lincoln, 1981) are alternative hypotheses for ore fluids, and corresponding, reasonable metal sources are the ferric oxides of the red beds (Zielinski and others, 1983) or the ferromagnesian minerals of the basalts. The presence of sulfide minerals in ordinary water-escape structures at several deposits (Hayes, 1983; Knutson and others, 1983; R. Lustwerk, U.S. Geological Survey and Pennsylvania State University, oral commun., 1984) implies that no tie is necessary between tectonism and ore deposition, though growth faults were potential solution feeders to some deposits.

## ABBREVIATED GENETIC MODEL

The descriptive data above can be assembled into a loosely constrained genetic model (fig. 45). The genetic model has many alternatives within it, but the alternatives are not unlimited. (1) Reduced marine host rocks are shallowly buried beneath a passive-margin sedimentary pile. (2) The host rocks are invaded by ore fluids escaping from underlying graben-fill rocks, including red beds, some evaporites, and interleaved basalt and rhyolite. (3) The same fluids may be responsible for mineralization of small reduced lenses within the red beds (red-bed copper deposits) and possibly are responsible for native copper deposits at the tops of basalt flows. An alternative hypothesis for ore solution parentage is derivation of the ore fluids from evaporite deposits (Thiede and Cameron, 1978). Solution movement in a mainly lateral direction might be driven by differential loading and compaction. Ore fluids were assumedly highly saline because of (1) derivation from evaporites, (2) clay membrane effects during burial diagenesis, (3) extensive interaction with the volcanic rocks (White and others, 1963, table 19), or (4) another, unknown reason. Warm, saline fluids dissolved metals from the red oxide minerals of rift-fill sedimentary rocks, or the ferromagnesian minerals of basalts, or both. Ore solutions moved upward through ordinary water-escape structures or along growth faults and moved laterally along permeable beds away from graben centers. Solutions may have been directed upward along margins of basement grabens. Host rocks, the lowermost extensive reduced marine beds in the stratigraphic sequence, were both physical and chemical traps. The host beds were physical traps because they presented impermeable barriers to flow. They were chemical traps because they contained abundant sulfur as pyrite or sulfate minerals to precipitate copper as sulfide minerals or because they contained abundant reductants to change ore-fluid sulfate to sulfide.

## POTENTIAL FOR RBEA STRATABOUND COPPER DEPOSITS WITHIN THE SPRINGFIELD QUADRANGLE AND ELSEWHERE IN THE MIDCONTINENT

By analogy with the model presented here, prospective host rocks for large RBEA stratabound copper deposits in the Springfield quadrangle are the upper parts of the basal Paleozoic clastic unit or the lowermost part of the carbonate section. Basal Cambrian sandstones overlying the Precambrian basement of the Springfield quadrangle are fluvial red beds (Rothbard, 1983; Bloch, 1985), and the overlying carbonate section represents marine platform deposition. Marine transgression occurred between deposition of the basal sandstone–conglomerate units and the carbonate rocks within the Cambrian Lamotte Sandstone (Bloch, 1985), or, to the west, within the Cambrian Reagan Sandstone. These earliest marine units were reduced during early diagenesis, in contrast to the underlying red beds (Bloch, 1985). The lowermost Paleozoic section virtually everywhere in the Midcontinent shares the depositional and early diagenetic history of the Springfield section.

No large RBEA stratabound copper deposits are likely to be found in the quadrangle because such deposits would probably have been detected by the existing drill holes. Where RBEA stratabound deposits are economic, they have immense lateral dimensions measured in tens of square kilometers. No occurrences of copper minerals are known in these favorable units in the Springfield quadrangle. Data from the scattered drill holes do not preclude the existence of small red-bed copper deposits, but these deposits are also considered unlikely because the basal clastic section, where it is exposed on the flanks of the St. Francois Mountains, contains no such deposits.

Minor copper and cobalt sulfide minerals are found together with major galena-sphalerite concentrations in the upper part of the Lamotte Sandstone in the Indian Creek District and locally within the Old Lead Belt and the Viburnum Trend, but these deposits are easily distinguished from RBEA stratabound copper deposits. These deposits are lead-zinc dominated and continue upsection into Bonneterre-hosted MVT deposits. Although the sulfide minerals in the Lamotte are mostly cements, ore controls in the laterally continuous MVT deposits are secondary, not primary, permeability features. Chalcopyrite is the principal copper sulfide mineral in all zones rather than chalcocite. Sandstone-hosted lead-zinc deposit potential in the basal clastic unit of the Springfield quadrangle is, by analogy with Indian Creek and other deposits in southeastern Missouri, closely related spatially to the MVT deposit potential in carbonate rocks.

The Springfield quadrangle differs from other areas of the Midcontinent, which have greater potential for RBEA stratabound copper deposits. The red-bed section beneath the Springfield quadrangle is thin (nowhere over a few hundred meters) and lacks bimodal volcanic rocks characteristic of the thick sections underlying or near RBEA stratabound copper districts elsewhere. Furthermore, thick evaporite sections are not developed anywhere nearby within the Paleozoic rocks. These differences and other data on regional structural-sedimentation patterns (Thacker and Anderson, 1977; Heyl and McKeown, 1978; Leach, 1979) suggest that the Springfield quadrangle is remote from any basement graben or half-graben where rapid sedimentation and subsidence might create and expel an ore fluid. Areas of the Midcontinent within or closer to such tectonic settings would be more prospective in host rocks equivalent in vertical sequence to the upper Lamotte. The area in the vicinity of the Reelfoot Rift, where time equivalents of the Upper Cambrian section of the Springfield quadrangle are much thicker (Thacker and Anderson, 1977), is an example. Middle Proterozoic equivalents of the Keweenawan rocks of Michigan, possibly present in the subsurface along the the Midcontinent gravity high, are another obviously prospective sequence.

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# Precambrian Geology and Mineral-Resource Potential

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## INTRODUCTION

With the exception of a single outcrop of pegmatite and schist at the center of the Decaturville structure in Camden County, Precambrian rocks are not exposed in the Springfield 1°×2° quadrangle. The data base for the Precambrian basement consists of 26 drill holes, 21 of which (fig. 46) cored an interval of Precambrian rocks. The distribution of these holes is rather uneven, most of them being clustered around Lebanon and the Decaturville structure in the northeastern quadrant of the area (fig. 41). The thickness of the platform-type sedimentary cover on the Precambrian erosional surface varies from a minimum of 1,204 ft in drill-hole Cm–2, northwest of the Decaturville structure, to a maximum of 2,120 ft in hole Gr–1, southwest of the City of Springfield. The 26 drill holes intersect a cumulative total of 3,692 ft of Precambrian rock, from 10 ft

[1]Missouri Geological Survey, P.O. Box 250, Rolla, Missouri 65401.

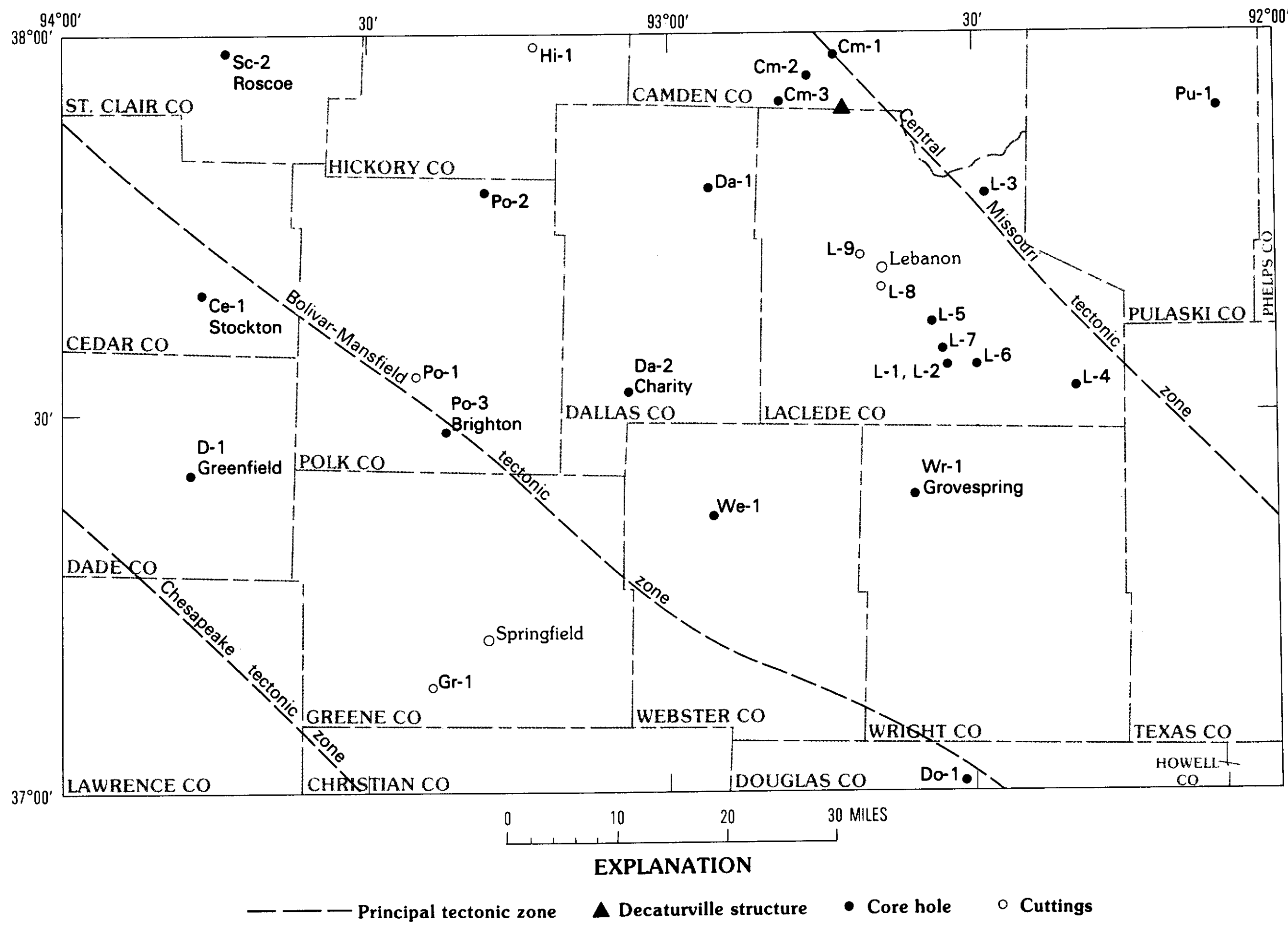


**Figure 46.** Locations of drill holes to the Precambrian basement in the Springfield 1°×2° quadrangle.

in hole L–9, in Lebanon, to 1,001 ft in hole L–1, near the Orla anomaly. Drill-hole numbers referred to in this report are those of the Missouri Geological Survey's Operation Basement data base (Kisvarsanyi, 1975).

Cores of the Precambrian rocks were logged, sampled, and described; at least one petrographic thin section was prepared from each cored interval to obtain a representative description of the composition and texture of the basement rock drilled. Several thin sections were made from cores that reach deeper into basement, particularly if there is a significant vertical variation in texture and composition. Cutting chips from the five holes not cored were examined under the binocular microscope, and thin sections were made from some of the larger chips suitable for mounting on a slide. Textural relationships between individual mineral grains are always more difficult to define in cuttings than in core, however, and identification of the overall rock fabric is less certain in cuttings.

Routine semiquantitative spectrographic analysis for 30 elements was made on bulk core samples selected from 17 core holes by the U.S. Geological Survey (M.S. Erickson, written commun., 1979; E.L. Mosier, written commun., 1985). U/Pb isotope ages on zircons were determined for 10 core samples by the Isotope Geochemistry Laboratory of the University of Kansas (M.E. Bickford and W.R. Van Schmus, oral commun., 1986). Rb/Sr and K/Ar ages on muscovite from the Decaturville pegmatite were obtained by Tilton and others (1962).

The magnetic anomaly map of Missouri (Zietz and others, 1984), aeromagnetic maps of the Springfield quadrangle (Missouri Department of Natural Resources, 1981a, b), and the Bouguer gravity anomaly map of the Springfield quadrangle (Grauch and Cordell, 1983) were studied to help interpret basement structures and to infer the extent of basement-rock terranes. These geophysical maps proved to be particularly helpful when used in conjunction with the information obtained from drill holes.

## PRECAMBRIAN ROCK TYPES

Two principal types of tectonic terranes containing specific types of basement rocks are recognized in the Springfield quadrangle: an orogenic suite of metamorphosed sedimentary and igneous rocks and an anorogenic suite of unmetamorphosed, epizonal granites. The orogenic suite includes a great variety of rock types: garnet-bearing quartz-microcline schist, biotite schist, muscovite-talc schist, quartzite, forsterite marble, sillimanite-bearing quartz-microcline gneiss, kyanite-bearing granite gneiss, metarhyolite, amphibolite, metagabbro, metadiorite, and migmatite. Cataclastic granulation, augen-type shearing, and mylonitization are locally associated with these rocks. These high-grade metamorphic rocks, which resulted from regional metamorphism, are mostly in the central part of the quadrangle; low-grade meta-argillite, meta-arkose, and metaconglomerate were recovered from cores in the western part of the quadrangle (fig. 47). Locally, the metamorphic rocks are intruded by granite and pegmatite. These rocks are part of an extensive terrane underlying most of northwestern Missouri (Kisvarsanyi, 1974), and they have been assigned to the Central Plains orogen (Sims, 1985).

The anorogenic suite is represented by rapakivi granite and coarse-grained biotite-quartz-orthoclase-microperthite granite very similar to the Butler Hill Granite mapped in outcrops in the St. Francois Mountains and widely distributed in the subsurface of the adjoining Rolla quadrangle. It is noteworthy, however, that unmetamorphosed volcanic rocks (rhyolite and trachyte) do not appear to be associated with the epizonal terrane in the Springfield quadrangle, although these rocks form a significant part of the outcrops in the St. Francois Mountains and were also encountered in a few drill holes in southwestern Missouri.

## BASEMENT STRUCTURE

The Springfield quadrangle is on the southern flank of the Central Missouri Precambrian structural high defined by Kisvarsanyi (1974). This structural high has a northwest-trending axis and is underlain mostly by the orogenic suite of basement rocks. It is interpreted as a horstlike, elongated tectonic window or salient of older crustal rocks, bounded on the east by the supracrustal and epizonal rhyolite-granite terrane of the St. Francois Mountains and on the west by the similar but younger Spavinaw terrane. The Spavinaw terrane refers to the subsurface granitic rocks of southwestern Missouri that are equivalent to the late Precambrian Spavinaw Granite of northeastern Oklahoma. In the Springfield quadrangle, the subcrop of Precambrian high-grade metamorphic rocks resulting from regional metamorphism indicates prolonged, very high uplift of deep-formed rock and an all-subduing erosion surface before the Paleozoic marine transgression. The rate of uplift probably was greatest in central Missouri, particularly along the Central Missouri tectonic zone (fig. 48), because basement rocks of the highest metamorphic grade occur there.

Three regional, northwest-trending tectonic zones that cross the Springfield quadrangle (fig. 48) have been defined by a combination of geophysical and subsurface geologic data (Kisvarsanyi, 1984, 1987). They extend for hundreds of kilometers in both directions: to the northwest as far as the Central North American rift system and to the southeast as far as the Reelfoot rift. The width of the basement tectonic zones is probably measured in thousands of meters; the lines on the map (fig. 48) represent the prevailing strike of their axial parts. Fracturing, faulting (normal, reverse, strike-slip), igneous activity (intrusive, extrusive, explosive), and (or) mineralization may have

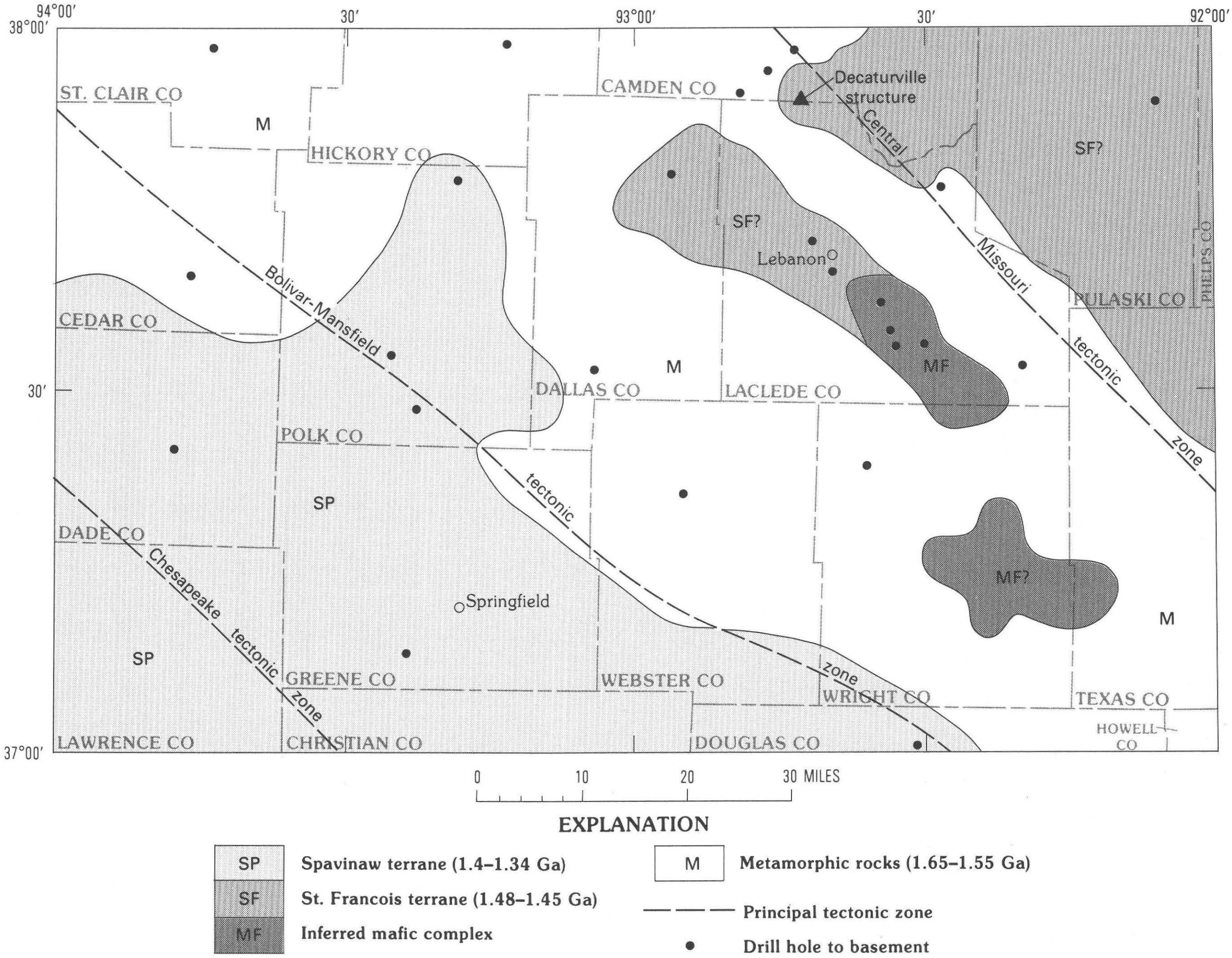


**Figure 47.** Basement-rock terranes in the Springfield 1°×2° quadrangle.

occurred and recurred along the tectonic zones. Deformation associated with the zones is likely to be more complex in the overlying sedimentary rocks. The brittle sedimentary rocks respond to crustal forces in many ways, including collapse, uplift, overturning, and fracturing in multiple directions, both inclined and parallel to the basement zones. Therefore, the structures mapped in the sedimentary rocks at the surface (Middendorf, 1985) do not correlate exactly with the inferred basement zones, but they reflect the principal, northwesterly tectonic grain of the region.

The tectonic zones shown in figure 48 were defined on the basis of the following data and geologic reasoning:

A. Chesapeake tectonic zone
   1. Coincidence with prominent magnetic lineament (Zietz and others, 1984).
   2. Close correlation with the Chesapeake fault mapped in the sedimentary rocks (Middendorf, 1985).
   3. Contrasting basement rock types: volcanic-epizonal south of the zone, mesozonal north of the zone.
   4. Inferred southeastward extension of a basement fault, downthrown on the north, defined by drill holes along the tectonic zone near the Kansas-Missouri State line (Kisvarsanyi, 1974).
   5. Apparently truncates the Spavinaw arch, a northeast-trending basement high (Denison, 1966).
   6. Identified as a regional lineament on remote-sensing imagery (Kisvarsanyi and Martin, 1977).

B. Bolivar-Mansfield tectonic zone
   1. Coincidence with prominent magnetic lineament (Zietz and others, 1984).
   2. Close correlation with the Bolivar-Mansfield fault system mapped in the sedimentary rocks (Middendorf, 1985).
   3. Contrasting basement rock types: mesozonal granite south of the zone, metamorphic terrane north of the zone.

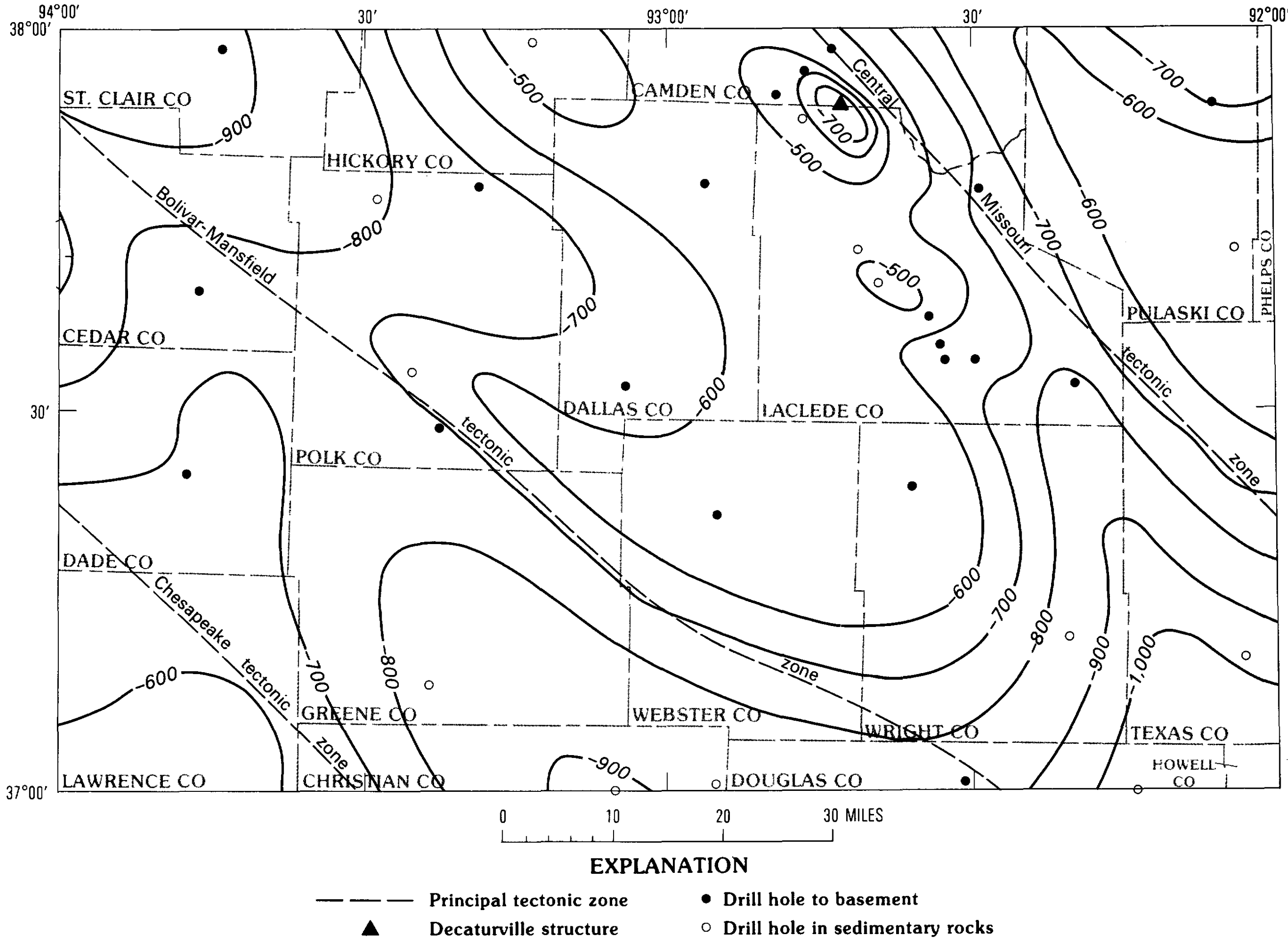


**Figure 48.** Structure contour map of the Precambrian surface in the Springfield 1°×2° quadrangle. Contour interval 100 ft; datum is mean sea level.

4. Inferred southeastward extension of a basement fault, downthrown on the south, defined by drill holes along the tectonic zone near the Kansas-Missouri State line (Kisvarsanyi, 1974).
5. Basement rocks near the tectonic zone are commonly cataclastic.
6. Identified as a regional lineament on remote-sensing imagery (Kisvarsanyi and Martin, 1977).

C. Central Missouri tectonic zone
1. Coincidence with prominent magnetic lineament (Zietz and others, 1984).
2. Close correlation with several surface faults (Middendorf, 1985).
3. Correlation with a prominent gravity gradient that forms the southern margin of the "Missouri gravity low," as defined by Arvidson and others (1984).
4. Suggested by lithologic data from drill holes (Kisvarsanyi, 1987).
5. Identified as a regional lineament on remote-sensing imagery (Kisvarsanyi and Martin, 1977).

The three tectonic zones form the boundaries of a series of alternating northwest-trending horsts and grabens. A graben bounded by the Chesapeake and Bolivar-Mansfield zones is underlain mostly by rocks of the Spavinaw terrane; a horst bounded by the Bolivar-Mansfield and Central Missouri zones is underlain mostly by the metamorphic terrane but locally contains granitic intrusive rocks. Basement rocks formed at deepest crustal levels are intersected along the Central Missouri tectonic zone and are structurally the highest in the quadrangle (fig. 48). Relief on the Precambrian surface probably is more moderate and gentle in the Springfield quadrangle than in the neighboring Rolla quadrangle. In the Springfield quadrangle the Precambrian surface has been eroded to a gently undulating, shieldlike platform, whereas in the Rolla quadrangle the Precambrian surface is extremely rugged. The style of deformation in the two quadrangles also is markedly different.

The Decaturville structure, an anomalous, local, intensely disturbed area near the boundary of Camden and Laclede Counties (fig. 48), was interpreted as an astrobleme by Offield and Pohn (1979). The Precambrian rocks exposed near the center of the structure are not in place, having been torn from the underlying basement and displaced 1,400 ft upward. Neverthless, local doming is apparently associated with the structure because the Precambrian high in the Springfield quadrangle is centered around Decaturville. The structure is just south of the Central Missouri tectonic zone and is along the gravity gradient forming the southern boundary of the Missouri gravity low. The Decaturville structure is one of several anomalous structures used to define the east-west–trending 38th-parallel lineament zone (Snyder and Gerdemann, 1965; Heyl, 1972). Two more of these structures, the Weaubleau, in St. Clair County, and the Hazelgreen, in Laclede County, are also in the Springfield quadrangle; however, neither the subsurface data nor the geophysical maps are sufficiently detailed and accurate to permit conclusive identification of a basement structural zone corresponding to this postulated lineament.

## BASEMENT TERRANES

U/Pb ages determined on zircons from 10 cores (Bickford and others, 1981; Thomas and others, 1984; W.R. Van Schmus, written commun., 1986) permit assignment of the major rock types to three distinct basement terranes in the Springfield quadrangle. The oldest of these, the metamorphic terrane underlying the central and western part of the quadrangle (fig. 47), yields ages of 1.55–1.65 Ga. The epizonal granitic rocks are assigned to two terranes having identical composition and emplacement characteristics but different crystallization ages. The older of the two is correlated with the St. Francois terrane identified in the Rolla quadrangle (Kisvarsanyi, 1981). The St. Francois terrane refers to the subsurface equivalent of the unmetamorphosed, dominantly silicic igneous rocks that crop out in the St. Francois Mountains of southeastern Missouri (Kisvarsanyi, 1974, 1981). Its crystallization age is 1.45–1.48 Ga. The younger epizonal terrane is correlated with the Spavinaw granite–rhyolite association and has been dated at 1.34–1.40 Ga. Recent Nd isotope analyses by Nelson and DePaolo (1985), however, suggest that the crust-formation age for this region is much older, 1.7–1.9 Ga, and that the epizonal terranes were formed by large-scale melting of older crustal rocks.

A mafic complex, associated with the Orla magnetic anomaly and referred to here as the mafic complex at Orla, is considered to be part of the older metamorphic terrane but is discussed separately below because of its distinctive composition.

### Older Metamorphic Terrane

Twelve of the twenty-six drill holes in the Springfield quadrangle intersected metasedimentary (paragneiss) and metaigneous (orthogneiss) rocks. Most of these rocks are associated with the elongated horstlike structure between the Bolivar-Mansfield and Central Missouri tectonic zones (fig. 47).

In the western part of the quadrangle, two drill holes (Ce–1 and Sc–2) intersected low to moderately high grade metasedimentary rocks. In Ce–1, near Stockton (fig. 46), 80 ft of meta-argillite, meta-arkose, and metaconglomerate were intersected. The fine-grained rocks are laminated and contain finely contorted bands of sericite and biotite and abundant granoblastic magnetite and ilmenite. The metaconglomerate section contains somewhat elongated, coarse porphyroclasts of quartzite. Among the geochemically analyzed core samples, those from the Stockton core are richest in iron (as much as 10 percent), chromium (as much as 500 ppm), nickel (as much as 100 ppm), and cobalt (as much as 50 ppm). These iron-rich sedimentary rocks may be spatially related to sedimentary environments favorable for banded iron formations. They may correlate with similar rocks described by Skillman (1948) in Vernon County, west of the Springfield quadrangle. Both the Vernon County and Stockton metasedimentary rocks most likely were preserved in a graben bounded by the Chesapeake and Bolivar-Mansfield tectonic zones.

The metasedimentary rocks drilled in hole Sc–2, near Roscoe (fig. 46), are of higher metamorphic grade. This drill hole intersected 244 ft of garnet-bearing biotite-quartz-microcline gneiss that has a granoblastic and lepidoblastic texture. The rock, identified as a regionally metamorphosed arkosic sedimentary rock, has well-developed metamorphic foliation; it contains local lenses of quartzite and is intruded by a very coarse grained granite pegmatite.

Drill-hole D–1 (fig. 46) intersected 77 ft of very coarse grained biotite granite that has been sheared, recrystallized, and partly converted to protomylonite; euhedral muscovite, formed by neomineralization, is believed to be associated with the mylonitization of this rock. Drill-hole Hi–1 is an older well from which only cutting chips are available for study. The granitic rock in this well was assigned to the metamorphic terrane on the basis of the predominance of muscovite over biotite in the samples. It is a muscovite-biotite-quartz-microcline rock having granoblastic texture but is difficult to identify more precisely from the available samples; however, because muscovite is usually not very abundant in the unmetamorphosed granitic rocks of the region, this rock is interpreted as part of the older metamorphic terrane.

Eastward across the quadrangle the metamorphic grade of basement rocks increases. Granoblastic and porphyroblastic, foliated, kyanite-bearing paragneiss, basic schist and amphibolite, and some orthogneiss were drilled on the northern flank of the Decaturville structure. These rocks yield ages of 1.55 and 1.63 Ga. At the center of the Decaturville structure, outcrops of muscovite schist and granite pegmatite attest to the extent of the metamorphic terrane in the underlying basement; however, the exposed pegmatite yields a Rb/Sr age of 1.45 Ga (Tilton and others, 1962) and probably correlates with the anorogenic granite magmatism that formed the St. Francois terrane.

Southeast of Decaturville, near the Central Missouri tectonic zone, drill-hole L–3 (fig. 46) encountered high-grade sillimanite- and garnet-bearing paragneiss. The drill hole intersected 79 ft of granite gneiss having infolded lenses of muscovite-talc schist exhibiting ptygmatic folds. The gneiss yields a U/Pb zircon age of 1.64 Ga; it is interpreted as a regionally metamorphosed pelitic sedimentary rock.

Four drill holes south of Lebanon (Da–2, We–1, Wr–1, and L–4) intersected moderately high grade meta-igneous rocks. One of these, Wr–1, intersected a meta-rhyolite that is foliated and regionally metamorphosed, and yields an age of 1.65 Ga. The other drill holes mentioned above intersected relatively fine grained granoblastic granite and granodiorite gneiss and foliated porphyroblastic basic schist. Augen-type shearing and cataclastic textures are common in the samples from drill hole L–4. The ortho-gneiss from We–1 yields a U/Pb age of 1.55 Ga.

## Mafic Complex at Orla

The mafic complex at Orla is but one of about a dozen similar layered complexes in the buried basement of Missouri (Kisvarsanyi, 1974, 1984). It is the only one drilled in the Springfield quadrangle, but another is inferred from a magnetic anomaly in the southeastern part of the quadrangle (fig. 47). The magnetic anomaly at Orla, in Laclede County, is shown on the magnetic map of Missouri published in 1943, as well as on subsequent aeromagnetic maps of the area. Between 1957 and 1968, three different companies drilled five exploration holes in the area of the magnetic high, with the result that there is now a cumulative total of 1,723 ft of Precambrian core available for study of the complex. Thus, the complex at Orla is by far the best documented part of the buried basement in the Springfield quadrangle and provides a wealth of geologic information.

The Orla mafic pluton was emplaced in the older metamorphic terrane of gneisses and schists. A large xeno-lith of siliceous dolomite, which measured 7 ft long in the core, is the only indication of calcareous rocks in the older terrane. The dolomite is contact metamorphosed to a grano-blastic skarn assemblage of calcite, forsterite, brucite, magnetite, serpentine, and minor quartz. At its deepest drilled level, in hole L–1, the mafic pluton is a fresh pyroxene gabbro composed of diallage, hypersthene, calcic plagioclase, a trace of olivine, much disseminated magnetite and chalcopyrite, and biotite. Most of the available core, however, is from shallower levels of the pluton. The gabbro has been pervasively intruded by mobile granitic material displaying three modes of occurrence: (1) distinct dikes and veins having sharp contacts, (2) porphyroblasts of alkali feldspar and quartz, and (3) diffuse bands and stringers. The latter produce a foliated hybrid rock, much like migmatite, composed of alternating bands of light-colored quartzo-feldspathic rock and dark-colored mafic rock. Zircons from the hybrid rock yield an age of 1.47 Ga (Bickford and others, 1981), which correlates in time with the formation of the St. Francois epizonal terrane. The data suggest, therefore, that the Orla mafic complex records a deeper, mesozonal level of the widespread St. Francois igneous activity in the region.

The pervasive emplacement of granitic magma under mesozonal conditions produced extensive metasomatic alteration in the gabbro. Detailed petrographic analysis of core samples indicates that the pyroxenes are uralitized and that the gabbro is essentially metamorphosed to an epi-diorite. In a recent study of the Orla cores, Sylvester (1984) suggested that the gabbro formed under granulite-facies conditions in very deep crustal levels and was tectonically uplifted to its present level, where it underwent retrograde metamorphism that produced the amphibolite-facies mineral assemblage now observed.

## St. Francois Terrane

The St. Francois terrane comprises unmetamorphosed epizonal granitic rocks and associated rhyolite ash-flow tuffs. It forms most of the basement in the adjoining Rolla quadrangle (Kisvarsanyi, 1981) and is a metallogenic province (Kisvarsanyi and Kisvarsanyi, 1977). Its extent in the Springfield quadrangle is tentatively drawn on the basis of only four drill holes and the 1.45-Ga-old pegmatite outcrop associated with the Decaturville structure. As shown in figure 47, the St. Francois terrane underlies the northeastern corner of the Springfield quadrangle, on the downdropped northern side of the Central Missouri tectonic zone. It must be emphasized, however, that volcanic rocks of the terrane appear to be absent in the Springfield quadrangle. Biotite granite in drill-hole Pu–1 is comparable in composition to the Butler Hill Granite exposed in the St. Francois Mountains but has gneissic texture and contains mylonitized sections. It is interpreted to represent a deeper, mesozonal level of the St. Francois terrane that shows the effects of dynamic metamorphism.

The pervasive "granitization" of the mafic complex at Orla is assumed to be the manifestation of igneous activity coeval with the rocks of the St. Francois terrane, an assumption supported by the 1.47-Ga crystallization ages of zircons obtained from the hybrid rocks of the complex (Bickford and others, 1981). The complex at Orla may thus represent the uplifted, deepest crustal level, or floor, of the St. Francois terrane.

## Spavinaw Terrane

The rock association identified as the Spavinaw terrane is similar in composition and tectonic setting to the

**Table 7.** Speculative ore deposit types in the St. Francois and Spavinaw terranes

| | |
|---|---|
| 1. | Iron with apatite and rare-earth elements in volcanic rocks (Kiruna type). |
| 2. | Iron-copper-cobalt-(gold) in contact metasomatic skarn associated with syenite and diorite intrusions (Boss type). |
| 3. | Tin-tungsten-silver-lead veins in granite (Silver Mine type). |
| 4. | Uranium and thorium in tin-granite central plutons and associated pegmatites. |

St. Francois terrane but is approximately 100 million years younger. U/Pb zircon ages determined on drill cores of granite assigned to the Spavinaw in the Springfield quadrangle are 1.35–1.37 Ga (M.E. Bickford, written commun., 1985). This epizonal granite-rhyolite terrane underlies most of southwestern Missouri and extends into adjoining parts of Oklahoma, Kansas, and Arkansas (Denison, 1966; Kisvarsanyi, 1974; Bickford and others, 1981). In the Springfield quadrangle it is represented mostly by granite, but rhyolite and trachyte are known from the buried basement west and southwest of the area.

Rocks assigned to the Spavinaw in the quadrangle are mostly red, coarse-grained rapakivi granites similar to the Butler Hill Granite of the St. Francois terrane. The biotite granite intersected in drill-hole Po–3 contains as much as 20 ppm Sn, 30 ppm Nb, and 5 ppm Be (E.L. Mosier, written commun., 1985). This geochemical signature is similar to that of tin-granite central plutons identified in the St. Francois terrane (Kisvarsanyi, 1981). An unusual metasomatized gabbro pegmatite intersected in drill-hole Do–1 is provisionally assigned to the Spavinaw terrane. The K/Ar age of biotite obtained from this rock is 1.27 Ga (Muehlberger and others, 1966).

## MINERAL-RESOURCE POTENTIAL

The buried Precambrian basement in the Springfield quadrangle is not a mineral producer, and ore-grade mineralization has not been observed in any of the cores or cuttings from the 26 drill holes. Therefore, potential mineral resources in the Proterozoic terranes recognized in the quadrangle are in the speculative category (U.S. Bureau of Mines and U.S. Geological Survey, 1980), and any appraisal of them must be based on (1) identification of favorable geologic environments for certain types of ore deposits, (2) analogies with similar terranes elsewhere, and (3) some definite but minor indication of potential mineralization. This approach, pertaining to the buried basement of the entire State, was used by Kisvarsanyi and Kisvarsanyi (1977).

Possible ore deposits in the unmetamorphosed epizonal granite-rhyolite terranes, the St. Francois and the Spavinaw, are easier to identify than in the older metamorphic terrane because in the adjoining Rolla quadrangle the St. Francois terrane is a known metallogenic province containing past and presently producing deposits (Kisvarsanyi and Kisvarsanyi, 1977; Kisvarsanyi, 1981). Petrographic, geochemical, and tectonic analogies between the St. Francois and Spavinaw terranes suggest that their metallogenesis may be similar and that the same types of ore deposits may be expected to form in both. Table 7 lists the speculative ore deposit types conceivably present in the epizonal rock associations of the Springfield quadrangle.

All the Kiruna-type deposits in the Rolla quadrangle are associated with the volcanic superstructure of the St. Francois terrane. In the Springfield quadrangle, inasmuch as the volcanic rocks have apparently been stripped off and deeper structural levels of the epizonal terranes are in contact with the overlying Phanerozoic sedimentary rocks, it is unlikely that Kiruna-type deposits are present unless undiscovered volcanic rocks are present. Syenite and diorite intrusions associated with mafic and intermediate complexes, as the one at Orla, may have Boss-type deposits; strong positive magnetic anomalies should indicate favorable locations for such deposits. Tin granites in both the St. Francois and Spavinaw terranes are favorable for deposit types 3 and 4 (table 7).

Ore deposits in the older Proterozoic metamorphic terrane may be analogous to deposits in the Canadian Shield. In the orogenic suite associated with the Central Missouri structural high, a number of speculative deposit types may be present, a few of which are listed in table 8.

Proterozoic clastic rocks in the quadrangle, particularly the meta-arkoses and metaconglomerates in the Roscoe and Stockton cores, are considered favorable geologic environments for deposit types 2, 3, and 4 (table 8). Anomalous Fe, Cr, Ni, and Co contents in the Stockton core are further indicators of potential mineralization; however, these criteria are clearly so tenuous that realistic evaluation of these deposit types in the quadrangle is not possible without further exploration. What *is* significant, however, is that the identification of a great variety of metamorphic rock types in the quadrangle opens up a wide range of possibilities for different types of mineralization.

Perhaps the most favorable geologic unit for mineralization in the entire quadrangle is the mafic complex at Orla and other possible similar complexes, as suggested by the magnetic anomaly map. It is highly significant that the mafic complex at Orla is the best-documented geologic unit in the quadrangle, the implication being that if efforts are focused on the Precambrian basement as an exploration target, a virtually unlimited potential for mineralization may

**Table 8.** Speculative ore deposit types in the older Proterozoic metamorphic terrane

| | |
|---|---|
| 1. | Massive volcanogenic sulfide deposits of copper-zinc-gold (Noranda type). |
| 2. | Uranium-thorium-gold in quartz-pebble conglomerate and arkosic sandstone (Blind River type). |
| 3. | Banded iron formation with or without manganese (Superior type). |
| 4. | Iron-copper-uranium-gold in clastic rocks (Olympic Dam type). |

**Table 9.** Speculative ore deposit types in layered mafic-ultramafic complexes exemplified by Orla

| | |
|---|---|
| 1. | Nickel-copper-chromium-(platinum) ores (Sudbury and (or) Bushveld type). |
| 2. | Iron-titanium ores in anorthosite zones (Allard Lake type). |
| 3. | Iron-copper-(gold) in contact metasomatic carbonate skarn (island-arc type). |

be identified. At Orla, both a favorable geologic environment and sulfide minerals are identified (table 9, type 1); anorthositic lenses in the core suggest deposit type 2 (table 9).

## SUMMARY AND CONCLUSIONS

This study of the Precambrian rocks in the Springfield quadrangle resulted in identification of a variety of metamorphic rock types and better definition of the extent of the older Proterozoic metamorphic terrane of the region. This terrane is known to extend north of the quadrangle and to underlie most of northern Missouri; however, it probably reaches its highest structural level in the Springfield quadrangle and is at a relatively shallow depth. These two factors, high structural level and shallow depth, are considered to be the most favorable aspects of the basement complex from a mineral-resource potential point of view. The costs of both exploration and mining are not prohibitive at the depths involved, 1,400–1,600 ft. Future exploration should take into consideration the variety of ore deposit types possible, use geophysical maps and geologic reasoning to formulate innovative exploration philosophies, and concentrate on the Precambrian basement as an exploration target. Table 10 summarizes the speculative resources, by metals, and the possible examples in terms of the available data from the Springfield quadrangle.

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**Table 10.** Speculative mineral resources in Precambrian rocks in the Springfield 1°×2° quadrangle—Summary by metal

| Metal | Type of deposit | Possible example in quadrangle |
|---|---|---|
| Chromium | In layered mafic intrusions | Orla |
| Nickel | In layered mafic intrusions | Orla |
| Titanium | 1. In anorthosite massifs | Rapakivi granite-anorthosite of St. Francois terrane |
| | 2. In anorthositic layers of mafic complexes | Orla |
| Iron | 1. Potassium-iron volcanic related (Kiruna type) | Volcanic rocks of St. Francois terrane |
| | 2. Banded iron-formation | None |
| Copper | 1. In layered mafic complexes | Orla |
| | 2. Potassium-iron volcanic related | Volcanic rocks of St. Francois terrane (Boss type) |
| | 3. Massive volcanogenic sulfides | None |
| Zinc | In massive volcanogenic sulfides | None |
| Silver | In epithermal veins | Plutonic rocks of St. Francois terrane |
| Gold | 1. Placers in conglomerate | Roscoe-Stockton cores |
| | 2. Massive volcanogenic sulfides | None |
| | 3. Epithermal veins | Pegmatites (?) |
| Uranium | 1. In granites and pegmatites | St. Francois terrane-type central plutons |
| | 2. Placers in clastic rocks | Roscoe-Stockton cores |
| Tin | In veins | Plutonic rocks of St. Francois terrane |
| Tungsten | In veins | Plutonic rocks of St. Francois terrane |


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# APPENDIXES 1, 2

**Appendix 1.** Principal maps and reports resulting from the Springfield CUSMAP project

Compiled by Heyward M. Wharton
Missouri Department of Natural Resources, Geological Survey

PUBLISHED MAPS AND REPORTS

| | | |
|---|---|---|
| *1. | | Erickson, R.L., Mosier, E.L., Odland, S.K., and Erickson, M.S., 1981, A favorable belt for possible mineral discovery in subsurface Cambrian rocks in southern Missouri: Economic Geology, v. 76, p. 921-973. |
| 2. | USGS MF-1830-A | Erickson, R.L., Erickson, M.S., Mosier, E.L., and Chazin, Barbara, 1985, Summary geochemical maps of the Springfield 1°×2° quadrangle and adjacent area, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-A, scale 1:500,000. |
| 3. | USGS MF-1830-B | Whitfield, J.W., 1986, Surficial materials map of the Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-B, scale 1:250,000. |
| 4. | USGS MF-1830-C | Wharton, H.M., 1987, Mines, prospects, and occurrences of metallic minerals and barite, Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-C, scale 1:250,000. |
| 5. | USGS MF-1830-D | Middendorf, M.A., Thomson, K.C., Easson, G.L., and Sumner, H.S., 1987, Geologic map of the Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-D, scale 1:250,000. |
| 6. | USGS MF-1830-E | Kisvarsanyi, E.B., 1987, Precambrian basement map of the Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-E, scale 1:250,000. |
| 7. | USGS MF-1830-F | Rueff, A.W., 1987, Industrial mineral resources of the Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-F, scale 1:500,000. |
| 8. | USGS MF-1830-G | Seeger, C.M., 1989, Structure contour maps on the base of Mississippian strata and the top of Upper Cambrian strata, Springfield 1°×2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1830-G, scale 1:250,000. |

*Not issued for the Springfield CUSMAP project, but information is relevant.

OPEN-FILE MAPS AND REPORTS
ISSUED BY THE MISSOURI DEPARTMENT OF NATURAL RESOURCES,
DIVISION OF GEOLOGY AND LAND SURVEY

I. MISCELLANEOUS OPEN-FILE MAPS AND REPORTS

| | | |
|---|---|---|
| 1. | MGS OFM-82-99-MR | Searcy, K.P., 1981, Drillholes with ore minerals, Springfield 2° quadrangle, Missouri: Scale 1:250,000. |
| 2. | MGS OFM-82-100-MR | Searcy, K.P., 1981, Ore minerals in drillholes--Cambrian, Springfield 2° quadrangle, Missouri: Scale 1:250,000. |
| 3. | MGS OFM-82-101-MR | Searcy, K.P., 1981, Ore minerals in drillholes--Ordovician/Canadian Series, Springfield quadrangle, Missouri: Scale 1:250,000. |
| 4. | MGS OFM-83-132-GI | Bohm, R.A., 1983, Isopach map of the Cambrian carbonates, Springfield 2° quadrangle, Missouri: Scale 1:250,000. |
| 5. | MGS OFM-83-145-GI | Palmer, J.R., 1983, Cambrian lithofacies cross section from southern Bates Co., Missouri to southeastern Pulaski Co., Missouri: Horizontal scale 1:250,000, vertical scale 1"=20 ft. |
| 6. | MGS OFM-83-146-GI | Palmer, J.R., 1983, Cambrian lithofacies cross section from western Christian Co., Missouri, to eastern Howell Co., Missouri: Horizontal scale 1:250,000, vertical scale 1"=20 ft. |
| 7. | MGS OFM-83-152-GI | Palmer, J.R., 1983, Structural contour map of the top of the Middle Bonneterre Formation, Springfield 1°×2° quadrangle, Missouri: Scale 1:250,000. |
| 8. | MGS OFM-83-169-GI | Bohm, R.A., compiler, 1984, Structure contour map on top of the Cambrian carbonates, Springfield 1°×2° quadrangle, Missouri: 1 sheet, scale 1:250,000. |
| 9. | MGS OFM-84-199-GI | Bohm, R.A., compiler, 1984, Isopach map of basal "Cambrian clastics" (Lamotte-Reagan sandstone), Springfield 1°×2° quadrangle, Missouri: Scale 1:250,000. |

| | | |
|---|---|---|
| 10. | MGS OFM-85-226-MR | Seeger, C.M., compiler, 1985, Ore minerals in drill holes--Mississippian (rocks); Springfield 1°×2° quadrangle, Missouri: 1 sheet, scale 1:250,000. |
| 11. | MGS OFM-85-227-MR | Middendorf, M.A., compiler, 1985, Structural features of the Springfield 1°×2° quadrangle, Missouri: 1 sheet, scale 1:250,000. |
| 12. | MGS OFM-85-228-MR | Martin, J.A., and Kisvarsanyi, G., 1985, Lineaments of the Springfield 1°×2° quadrangle, Missouri: 1985, 1 sheet, scale 1:250,000. |
| 13. | MGS OFM-85-230-GI | Palmer, J.R., 1985, Lithofacies maps of the Cambrian carbonates of the Springfield 1°×2° quadrangle, Missouri: 2 sheets, scale 1:500,000. |
| 14. | MGS OFR-85-42-MR | Martin, J.A., and Pratt, W.P., eds., 1985, Geology and mineral-resource potential of the Springfield 1°×2° quadrangle, Missouri, as appraised in September 1985: 82 p. |
| 15. | MGS OFM-86-235-GI | Palmer, J.R., 1986, Isopach and structure maps of the Lamotte and Reagan Sandstone lithofacies with an interpretation of depositional environments, Springfield 1°×2° quadrangle, Missouri: Scale 1:1,000,000. |

II. GEOCHEMICAL REPORTS

| | | |
|---|---|---|
| 1. | MGS OFR-83-18-MR | Erickson, M.S., 1983, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 23, 24, and 25. |
| 2. | MGS OFR-83-19-MR | Erickson, M.S., 1983, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 9, 12, and 16. |
| 3. | MGS OFR-83-24-MR | Erickson, M.S., and McDougal, C.M., 1983, Spectrographic analyses of whole-rock and insoluble residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 1, 2, 3, 4, and 5. |
| 4. | MGS OFR-83-25-MR | Erickson, M.S., 1983, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 20 and 21. |
| 5. | MGS OFR-84-28-MR | Erickson, M.S. 1984, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle and adjacent areas, Missouri: Drill holes 6, 7, and 8. |
| 6. | MGS OFR-85-31-MR | Erickson, M.S., 1985, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 10, 11, and 14. |
| 7. | MGS OFR-85-32-MR | Erickson, M.S., and Chazin, B., 1985, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 15, 17, and 19. |
| 8. | MGS OFR-85-41-MR | Erickson, M.S., and Chazin, B., 1985, Spectrographic analyses of whole-rock and insoluble-residue samples, Springfield 1°×2° quadrangle, Missouri: Drill holes 36, 37, 38, and 40. |

III. GEOPHYSICAL MAPS

| | | |
|---|---|---|
| 1. | MGS OFM-81-40-GI | Aeromagnetic map compilation of part of the Springfield 1°×2° quadrangle, Missouri: 1981, scale 1:250,000. |
| 2. | MGS OFM-81-41-GI | Aeromagnetic map compilation of part of the Springfield 1°×2° quadrangle, Missouri: 1981, scale 1:250,000. |
| 3. | MGS OFM-83-159-GI | Grauch, V.J.S., and Cordell, Lindrith, 1983, Bouguer gravity anomaly map of the Springfield 1°×2° quadrangle, Missouri: Scale 1:250,000. |
| 4. | USGS OF-84-648 | Aeromagnetic map compilation of part of the Springfield 1°×2° quadrangle, Missouri: 1984, scale 1:250,000. |

## **Appendix 2.** Field guide, Springfield area, Missouri

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This guide is modified slightly from a guide prepared for a 1-day field trip held in conjunction with the public Springfield CUSMAP review in November 1985. The trip was designed to show primarily the Lower Mississippian (Kinderhookian and Osagean Series) rock types and relationships, the nature of the Mississippian-Ordovician contact, and a major fault (Chesapeake fault) in the area.

### INTRODUCTION

A broad carbonate shelf extended southwestward and eastward from the transcontinental arch into Missouri in Osagean time. Continuous deposition of limestone typified by the Burlington and Keokuk Limestones occurred on the shelf proper north of Springfield; however, approximately from Springfield south, a southward-prograding shelf edge existed. Here the time-transgressive upper Pierson Limestone and the fine-grained, cherty limestones of the Elsey and Reeds Spring Formations were deposited prior to deposition of the Burlington Limestone. Stop 1 is near the northern extremity of the prograding shelf edge, where the cherty Elsey Formation separates the Burlington and the Pierson. The stops on State Highway 13 north of Springfield are on the shelf proper, where the Burlington rests directly on the Pierson.

Features related to faulting, which may be observed at Stops 4 and 5, include (1) dolomitization of limestones in the vicinity of fault zones, (2) calcite veins and some intense replacement of chert by calcite, (3) breccia zones, and (4) post-Canadian, pre-Mississippian deformation.

The road log begins at the junction of Glenstone Avenue and Interstate 44 on the northeast side of Springfield. It ends 78.7 mi later on Interstate 44 about 27 mi west of the starting point.

### ROAD LOG

| Mileage | |
|---|---|
| 0.0 | Exit from Glenstone Avenue right (east) onto Interstate Highway 44 (I-44), and proceed east to U.S. Highway 65 overpass. Scattered outcrops of Burlington and Keokuk Limestones are present in roadcuts. Note uneven upper surface of the Burlington and its tendency to form enlarged joints and pinnacles. Large irregular pinnacles are troublesome obstacles to construction projects. |
| 1.8 | Exit I-44 right (south) onto U.S. Highway 65 and continue south to State Route D (Sunshine Street). Burlington and Keokuk Limestones are exposed in cuts. |
| 6.5 | Exit U.S. Highway 65 on off ramp for Sunshine Street. Turn left (east) at traffic signal onto Route D and continue east to Stop 1. |
| 10.8 | *Stop 1.* Turner's Station, original type section for the Pierson Limestone. Lower part of the Pierson is exposed in a roadcut on the old road leading to Turner's Station just south of Route D. Alternating fine-grained limestone beds and zones of large, light-colored chert nodules of the Elsey Formation overlie the Pierson at this locality. Turn around and return west on Route D toward U.S. Highway 65. |
| 11.7 | Elsey Formation in cut. |
| 11.9 | Burlington and Keokuk in cut. |
| 13.3 | *Stop 2.* Elsey Formation in roadcut at Pearson Creek bridge. Here the Elsey consists of alternating beds of fine-grained gray limestone and light-colored, mottled chert. Continue west on Route D back to U.S. Highway 65. |
| 14.9 | Exit Route D (Sunshine Street) right (north) onto U.S. Highway 65. |
| 19.5 | Exit U.S. Highway 65 onto westbound I-44 (Tulsa), and proceed west to Mo. Highway 13. Roadcuts are in Burlington and Keokuk Limestones. |
| 24.4 | Exit I-44 right (north) onto Mo. Highway 13; bear right at traffic signal and proceed north. |
| 24.8 | Burlington and Keokuk Limestones in cuts for next several miles. Several good examples of uneven, pinnacled surface. |
| 31.5 | Exposures of Burlington and Keokuk Limestones. |
| 34.9 | Northview Formation in roadcut on left (west). Shale and siltstone of the upper part of the formation. |
| 35.6 | Pierson Limestone on right. |
| 37.5 | Crossing North Dry Sac River. |
| 37.7 | Cotter Dolomite, Compton Limestone, and Northview Formation in roadcut on right (east), just north of bridge. |
| 39.1 | Northview shales in cut on left (west). |
| 39.8 | Turn left (west) at junction with Mo. Highway 215. Cross over to southbound lane of Mo. 13. |
| 40.1 | Turn left (south) onto southbound lane of Mo. 13. |

41.4 *Stop 3.* At this locality, the Burlington Limestone rests directly on the brown dolomitic Pierson Limestone. The Reeds Spring and Elsey Formations, which occupy the interval between the Burlington and Pierson at and south of Springfield, are not present here. Their absence is the result of tectonodepositional conditions rather than erosion. While the Burlington was being deposited here on the shelf, upper Pierson, Reeds Spring, and Elsey rock types were being deposited on the prograding shelf to the south. At this exposure, the Pierson is 8-10 ft thick; 10 ft of the overlying Burlington and more than 10 ft of the underlying Northview are also exposed. Continue south on Mo. 13.

42.0 Cotter Dolomite in cut on left. Compton and Northview are in view in the cut on the northbound lane.

42.2 Cross bridge over North Dry Sac River.

43.2 Northview shale and siltstone in roadcuts on highway and on side road.

43.7 Burlington Limestone overlying Pierson in road cut.

44.2 Crossing fault, upthrown to the south. Northview shale is exposed just north of junction with Routes BB and CC.

44.5 *Stop 4.* Highly dolomitized Compton Limestone resting on Cotter Dolomite on upthrown side of fault. A low-magnitude angular unconformity is visible between the Compton and Cotter. Low-amplitude folds in the Cotter are truncated regionally by the overlying Compton. Small-scale faults, which are not reflected in the overlying strata, are also in the Cotter. These structures are likely related to Middle Ordovician tectonism. Note also sandstone "dikes" in the Cotter Dolomite. These are fillings of small joint-oriented solution features by sandstone of the basal Kinderhookian (basal Mississippian) Bachelor Formation that lies between the Cotter and the Compton. Continue south on Mo. Highway 13 to interchange with I-44.

44.9 Upper Northview siltstone and shale in road cuts.

55.2 Exit Mo. Highway 13 right (west) onto I-44 and proceed west.

66.6 Deformed Burlington Limestone adjacent to (east side of) northwest-trending Republic fault. Fault follows valley of Pond Creek.

68.1 Burlington and Keokuk Limestones overlying limestone and chert of the Elsey Formation in roadcut. Pierson Limestone exposed in creek bed to west of exposure.

76.9 Bridge over Goose Creek.

77.4 Burlington and Keokuk Limestones in roadcut on right. The Burlington has been partly dolomitized because of its proximity to the Chesapeake fault just to the west.

78.7 *Stop 5.* Chesapeake fault exposed just west of overpass of County Road N over I-44. This major crustal break is well exposed at this locality and exhibits many of the features common to faulting in southwestern Missouri such as brecciation, dolomitization, and calcite veining. The fault is upthrown to the west, and although the exact amount of throw is difficult to determine at this locality, it is well over 100 ft. Steeply dipping beds along the fault are exposed on both sides of I-44. The accompanying sketch (fig. A-1) illustrates an interpretation of structure and stratigraphy as exposed on the south side of the cut. Rocks above (east of) the Northview shales are strongly altered by dolomitization and replacement by calcite, and formational units are difficult to identify. The mass identified as altered Reeds Spring has been severely dolomitized; chert beds and nodules are replaced by calcite. There is noticeably less alteration stratigraphically below the Northview Formation (away from the fault).

**End of road log**

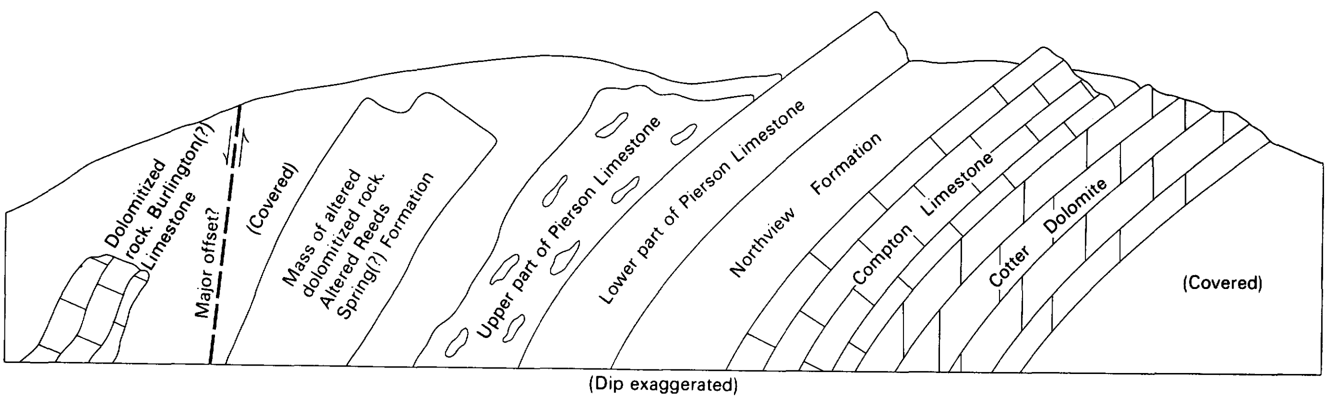


**Figure 49.** Diagrammatic sketch of south side of roadcut, Stop 6.



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