FIELD GUIDE TO THE UPPER CAMBRIAN OF SOUTHEASTERN MISSOURI: STRATIGRAPHY, SEDIMENTOLOGY, AND ECONOMIC GEOLOGY

(Prepared in conjunction with the
1989 Annual Meeting of the Geological Society of America)

edited by

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FIELD GUIDE TO THE UPPER CAMBRIAN OF SOUTHEASTERN MISSOURI:
Stratigraphy, Sedimentology, and Economic Geology

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INTRODUCTION

This guidebook was prepared for both the SEPM Midcontinent Section field trip, held October 14-15, 1989 and a pre-meeting field trip on November 3-4, in conjunction with the 1989 Annual Meeting of the Geological Society of America, held in St. Louis, Mo. both field trips covered the Upper Cambrian of southeastern Missouri and visited many of the same outcrop localities. The SEPM trip, led by Jay Gregg and Jim Palmer, lasted for a day and a half, visiting 10 outcrops. The GSA field trip led by Vince Kurtz and Jim Palmer, lasted for 2 days and visited 17 outcrops.

The Upper Cambrian sedimentary sequence of the St. Francois Mts. region hosts one of the world's largest Mississippi Valley-type (MVT) ore deposits. This district, located in southeastern Missouri on the west bank of the Mississippi river, is in fact tye type locality for this genera of ore deposits. Lead was discovered by the French explorer M. Lamotte in 1720 near modern Fredericktown, Missouri, although the ores had been exploited by native Americans for many years prior to this. The district has been the center of mining activity in Missouri almost continuously since then. During the Civil War sharp battles were fought between pro-Union miners and Confederate raiders in the lead belt. One such engagement, in 1864, resulted in the fledgling St. Joseph Lead Company losing a substantial part of their first years production. The lead was returned by the Rebels of course; piece by piece!

By the end of World War II the reserves in the "Old Lead Belt" were nearly depleted. At this time St. Joseph Lead Company began a concerted exploration effort, under the guidance of John S. Brown, which led to the discovery of the Viburnum Trend. The history of this discovery is outlined by Ernie Ohle and Paul Gerdemann in the last paper in this volume. Both Paul and Ernie were intimately involved in this remarkable discovery. Paul Gerdemann, before his retirement in 1986, was Chief Geologist and Vice President of Exploration for St. Joe Minerals Corporation and Ernie Ohle is recognized as one of the world's leading authorities on MVT mineral deposits.

The rest of the papers presented in this volume cover a number of aspects of the geology of southeastern Missouri important to our understanding of the regional tectonic and stratigraphic framework, as well as the economic geology of the ore deposits. The first paper, by Jim Palmer, outlines the stratigraphic framework of Upper Cambrian units from the St. Francois southward into the Reelfoot Graben. The second paper, by Dave Houseknecht details the facies relationships and tectonic milieu of the Lamotte Sandstone in the St. Francois Mts. region as well as presenting new ideas about the timing of rifting relative to the accumulation of thick sedimentary sequences in the Reelfoot Graben. Jay Gregg and Paul Gerdemann give an overview of the sedimentary facies of the Bonneterre Formation, the principal host of the southeast Missouri ore deposits. A brief synopsis follows of the work done at the University of Missouri-Columbia, on the Bonneterre, by Tom Freeman and his students John Lyle, John Ellison, and Tom Medary. Mike Sargent then discusses the facies and stratigraphy of the Eau Claire Formation (=Bonneterre) in Illinois. He suggests that ore grade MVT mineralization may exist in the subsurface of southern Illinois. Vince Kurtz presents stratigraphic correlations between Upper Cambrian sequences of the Ozarks and the upper Mississippi Valley region. This work ties together two earlier published cross-sections. Gordon Wood and Todd Stephenson presents correlations between Upper Cambrian Units of the St. Francois Mts. region and the Reelfoot Graben using palynology. Additionally, they document progressive thermal maturity of sedimentary rocks from the St. Francois Mts. region into the Graben. A summary of the sulfide paragenesis in southeast Missouri, based on years of study, is presented by Dick Hagni.

The last section of this volume contains descriptions of the stops to be visited on both field trips. As accurate of locations are given as possible so that this book may continue to be used as a guide for future field excursions.

We wish to thank the Amoco Production Company for providing the color plates used in the paper by Wood and Stephenson. A special thanks goes to Cheryl M. Seeger for her work on several of the stop descriptions that appear in this book. We also thank Paul Gerdemann who spent many hours passing along some of his vast knowledge of the surface geology of the St. Francois Mts. region to the senior editor. Finally we thank Data-Pro Computers of Rolla, MO for their help in producing this volume which was "desk-top published" using Apple™ Macintosh™ computers and a laser printer.

LATE UPPER CAMBRIAN SHELF DEPOSITIONAL FACIES AND HISTORY, SOUTHERN MISSOURI

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ABSTRACT

Depositional patterns of basal Paleozoic alluvial-fluvial clastics followed by Upper Cambrian carbonate-dominated shelf sediments, in southeast Missouri, were controlled by structures related to the Reelfoot Rift. These patterns and local large-scale sequences reflect a tectonic framework that included formation of a large graben basin in the Reelfoot Rift; the rift graben margin, a regional carbonate shelf margin; rift mountains, the St. Francois Mountains; and back basins, the latter developing into intrashelf basins. The post-rift Cambrian sedimentary sequence, +4,700 ft thick at the failed Reelfoot Rift margin, thins to 700 ft in the western Ozarks. These strata nonconformably overlie pre-rift Precambrian basement, and are thin to absent over rift mountains and isolated hills of igneous and metamorphic rocks.

The first of three regional transgressions, possibly as old as late-Middle Cambrian in southeast Missouri, deposited quartzose sandstones in the middle to upper Lamotte. Later transgressions, deposited clastic-rich, glauconitic carbonates of a drowned shelf facies. During or before drowning, ribbon-rock deposition aggraded much of the shelf to a homoclinal ramp. Rimming of the regional carbonate shelf, during the Dresbachian and Franconian, may have been controlled by uplift of the Reelfoot Graben margin. Intrashelf basins, containing shales and limestones, developed after each transgression. The transition between intrashelf basin areas and carbonate platforms were along homoclinal ramps during periods of transgression. After each major transgression, some ramps became distally steepened, and many became sites for isolated thrombolite bioherms. Progradation of shoal complexes into areas of active ramp bioherm-upbuilding resulted in widespread thrombolite-stromatolite fringing banks. These fringing banks grade platformward into peritidal cycles of ooid-intraclast packstone-grainstone, thrombolite-stromatolite, and supratidal laminite.

INTRODUCTION

The Upper Cambrian sequence in Missouri comprises six formations, in ascending order (Fig. 1 and 2): the Lamotte Sandstone; Bonneterre Formation (with Sullivan Siltstone and Whetstone Creek Members); Davis Formation; Derby-Doe Run Dolomite; Potosi Dolomite; and the Eminence Dolomite. These units are completely exposed only in and around the St. Francois Mountain portion of the Ozark Uplift. The type sections for all formations, excepting the Lamotte Sandstone and the Eminence Do-

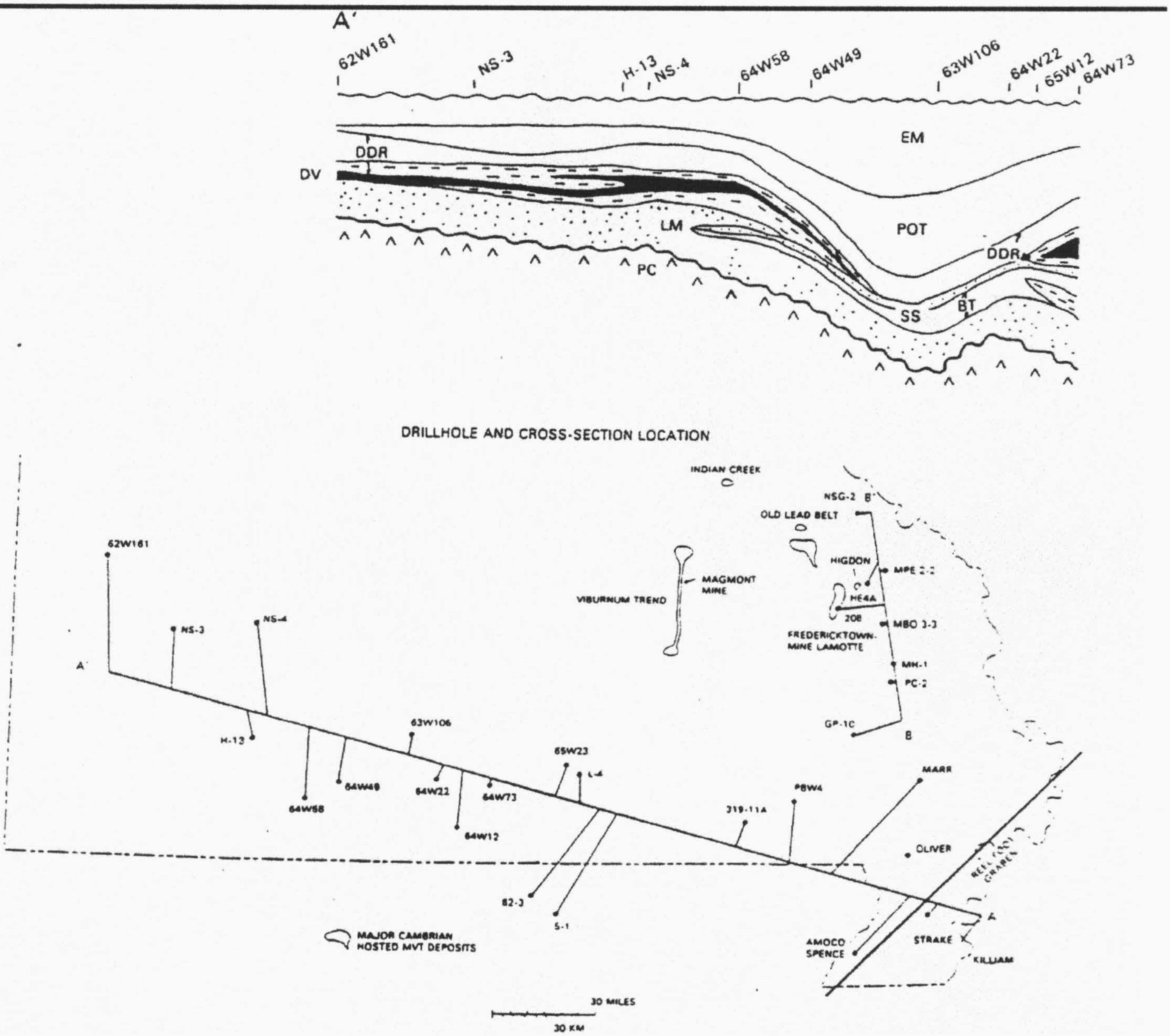
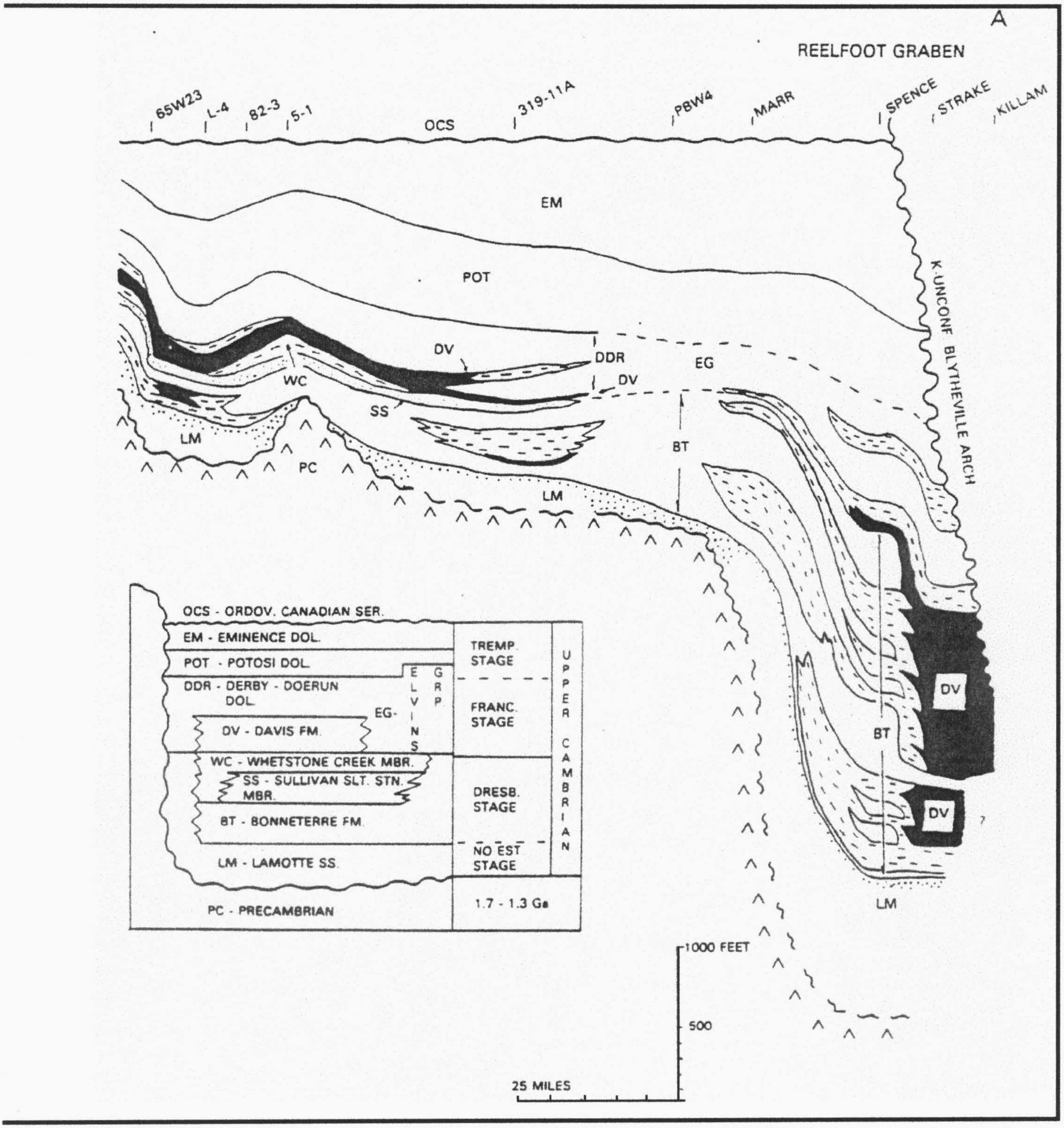


Figure 1. Cross-section A-A' looking across the south flank of the Ozark Uplift from the Reelfoot Graben to western Missouri. A-A' and B-B' are both constructed with the base of the Lower Ordovician as the datum. Cross-section locations are shown on the index map. Shales are shown in black; shaly limestone or dolomite are shown with dashed lines; sandstone, conglomerate and siltstone are shown in dots; non-shaly dolomite and limestone are shown in white. Formation abbreviations are shown on the correlation chart.

lomite, are in the northern part of the Cambrian outcrop belt, near the east margin of the Central Missouri Intrashelf Basin.

The paleodepositional and tectonic framework (Fig. 3) is reflected in four distinct stratigraphic sequence types: 1) rift graben basin, 2) graben margin and carbonate shelf margin, 3) intrashelf basin-carbonate ramp, in the northern part of the outcrop belt, and 4) carbonate platform inte-



rior, which dominates the St. Francois regional shelf. Large-scale, unconformity bounded, transgressive-regressive (T-R) sequences, sedimentation patterns and basin geometry show failed rift structures as controls on sedimentation during the Late Cambrian.

This paper presents a summary of this Upper Cambrian sequence in southern Missouri, describing its depositional history and

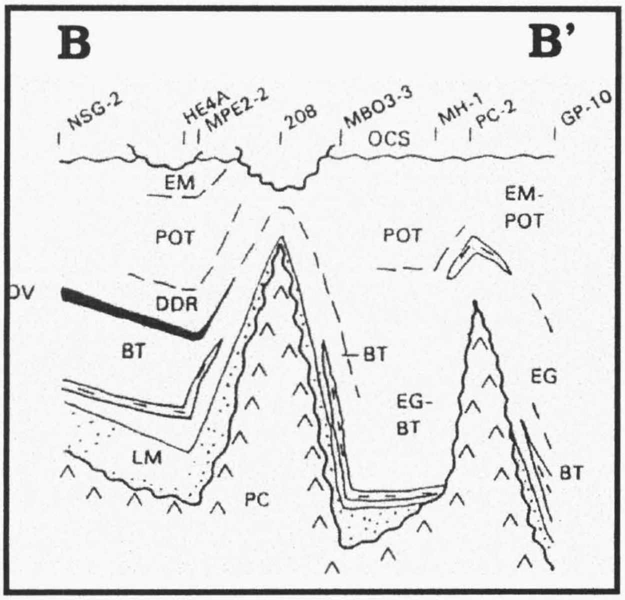
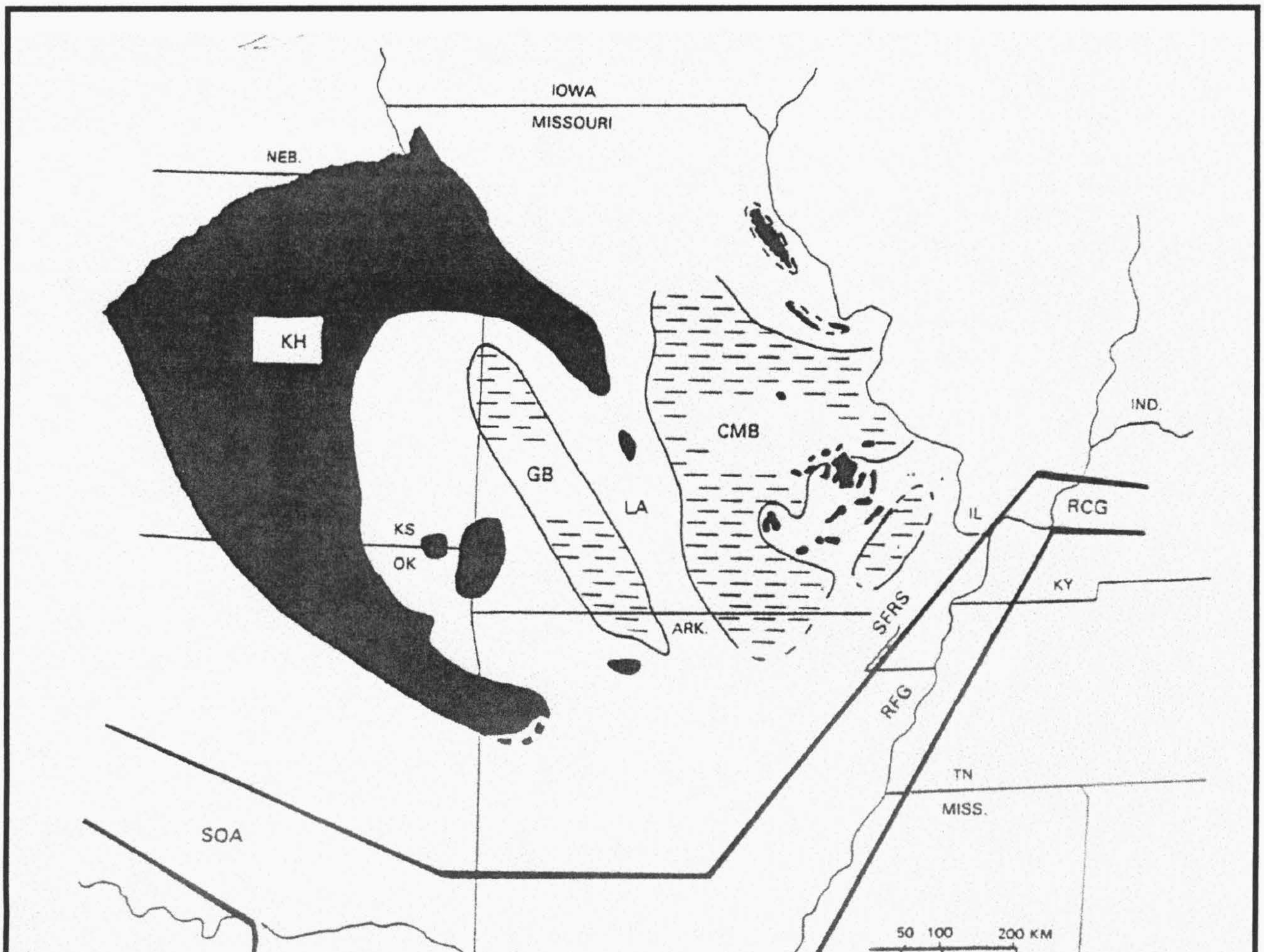


Figure 2. Cross-section B-B' is up the east flank of the Ozark uplift, begins in the regional St. Francois carbonate shelf, goes northward into the Central Missouri intrashelf basin. Symbols and abbreviations are the same as Figure 1.

Figure 3. Regional depositional and tectonic framework. Intrashelf basin areas are shown in dashed lines. Central Missouri intrashelf basin (CMB) and Greenfield intrashelf (GB) and the Lebanon Arch (LA) are shown as they were during the Franconian (Davis Fm.). The Kansas Highland (KH) and other areas with thin Upper Cambrian rocks over Precambrian highlands are shown in black. The St. Francois regional carbonate shelf (SFRS) flanks the Reelfoot Graben (RFG). Other abbreviations: Southern Oklahoma aulacogen (SOA) and Rough Creek Graben (RCG). Modified after Bohm (1981), Braile et al. (1984), Bushbach and Schwalb (1984), Howe (1969), Lochman-Balk (1971).



facies. Not surprisingly, this sequence is very similar to temporally equivalent passive-margin carbonate shelf-intrashelf basin systems, described from the Cambrian of the southern Canadian Rockies (Aitken, 1978) and the southern Appalachians (Markello and Read, 1981 and 1982).

Regional Geologic Setting

Paleozoic rocks in Missouri dip a few degrees away from the broad, assymetrical Ozark Uplift. Throughout its Paleozoic history the Ozarks were uplifted repeatedly, as is evidenced by unconformity-bounded sequences between and within nearly every Paleozoic System.

The buried Precambrian complex beneath this cratonic swell includes an extensive fold belt of early proterozoic meta-sediments and meta-igneous rocks in north-central Missouri (1.63-1.8 GA; Sims et al., 1987); the well known St. Francois Mountain (1.38-1.47 GA) and the Spavinaw (1.32-1.40 GA) anorogenic granite-rhyolite terranes, the latter centered in northeastern Oklahoma; and basaltic dikes exposed locally in the St. Francois Mountains, known only to be younger than the granites and rhyolites they intrude. Their relationship to Spavinaw terrane rocks is uncertain. In addition, intrusive gabbro-norite layered—maic complexes (Kisvarsanyi, 1984), between 1.47-1.8 Ga, are emplaced along northwest-striking tectonic zones in the central Missouri region. For an excellent discussion and references to these and other Precambrian rocks in the Midcontinent see Sims et al. (1987).

As much as 700 million years of geologic record was removed in the southern Ozarks before the Reelfoot Rift (Fig. 3) was imposed on this basement complex. The failed Reelfoot Rift is thought to be related to continental separation and rifting during the last Precambrian or early Cambrian (Ervin and McGinnis, 1975; Braile et al., 1984). The 70 km wide Reelfoot Graben, beneath Cretaceous sediments and Cenozoic alluvium in the Mississippi Embayment, is in the central part of the rift area, and has been described as a full graben by Hildegrand et al. (1977). Paleozoic sediments in the Reelfoot and the associated Rough Creek Graben may have exceeded 23,000 ft in total thickness (Schwalb, 1982).

Regional-scale facies evidence of syndepositional tectonics during the Upper Cambrian, was not available to Ervin and McGinnis (1975). As noted by Houseknecht (this volume) the earliest sediments in the Reelfoot Graben are likely to be non-fossiliferous alluvial or fluvial sediments whose age will remain uncertain. Regardless of their age, the first sediments to overlie the pre-rift Precambrian basement in the southern Ozarks are alluvial fan deposits, which represent the first stage of post-rift sedimentation. I suggest that the St. Francois Mountains formed as rift mountains in a northeast-trending series of blocks that parallels the Reelfoot Graben. The erosional relief on this surface in southeast Missouri may have exceeded 2,500 ft, increasing from the southwest to the northeast, and becomes abruptly less rugged north of a line extending from the north margin of the Rough Creek Graben (Fig. 3). The St. Francois Mountains are either part of the rift border fault system, an accommodation zone between the Reelfoot and Rough Creek Grabens, an uplifted rift shoulder behind the rift border fault system, or some combination of these settings. Effects of rift-related thermal and mechanical uplift and subsidence extended at least 150 miles from the Reelfoot Graben into the regional shelf.

Within the Mississippi Embayment pre-Cretaceous uplift and erosion attributed by Grohskopf (1955) to the northwest-striking arm of the Ozark Uplift, the Pascola Arch, truncates as much as 7,000 ft of Paleozoic strata (Fig. 1). However, Hamilton and McKeown (1988) have shown a northeaast oriented uplift inside and parallel to the Reelfoot Graben, the 10-15 km wide and 110 km long Blytheville Arch, to be responsible for this large amount of pre-Cretaceous truncation.

PHYSICAL STRATIGRAPHY

Intrashelf Basin Areas

Lamotte Sandstone. - Lamotte sandstones and/or conglomerates (0-500 ft) are present throughout the region except where they pinch-out against isolated erosional hills and highland regions of Precambrian rocks (Hayes and Knight; 1961). The transgressive marine upper Lamotte in western Missouri is equivalent in part to the Dresbachian Bonneterre (Kurtz et al., 1975). No formal stage has been established for the Lamotte in southeastern Missouri.

The contact between the Lamotte and overlying Bonneterre has been described as conformable (Hayes and Knight, 1961; Thacker and Anderson, 1977). Locally, this contact is a transgressive diastem or disconformity.

Dresbachian Stage

Bonneterre Formation. - The Bonneterre Formation in southern Missouri consists of shales, thin sandstones and siltstones, and carbonates. Dolomites in the Bonneterre host the world class Mississippi Valley-type (MVT) lead-zinc-copper deposits of southeast Missouri. In the southern Ozarks the Bonneterre is 0-400 ft thick (Hayes and Knight, 1961). The Bonneterre Formation is readily identified where its upper members and the Davis Formation are present in the Central Missouri Basin (Fig. 4). It is absent west of the Lebanon Arch.

In the Central Missouri Intrashelf Basin the upper Bonneterre contains two named members (Kurtz et al., 1975), the Sullivan Siltstone (0-65 ft) and overlying Whetstone Creek (0-100 ft). Facies with one another, the Sullivan Siltstone grades into the glauconitic Whetstone Creek in the area of the Lebanon Arch. At the eastern margin of the Central Missouri Basin, the Sullivan Siltstone changes facies to ribbon rock dolomites (Kurtz et al., 1975). The contact between the Sullivan Siltstone and ribbon rocks in the underlying Bonneterre is conformable. However, in parts of southwestern Missouri a regional transgression that took place in steps produced a disconformity between the Sullivan Siltstone and the underlying Bonneterre shoal facies. This transgression began during the middle part of Bonneterre deposition in the Central Missouri Basin (Palmer in prep.). The Whetstone Creek Member onlaps part of the Bonneterre platform in southeastern Missouri (Leadwood Section [Stop 17]), but locally changes to homoclinal carbonate ramp (French, 1981). In the Central Missouri Basin the Sullivan Siltstone is an important marker between shaly Bonneterre limestones and shaly limestones of the overlying undifferentiated Whetstone Creek-Davis sequence.

Ultra-mafic lappili tuffs up to 146 ft thick are interbedded with Bonneterre carbonates at three sites (Snyder and Gerdemann, 1965; Wagner and Kisvarsanyi, 1969; Kisvarsanyi and Howe, 1983).

Franconian Stage

Davis Formation. - This unit is an intrashelf basin facies; i.e., a series of shales interbedded with shaley limestones, clean limestones, local dolomites, and in the basal to lower parts of some sections, thin glauconitic fine-grained quartzose sandstones. The distribution of the Davis is shown on Fig. 3, where it marks the maximum extent of intrashelf basin areas during the upper Cambrian.

Derby-Doerun Dolomite. - Within and at the margins of intrashelf basin areas a series of brown to gray, thinly- to thickly-bedded dolomites overlie the shales and shaly limestones of the Davis Formation. This slightly to very vuggy dolomite contains only minor megaquartz and chalcedony cement.

Trempealeauan Stage

Potosi Dolomite. - The Potosi consists of a series of thick to massively bedded, brown to gray dolomites that overlies the

Derby-Doerun, and has locally large amounts of megaquartz and chalcedony cement in vugs and solution enlarged fractures.

Eminence Dolomite. – This unit consists of mostly light-colored crystalline carbonate dolomites, and has "early" replacement chert, with ooids, pellets, and intraclasts; a "late" open-space microcrystalline chert; and less megaquartz and chalcedony than the underlying Potosi Dolomite.

Dolomites of the St. Francois Regional Shelf

The Cambrian sequence in the St. Francois Regional Shelf (2,000-2,500 ft; Fig. 3) has at least six large-scale (60-200 ft thick) platform T-R sequences (Fig. 5) with bases of dark-colored dolomites, that grade upward to coarsely crystalline light-colored "whiterock" dolomites (see depositional facies discussion). This region is the northwest shoulder of the Reelfoot Rift (Saco Section [Stop 8], this volume). There are two similar sequences in the Franconian and Trempealeauan of the Lebanon Arch. Stratigraphic units that were established at the margin of the Central Missouri Basin are not recognizable in these platform core areas (see Fig. 5, drillcores HE 4A to MPE 2-2).

Reelfoot Graben Margin and Basin

The +4,700 ft thick Cambrian section in the region of the Reelfoot Graben (Fig. 1, Spence, Strake, and Killam drill holes) has an upper Lamotte-basal Bonneterre sequence that is variably shaly containing quartzose sandstone with 20-30 ft of pelletal glauconitic dolomites. This basal sequence appears to be identical throughout the southern Ozarks. The basal dolomite even has a nonplanar crystal fabric like that described in the Bonneterre of central Missouri (Gregg, 1985).

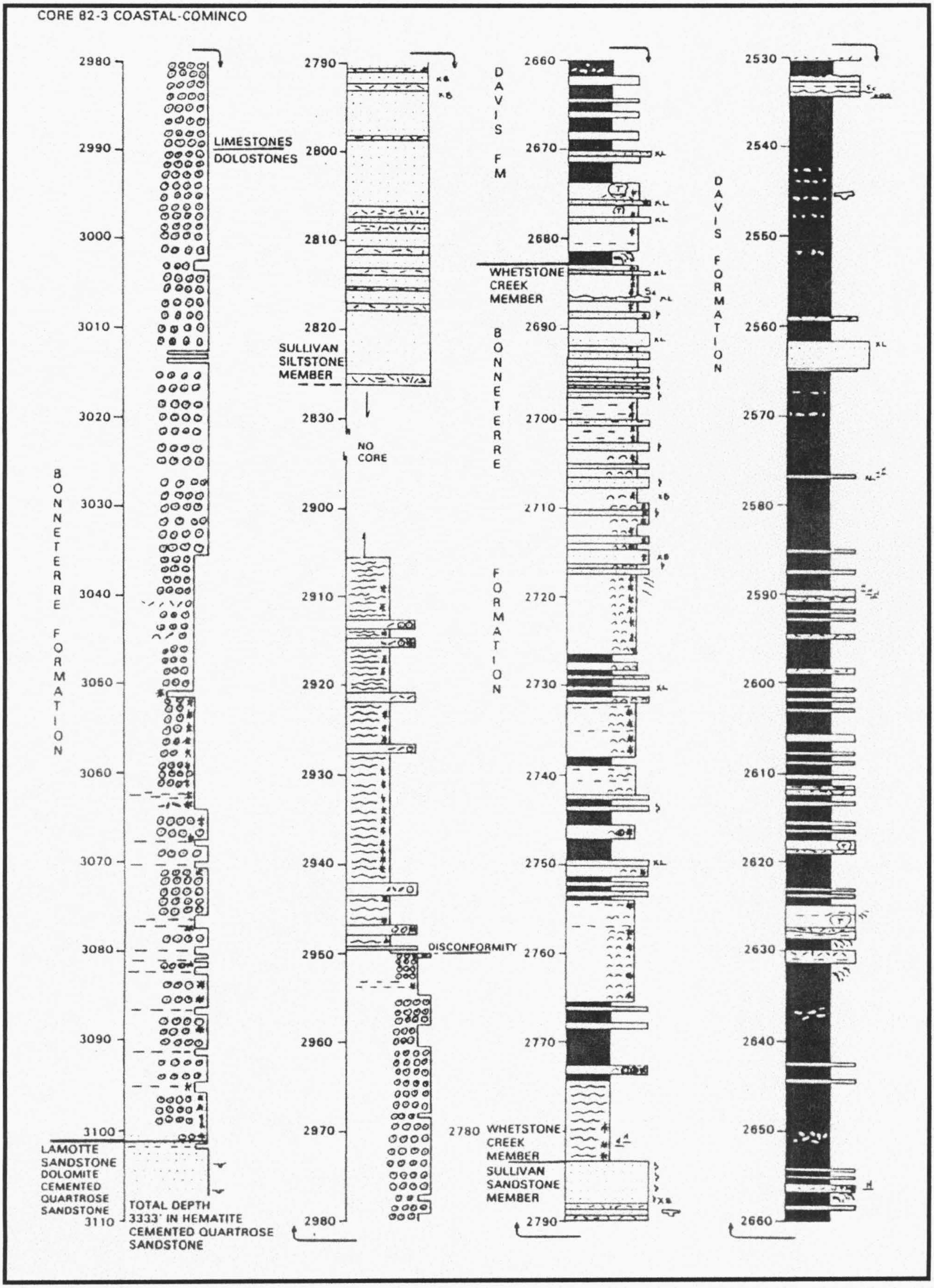
The distance along depositional strike between the Strake and Spence drillholes is less than 10 miles, yet these wells have dramatically different Bonneterre-Davis sequences. The graben basin sequence in the Strake well has 1600 ft of black shale that grades upward to shaley limestones and dolomites (Fig. 1). The Amoco Spence drill hole has 11 T-R sequences (120-600 ft thick) of dark shaly or non-shaly limestones that grade upward to clean limestones and dolomites (Fig. 1), that must have been in a periodically subsiding border fault block of the graben margin. The Bonneterre-Davis correlations between graben basin and graben margin is based on the idea of Dresbachian shelf drowning and intrashelf basin expansion in the southern Ozarks. The top of the +4,700 ft thick Upper Cambrian in the Spence drillhole is at the base of a quartzose sandstone in a sequence of light-colored dolomites.

Cambro-Ordovician Boundary. – Lower Ordovician rocks of the Canadian Series probably rest unconformably on the Eminence Dolomite. This contact must be inferred in sections where the sequence is continuous crystalline carbonate dolomites in both the Eminence and overlying Gasconade Dolomites. In areas where the Gunter Sandstone Member intervenes at the base of the Gasconade the contact is readily distinguishable. The actual Cambro-Ordovician boundary is within the upper Eminence (Kurtz, 1981).

DEPOSITIONAL FACIES

Lamotte Sandstone facies

The basal to lower part of the Lamotte Sandstone in the St. Francois Mountains and the northern part of the Lebanon Arch, are alluvial fan-dominated, debris- and mud-flows, fining-upward conglomerate based sandstone channel deposits, and sheet-flood deposits (Oak Grove Sections [Stop 11], Simms Mountain Fault Lamotte Section [Stop 12]) (Houseknecht and Ethridge, 1978; Yesberger, 1982; and Palmer in prep.). Fan-dominated deposits grade upward and away from "mountainous" ar-


CORE 82-3 COASTAL-COMINCO
2980
2990
3000
3010
3020
3030
3040
3050
3060
3070
3080
3090
3100
3110
LIMESTONES
DOLOSTONES
BONNETERRE FORMATION
LAMOTTE SANDSTONE DOLOMITE CEMENTED QUARTROSE SANDSTONE
TOTAL DEPTH 3333' IN HEMATITE CEMENTED QUARTROSE SANDSTONE
2790
2800
2810
2820
2830
2900
2910
2920
2930
2940
2950
2960
2970
2980
SULLIVAN SILTSTONE MEMBER
NO CORE
DISCONFORMITY
DAVIS FM
BONNETERRE FORMATION
2660
2670
2680
2690
2700
2710
2720
2730
2740
2750
2760
2770
2780
2790
WHETSTONE CREEK MEMBER
WHETSTONE CREEK MEMBER
SULLIVAN SANDSTONE MEMBER
2530
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DAVIS FORMATION

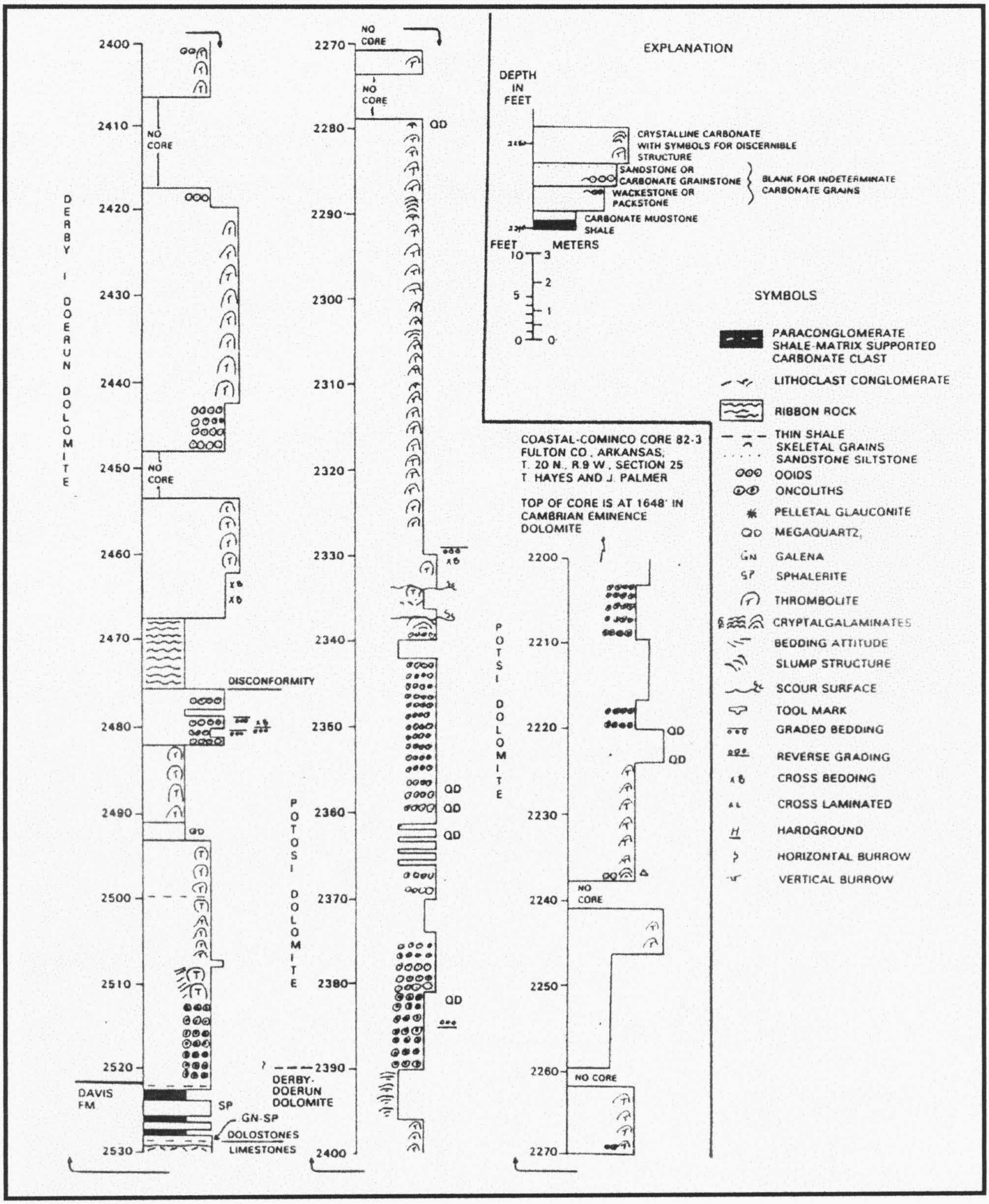


Figure 4. Detailed description of drillcore 82-3 in northern Arkansas, on file at the Arkansas Geologic Commission in Little Rock, Arkansas. The width of the column reflects textural classes, narrowist for shale and carbonate mudstone, widest for crystalline carbonate dolomites. Compare this sequence to the Frankclay Davis-Derby-Doerun section and the Elvins Derby-Doerun section [Stop 12, 16, and 18] in this volume.

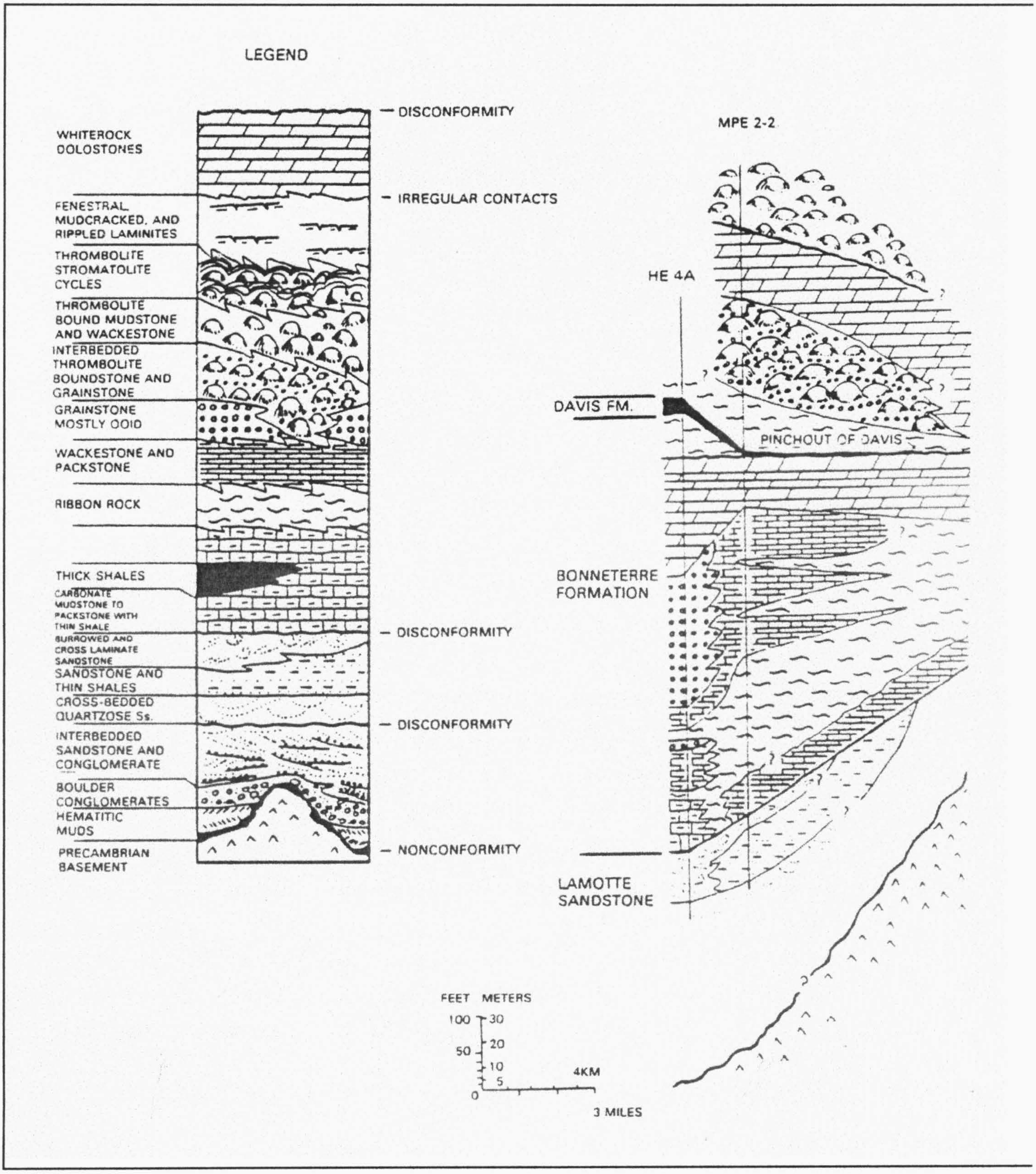
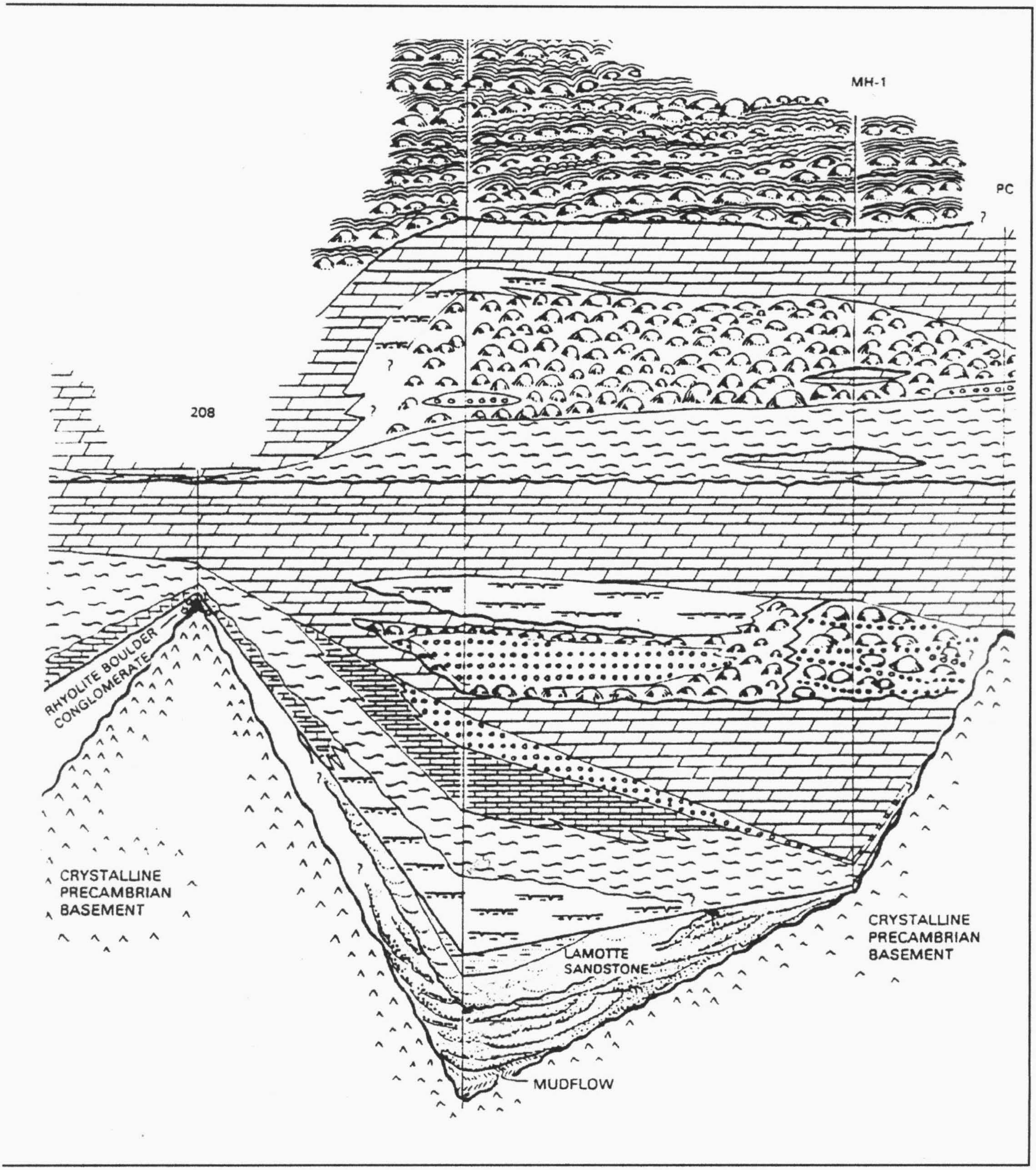


Figure 5. This is a detailed portion of cross-section B-B' (see index map Fig. 1). The Datum is a disconformity believed to mark the late Dresbachian-Franconian transgression. Part of the thickness changes are due to the line of section snaking through the eastern St. Francois Mountain highlands. The legend shows a generalized shallowing upward sequence typical of the Upper Cambrian in the region.


MH-1
PC
208
RHYOLITE BOULDER CONGLOMERATE
CRYSTALLINE PRECAMBRIAN BASEMENT
CRYSTALLINE PRECAMBRIAN BASEMENT
LAMOTTE SANDSTONE
MUDFLOW

eas to aggradational braided fluvial plain facies of fining-upward sequences of trough and planar cross bedded quartzose-dominated sandstones (Houseknecht and Ethridge, 1978; Yesberger, 1982) (see Fig. 5) (Saint Francois River Lamotte Section [Stop 11]). The basal Lamotte in the Central missouri and Greenfield basins is mostly quartzose braided fluvial plain deposits (Palmer in prep.).

Fluvial plain deposits in western Missouri are conformably overlain by widespread (0-100 ft) parallel laminated fine-grained quartzose sandstones. These appear to be interdune aeolian sandstones that have local adhesion ripples, and in one core, ghosts of poikilotopic gypsum crystals that are now pyritic clay (Palmer in prep.). These are similar to interdune sandstones interbedded with fluvial sequences in Lamotte of the St. Francois Mountains described by Yesberger (1982). Parallel laminated fine-grained quartzose sandstones are truncated in an apparent angular unconformity in part of the Lebanon arch, and transgressive marine sandstones overlie fluvial plain sandstones.

In the St. Francois Mountains alluvial and fluvial sandstones are locally overlain by burrowed and cross bedded marine sandstones that are interbedded with local fan delta deposits derived from nearby high-standing mountains (Houseknecht and Ethridge, 1978; Yesberger, 1982). Interbedded Lamotte-Bonneterre sandstones and marine carbonates 1-3 ft thick in sequences up to 200 ft (Hayes and Knight, 1961), are in these areas because fan deltas were still active (Yesberger, 1982). Lamotte-Bonneterre contacts of this nature indicate that a Lamotte pinch out is nearby, particularly if fan conglomerates are in the sequence.

The transgressive nature of the Lamotte (Kurtz et al., 1975) results in complex facies relationships with the Bonneterre where ramp and platform carbonates in the Lebanon Arch grade westward into intrashelf basin shales and glauconitic sandstones in the upper Lamotte of the Greenfield basin (Fig. 3). The Greenfield Basin was filled with a prograding sequence of quartzose burrowed and cross bedded sandstones that breached the Lebanon Arch coincident with regional shelf aggradation and drowning at the end of the Dresbachian, and supplied clastics for the Sullivan Siltstone and Whetstone Creek Members.

Carbonate Shelf Facies

Studies of upper Cambrian facies and facies relationships have dominantly been of the MVT host rock dolomites of the Bonneterre Formation (Ohle and Brown, 1954a and 1954b; Snyder and Gerdemann, 1968; Gerdemann and Myers, 1972; Larsen, 1977; Lyle, 1977; and French, 1981). Gerdemann Myers (1972) and Larsen (1977) are the most-cited papers. Their equivalent depositional facies terms are shown below.

Gerdemann & Myers	Larsen
Offshore facies	Basin
Forereef	Slope
Reef	Platform margin
Back reef	Platform

The Upper Cambrian sequence can be further subdivided using the carbonate platform models of Read (1985). The resulting Upper Cambrian carbonate shelf facies are described below.

The order of the facies descriptions lead the reader through a large-scale T-R sequence, beginning with the transgressive drowned shelf, upward to intrashelf basin, to carbonate ramps and shoal complexes, and finally platform facies.

Transgressive Drowned Shelf Facies. - Drowned shelf facies are in the basal Bonneterre (in part the 19 zone of St. Joe Minerals terminology, Ohle and Brown, 1954a), and the Whetstone Creek Member of the upper Bonneterre. These facies are thin to absent in platform areas of the St. Francois regional shelf, but may be up to 100 ft thick at intrashelf basin margins where they are interbedded with pelletal glauconitic-skeletal grainstone and glauconitic quartzose sandstones. In the Intrashelf basin areas, there are five interbedded lithologies thinly interbedded glauconitic sandstones, shales and skeletal limestones (Fig. 4, footages 2784-2683). Glauconite, micrite-cemented hardgrounds, and horizontally oriented burrows are indicative of slow depositional rates (Wilson, 1975) and characteristic of incipiently drowned- and drowned-shelves (Read, 1985). Examples of glauconitic quartzose sandstones are at the Leadwood Bonneterre-Davis Section [Stop 16 and 17], and the City of Bonneterre Davis section (U.s. 67 and route K).

Intrashelf Basin Facies

Shale Facies. - Intrashelf basin shale facies occur in the lower to upper parts of the Bonneterre Formation in the Central Missouri basin, the Davis formation, and in the upper part of the Lamotte of the Greenfield basin. The shales are green to dark gray and locally black, and are interbedded with limestones and minor dolomites, and local quartzose glauconitic siltstone-sandstone beds. Shale facies are thickest (250 ft of Davis Formation in the Central Missouri basin) at intrashelf basin-deep-ramp margins. They thin toward basin centers where limestone and/or siltstone beds are thin to absent, and have abrupt off-ramp thickening to more feather-edge thinning along intrashelf basin margins. The latter suggests that intrashelf basin margins may have been controlled by series of half grabens. Carbonate interbeds in shales have (see Fig. 4, Davis section): 1) radial ooid and pelletal packstone; 2) skeletal wackestone and packstone; 3) resedimented debris- and fluidized-flow lithoclast conglomerate beds; 4) rare, but locally abundant, paraconglomerate debris flows; 5) encrustations and mounds of Renalcis-Epiphyton thrombolite boundstone with geopetal-sediment floored growth cavities; and, 6) dark-colored nodular lime mudstone and fine grainstone (Palmer in prep.).

The conglomerates are evidence of ramp-style transitions to platform areas rather than rim-style transitions because they contain re-sedimented ramp clasts, rather than platform clasts. At the edges of intrashelf basin areas carbonate beds increase volumetrically and commonly include ribbon rock (described below). Carbonate interbeds have micrite-cemented hardgrounds, truncated surfaces, and local glauconite coated and hematite coated surfaces. Intrashelf basin centers have only shales with thin nodular dark-colored mudstone or wackestone. This facies is identical to intrashelf basin shales of the southern Appalachian Cambrian Nolichucky Formation, described by Markello and Read (1981 and 1982).

Dark "Parted" limestone. - The Greenfield intrashelf basin (Fig. 1), and other southern intrashelf basin settings, contain dark gray, green or brown lime mudstone to wackestone with very thin argillaceous beds or lamina. These are up to 300 ft thick, and occasionally contain thin ooid-intraclast packstones, lithoclast conglomerate, and thin glauconite encrusted scoured hardground surfaces. These limestones are similar to the parted limestones of the Cambrian Cow Head Group in western Newfoundland, which are a lithofacies in a by-passed carbonate shelf margin (James and Stevens, 1986). In Missouri these are thought to be shale-starved intrashelf basin areas because they grade upward to ribbon rocks, identical to those that have facies relationships with intrashelf basin shales elsewhere.

Carbonate Ramp Facies

Homoclinal Ramp. - These sequences in southern Missouri commonly contain ribbon rocks that grade upward to more thickly interbedded mudstone-wackestone and packstone-grainstone (Elvins Derby-Doerun Dolomite section this volume [Stop 12]), these units appear to be identical to southern Appalachian Cambrian Nolichucky Formation transitions between intrashelf basin and shoal facies (Markello and Read, 1981). Ribbon rocks are thinly and irregularly wavily bedded, fining-upward storm-generated sequences (1.5-10 cm thick) of fine-grainstone, wackestone-mudstone and locally thin calcareous or dolomitic brown to green shale, and local resedimented ramp lithoclast conglomerate beds. Thin grainstones locally have scoured or truncated bases and consists of ooids, ooid-grapestone clasts (locally abundant in the Bonneterre), pelletal mud, and skeletal grains.

Shallow homoclinal ramp carbonates lack shale (Fig. 4, 3035-3060 ft), and consist of coarsening- and thickening-upward sequences of mudstone-wackestone interbedded with ooid-skeletal packstone-grainstone beds that thicken upward to >6 ft thick grainstones of the shoal complex. These also have scour surfaces, truncated surfaces, and hardgrounds. Homoclinal ramps sequences are widespread in the Bonneterre (Fig. 4, 2905-2950 ft; and Fig. 5). It appears that homoclinal ribbon rock ramp sequences are largely transgressive in Missouri.

Distally Steepened Ramps. – These differ from rimmed shelves by having depositional slope breaks many miles from the shoal complex rather than at the shoal complex margin (Read, 1985). Intrashelf basin deep ramp margins, such as the Frankclay Davis-Derby-Doerun section [Stop 16 and 17] (this volume) with abundant lithoclast conglomerates, are probably distally steepened. Other distally steepened ramps have slumps 6 ft thick with contorted and sheared bases, and contorted to rotated middle and upper portions within ribbon rock sequences (Palmer, in prep.). This type of ramp margin appears to be related to prograding ramp periods, though the actual "steepened" location may be controlled by down-to-the intrashelf basin faults.

Isolated Ramp Buildups. – Ramp buildups of stacked thrombolite to stromatolite mounds in sequences up to 60 ft thick and are commonly associated with ribbon rocks near the intrashelf basin-deep ramp margin (see Frankclay Davis – Derby-Doerun section [Stop 16 and 19]). Thrombolites, subtidal cryptalgal boundstones (Aitken, 1967), have massive clotted (cryptomicrobial fabric in the sense of Kennard and James, 1986), to clotted columnal cryptalgal structures. Illustrations of thick biohermal boundstone sequences in the Bonneterre Formation of the Old Lead Belt (Ohle and Brown, 1954a; Wagner, 1960; Snyder and Gerdemann, 1968), appear to interbedded with ribbon rocks and mudstones, that are overlain with prograding shallow ramp rocks. Isolated thrombolite-stromatolite buildups locally coalesce and form fringing banks with shoal complex progradation. The Irondale section ([Stop 19] this volume) is an example.

Shoal Complexes

Barrier Ooid-Skeletal Grainstone Complexes. – Barrier complexes contain lagoonal facies between barrier grainstones and tidal flat facies (Read, 1985). Drillcore sequences, from southeast Missouri, with thick ooid-skeletal or indeterminant graindstones, overlain by thrombolite bound mudstones and wackestones may be behind barriers in shallow platform settings. An example is shown in Fig. 5 in the middle part of the Bonneterre Formation (drillcore MBO 3-3). There are no known exposed barrier- lagoonal-complexes, however the Elvins Derby-Doerun section [Stop 12] contains large-scale trough cross bedded grainstones, that is part of a barrier sequence.

Fringing Bank Complexes. – Fringing banks may be the dominant type of shoal complex in prograding ramps of Ozark upper Cambrian. Fringing banks commonly contain shoal to tidal flat sequences without intervening lagoonal facies (Read, 1985). An example is shown in Figure 6, where a thrombolite buildup beings in ramp ribbon rocks and passes upward to stromatolites and tidal flat laminites. Facies cross-sections from the Bonneterre Formation (Lyle, 1977; Larsen, 1977) also show "stromatolite reef" interbedded with "offshore facies", and pass platformward into "backreef facies" without intervening mudstones or wackestones of a possible lagoon, and probably are a fringing bank. Supporting observations were made by French (1981), who recognized laterally continuous thrombolites boundstones basinward in the Bonneterre that become stromatolites with birds-eyes towards the platform interior.

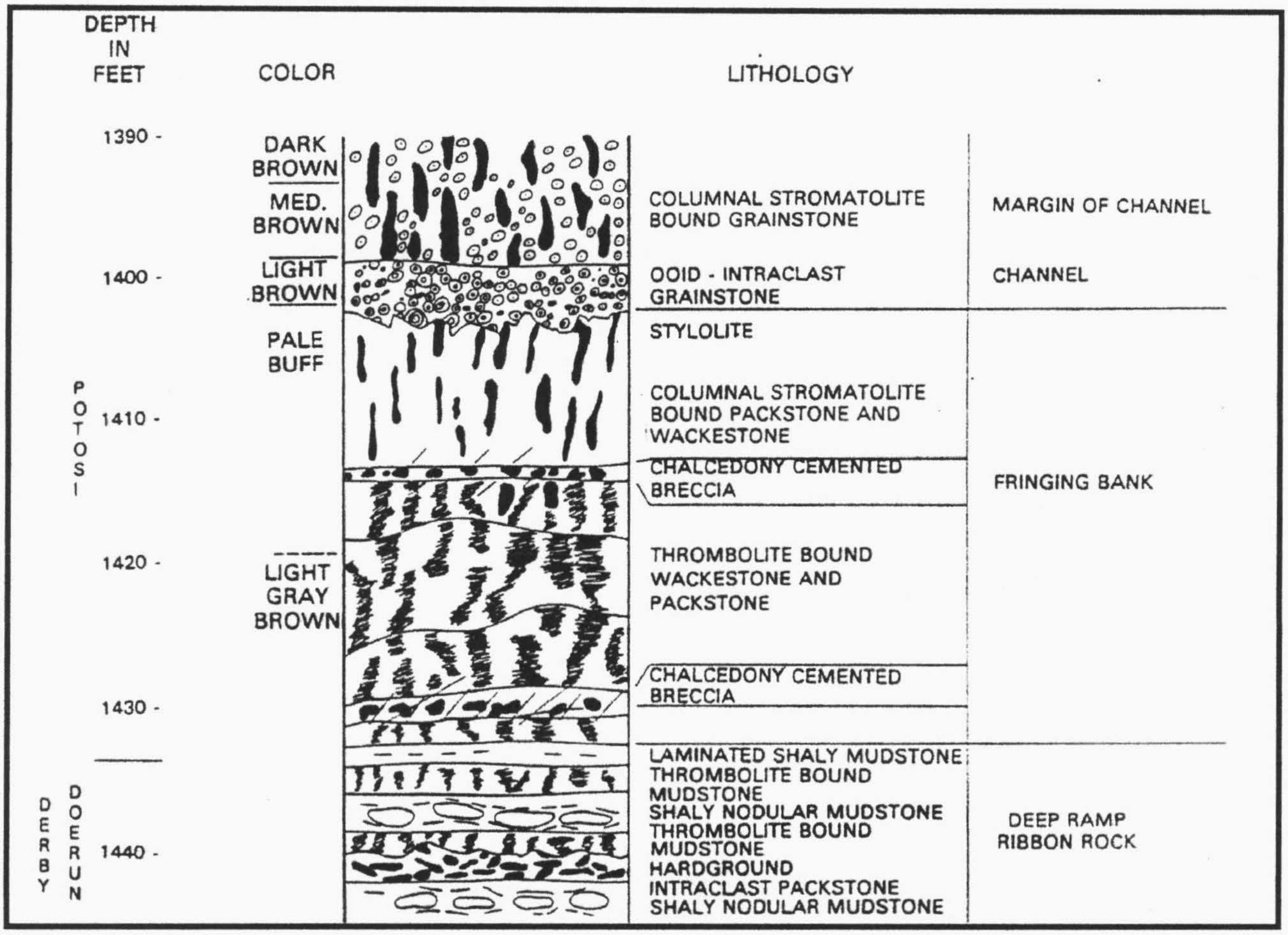


Figure 6. Lower part of a fringing bank sequence from the Greenfield intrashelf basin, drillcore H-13 (see index map Fig. 1). Tidal flat laminites overlie this sequence of thrombolites and columnal stromatolite 220 ft. above the ribbon rock dolomites shown here. Compare this section to the Irondale Bonneterre section ([Stop 19] this volume).

Other fringing bank sequences in southern Missouri, have ooid or indeterminant grainstones that grade to cyclically bedded thrombolite, stromatolite, and laminite (Fig. 7). The Leadwood Bonneterre-Davis section (this volume [Stop 17]) has small-scale trough and herring-bone cross bedded grainstone with small (4 ft) crypt-algal boundstone mounds. Though the mounds are not continuous, this may be the nearest analog in outcrop of this bank type.

Platform Interior Facies

Cyclic Bedded Thrombolite-Stromatolite-Laminite. – Peritidal cyclic sequences 3-30 ft thick, have intraclast or ooid packstone-grainstone, branching to columnar thrombolite and stromatolite boundstones that grade upward to light-colored fenestral and mudcracked laminites. Figure 7 shows a section that may be marginal to a channel in a fringing bank, or within a migrating channel sequence. One or more of these lithologies may be missing from some sequences, and have thick continuous sections of one lithology from a cycle (see Fig. 5).

Laminites are light-colored, micrograded- and ripple-laminated pelloidal finegrainstone or mudstone, with horizontal and tubular fenestrae, mudcracks, and local breccias (see Lesterville section [Stop 3] this volume). These are analogous to supratidal flat levee carbonates described from ancient and modern examples by Roehl (1967) and Shinn (1983).

These peritidal cycles are similar to cyclic peritidal facies of the southern Appala-

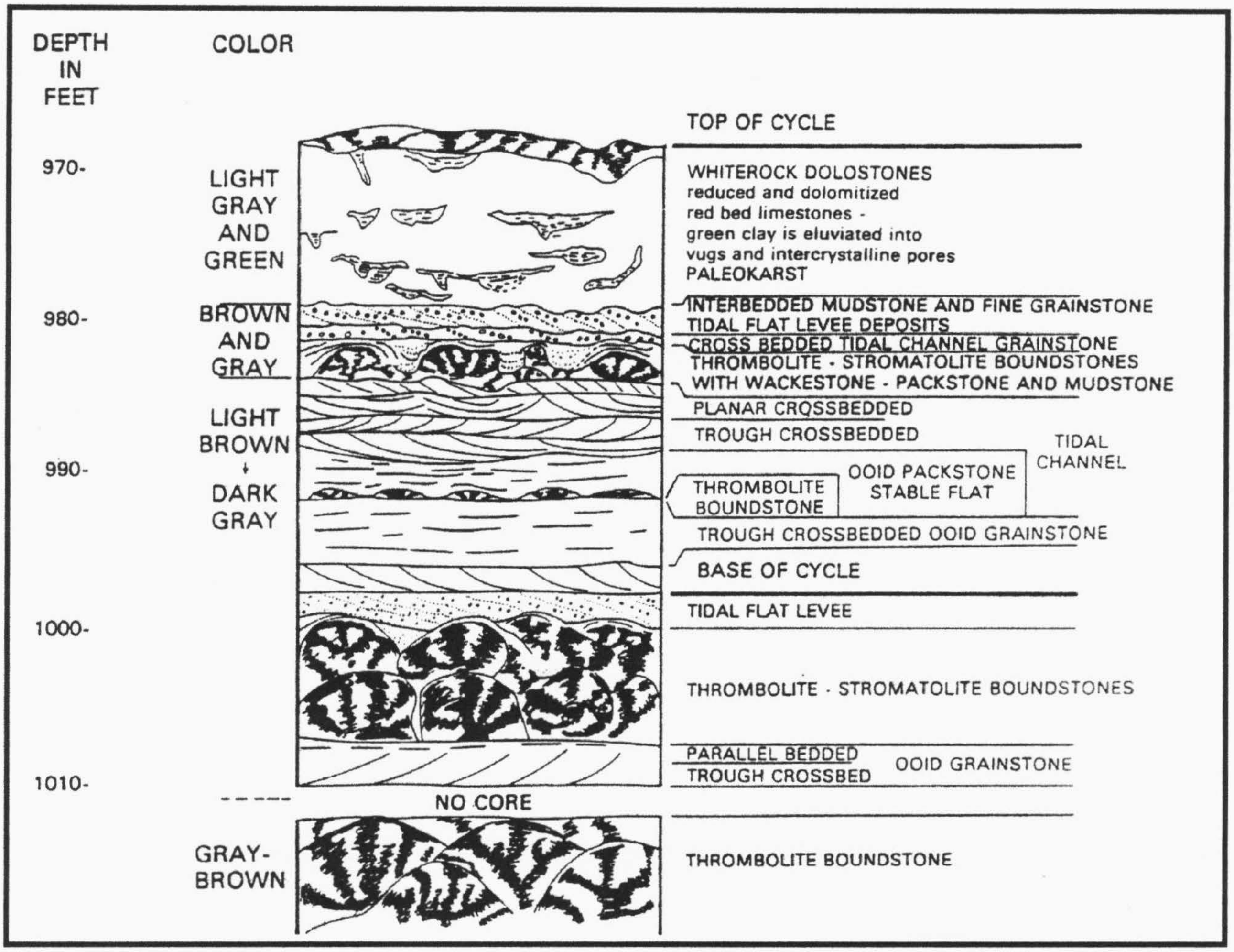


Figure 7. Small-scale platform T-R sequence from drillcore 64W22 (see index map Fig. 1). This drillcore is from the west flank of the Lebanon Arch.

chian Cambrian Elbrook-Honaker and Cooper Ridge-Conococheague Formations, which formed in response to repeated platform submergence and progradation of tidal flats (Markello and Read, 1981 and 1982). In Missouri these sequences have local transitions to tidal channels and the first cycle begins a fringing bank. In the Lebanon arch these sequences are up to 220 ft thick.

"Taum Sauk" Limestones and "White Rock Dolomites." – Rocks and fabrics interpreted as paleokarsted limestones, and Fe-reduced dolomitized paleokarst in southern Missouri are the reddened limestones of the so-called "Taum Sauk Limestone" in the southeast flank of the St. Francois Mountains, and certain finely- to coarsely-crystalline "whiterock" dolomites. Both of these are found at the interior-most parts of platforms at the top of shallowing-upward cycles, and thin in off-platform directions. "Taum Sauk" limestones have a variety of primary depositional textures including, burrowed pelletal mud-skeletal wackestones, small stromatolites (Howe, 1969; Frank, 1979), pelletal mud packstone, and cut and fill scours with laminites that have both horizontal and tubular fenestrae.

Features indicative of an early meteroric and karsting history include terra rossa red clays and speleothemic cements (Lown and Farr, 1986). Stalactitic milky white, and reddish massive acicular calcite is present and locally abundant in vugs and mesopores of some sections. Red clay in vugs, grikes (sediment filled joints), and open burrow networks reddens the margins of white to very light-gray pristine limestone. In the southeastern portion St. Francois shelf some ribbon rock has its upper portions reddened in the same manner (Fig. 5, note "whiterock" over ribbon rocks). Along MVT stage fractures, and at the tops and bases of the "Taum Sauk", red clays are reduced to pale olive green, and limestones have transitions across few centimeters to "whiterock" dolomites. This was the direct physical evidence that reddened limestones were the precursor to "whiterock" dolomites (Howe, 1969). "Whiterock" dolomites have gradational and interbedded contacts with dark-colored fabric-preserved marine carbonate dolomites. However, many of these crystalline carbonates have fabrics and textures that are not found in the marine carbonates they are interbedded with, such as: 1) irregularly laminated tufa- or caliche-like fabrics; 2) matrix- and clast-supported collapse breccias with bleached clast margins, in fine-grained light-colored dolomite matrix; 3) negative breccia or box-work; 4) green pyritic clay as clasts and as eluviated geopetal sediment in vugs and large voids. Reddened hematitic patches remain in many "whiterock" sequences, and grade outward to pale olive-green clay-rich coarsely crystalline dolomite.

There are of course gradational contacts between many fabric-preserved brown dolomites and "whiterock" dolomites with ghosts of original primary marine fabric, that are of undisputed epigenetic or burial diagenesis origin (Howe, 1969; Lyle, 1977). Much of the upper Eminence Dolomite and many other crystalline carbonate dolomites probably did not have an early paleokarst history. However many of the fabrics preserved within "whiterock" dolomites are characteristic of meteorically karsted carbonates (Palmer in prep.).

Because "whiterock" dolomites are at the top of large-scale shallowing-upward platform cycles and are disconformably overlain by dolomites with well preserved marine depositional fabrics, each cycle top was karsted prior to transgression. There are only two T-R sequences of brown dolomite to "whiterock" dolomite in the Lebanon arch compared to five in parts of the St. Francois regional shelf (Fig. 5). There are two brown-whiterock sequences in the Marr welll, at least three in the Oliver well, and nine in Amoco Spence. These often have significant asymmetric changes in thickness in platform aras (Fig. 5, MH-1 to MBO 3-3 and MPE 2-2 to HE 4-A), suggesting uneven rates of regression. The paleokarsted sequences are up to 200 ft thick suggesting substantial uplift to establish meteoric recharge, but I cannot yet point to deep ramp-basin margin T-R sequences that reflect every period of platform karsting. I believe that these asymmetrical paleokarsted cycles were generated by back tilting rift border fault blocks, and are angular, unconformity bounded.

DEPOSITIONAL HISTORY

Depositional facies in the Missouri Cambrian shelf are very similar to the Middle to Upper Cambrian in the Southern Appalachians as described by Markello and Read (1981, 1982). These two areas have somewhat similar transgressive-regressive histories (Fig. 8); a major dissimilarity is the timing of final intrashelf basin shoaling. In Missouri the largest intrashelf basins developed during the Franconian, with Davis Formation intrashelf shales stretching across a quarter of Missouri (Fig. 1). In contrast, the Nolichucky intrashelf basin was shoaled earlier at the Dresbachian-Franconian boundary (Markello and Read, 1982). Figure 9 shows a series of cross-sections that portray part of the shelf history in southern Missouri.

Late-Middle Cambrian (?). – Uplift of the St. Francois Mountains area and formation of the Reelfoot Graben are probably synchronous. Alluvial fan conglomerates and sandstones are the first sediments to be deposited within the rift and adjacent to rift mountains. Fluvial plain aggradation was a response to this regional uplift.

Initial Transgression and Early Dresbachian. – The age of the initial transgression in the Lamotte Sandstone is not known. The oldest identifiable fauna, that of the Cedaria Zone, has been recognized in the lower Bonneterre in southeastern Missouri (Lochman, 1940), and only tentatively

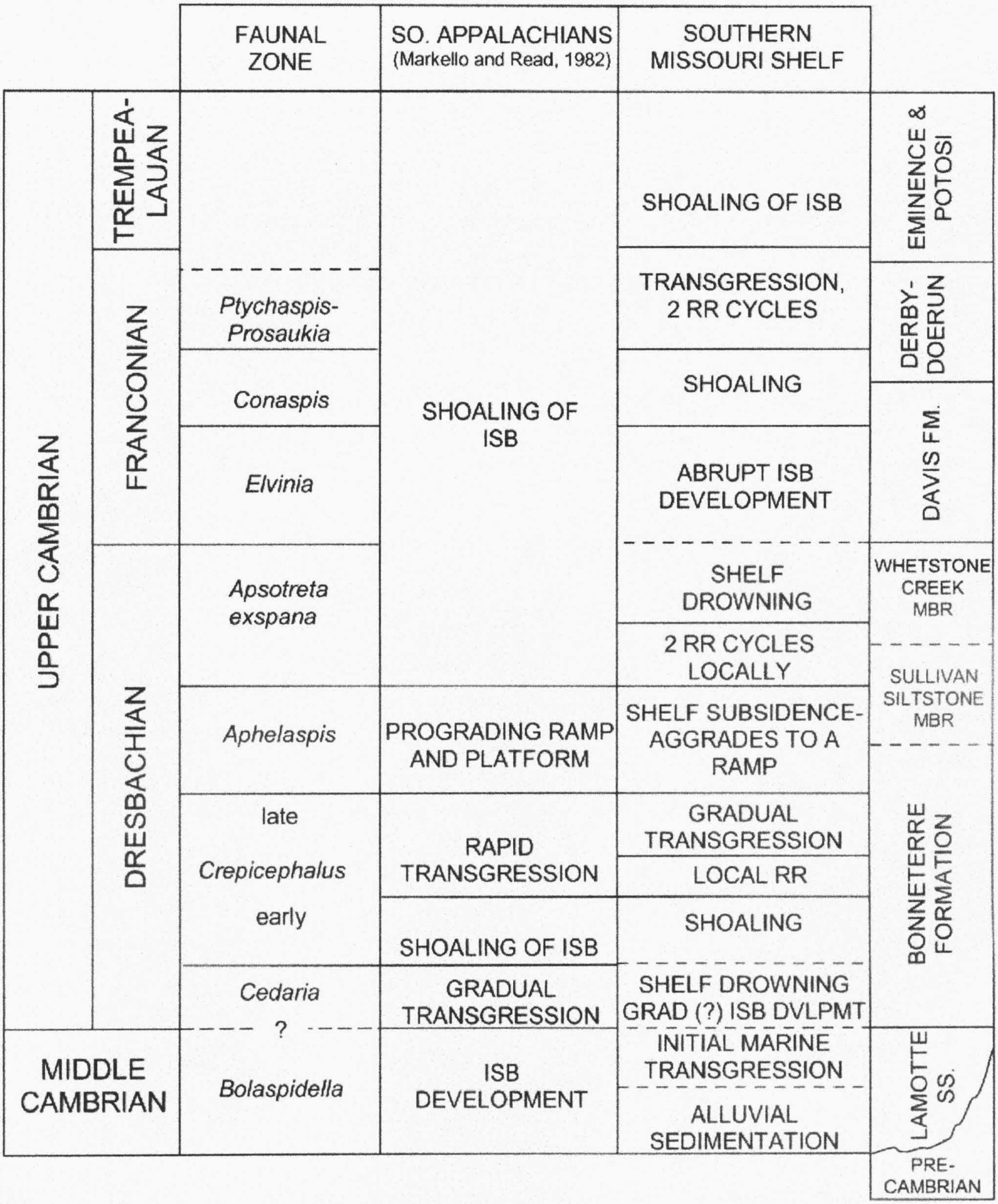


Fig. 8. Comparison of Transgressive-Regressive history and intrashelf basin development, southern Appalachians (Markello and Read, 1982) to the margin of the Central Missouri intrashelf basin in southeastern Missouri. Correlation of the initial marine transgression in the Middle Cambrian is tentative. This initial marine transgression may in fact be equivalent to the Cedaria *zone gradual transgression in the southern Appalachians. No Middle Cambrian fauna have been identified in Missouri.* Cedaria *Zone fauna have been recognized in the basal Bonneterre (Lochman, 1940), which is only tentative in western Missouri (Kurtz, et al, 1975). Faunal zone comparisons are from Kurtz et al (1975). This does not address the Reelfoot Graben margin. Dashed lines are uncertain boundaries. Abbreviations: ISB, intrashelf basin; ISB DVLPMT, intrashelf basin development; RR, transgression with ribbon rock facies.*

in south-central Missouri (Kurtz et al., 1975). Therefore, the initial transgression in the Lamotte may have occurred in the Cedaria Zone, or was pre-Cedaria.

The initial marine transgression of the upper Cambrian followed possible local fault block activation, forming angular conformities in some areas. Areas with alluvial fans were submerged, and formed marginal marine embayments and fan deltas (Houseknecht and Ethridge, 1978; Yesberger, 1982). Continued gradual transgression, or clastic source area inundation, occurring at about the Cedaria Zone, established broad shallow ramps that extended from the Reelfoot Graben to the Greenfield Basin upon which shallow carbonate sedimentation began. Further subsidence in early Dresbachian caused incipient drowning, or drowning of the shelf, and deposition of glauconitic- and clastic-rich carbonates.

Dresbachian Intrashelf Basin Development. – During late Cedaria (?) or early Crepicephalus Zone, intrashelf basins and carbonate platforms appeared simultaneously. The location of intrashelf basins may have been controlled by rift shoulder uplift, which also subaerially exposed ramp and platform carbonates. These earliest ramps were homoclinal, and contained thin ribbon rock sequences. Local or regional subsidence may have caused some isolated thrombolite bioherms to begin upbuilding on the deep and shallow ramp, which later evolved to fringing banks. Cyclic peritidal platform sedimentation probably began during this stage. Local and gradual transgression began in middle and late Crepicephalus Zone; distally steepened ramps appeared where some fringing banks were onlapped by ribbon rock. In the central and southern part of the Lebanon Arch, and in many areas marginal to the Central Missouri Basin, the Bonneterre ooid-skeletal bank was entirely onlapped by ribbon rocks (Fig. 4).

Late Dresbachian. – Deposition of the quartzose ribbon rocks of the Sullivan Siltstone and upper Bonneterre ribbon carbonates in much of western and southeastern Missouri occurred with southeastward shelf subsidence, which began during the late Crepicephalus Zone and continued through the Aphelaspis Zone, aggrading the shelf to a homoclinal ramp. Oddly, the first areas to subside were the western Central Missouri Basin and Lebanon Arch. The homoclinal ramp extends from the Lebanon Arch to the western St. Francois Mountains, and as far south as northern Arkansas. Gradual uplift of the shelf at the Reelfoot Graben margin, accompanied by sagging in the Central Missouri Basin, probably triggered shelf drowning and deposition of the Whetstone Creek Member.

Dresbachian-Franconian Boundary. – Intrashelf basin areas have gradual changes from drowned shelf Whetstone Creek to basinal shaly Davis. In some platform areas early Elvinia Zone Davis Formation appears abruptly without an underlying drowned shelf Whetstone Creek Member. Carbonate platforms and ramps that appeared in some areas for the first time may have been controlled by fault block uplift.

Franconian and Trempealeauan. – Several periods of ramp and carbonate platform progradation occurred during the Franconian. In the Lebanon Arch and the St. Francois Shelf northwest of the Reelfoot Graben, uplift and subsidence caused T-R paleokarsted platform cycles during the early Franconian. Isolated thrombolite buildups appeared in some deep ramp areas during a middle Franconian regression, were onlapped by a homoclinal ramp ribbon sequence in the parts of eastern Missouri, but evolved to fringing banks that prograded across the narrow Greenfield Basin in western Missouri. The Franconian probably ended with two transgressive widespread ribbon rock sequences.

Paleokarsted T-R platform cycles are present locally in the St. Francois Shelf and Lebanon Arch through the Trempealeauan, indicating continued uplift and subsidence. The shelf probably shoaled completely during the Trempealeauan. Rift shoulder uplift prior to deposition of the basal Ordovician, caused local karsting in the uppermost Eminence and the disconformable contact.

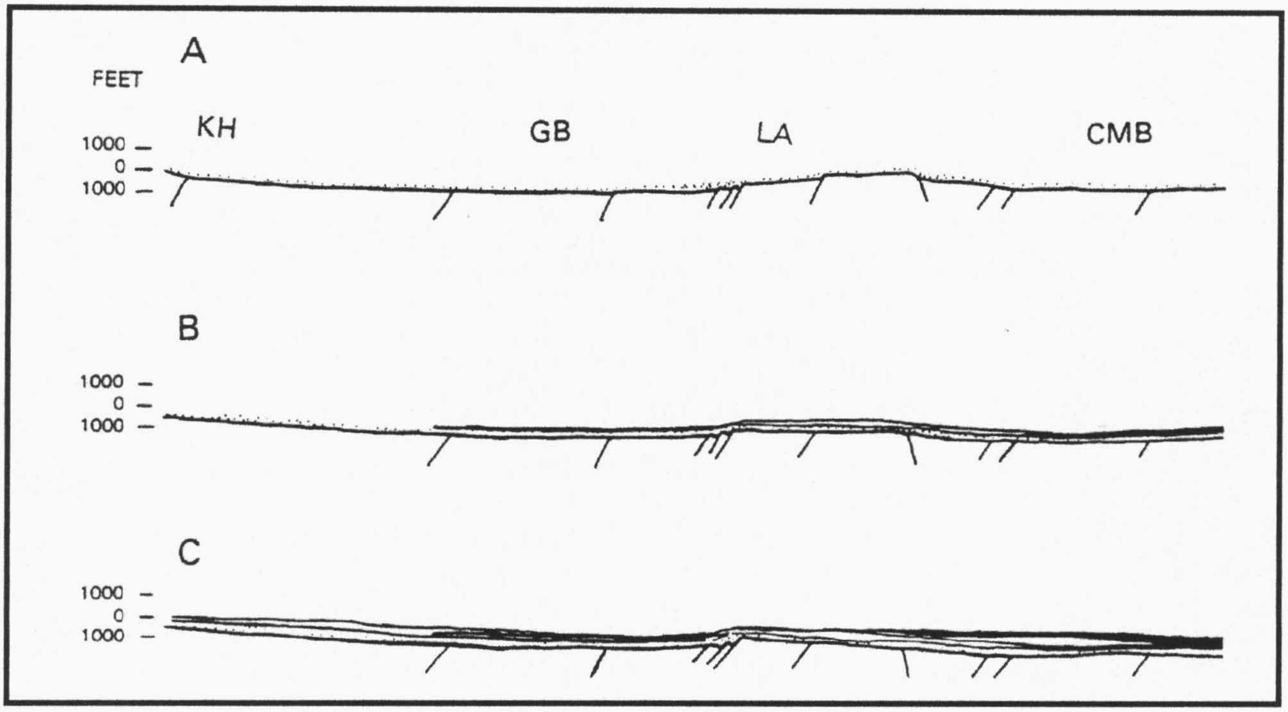


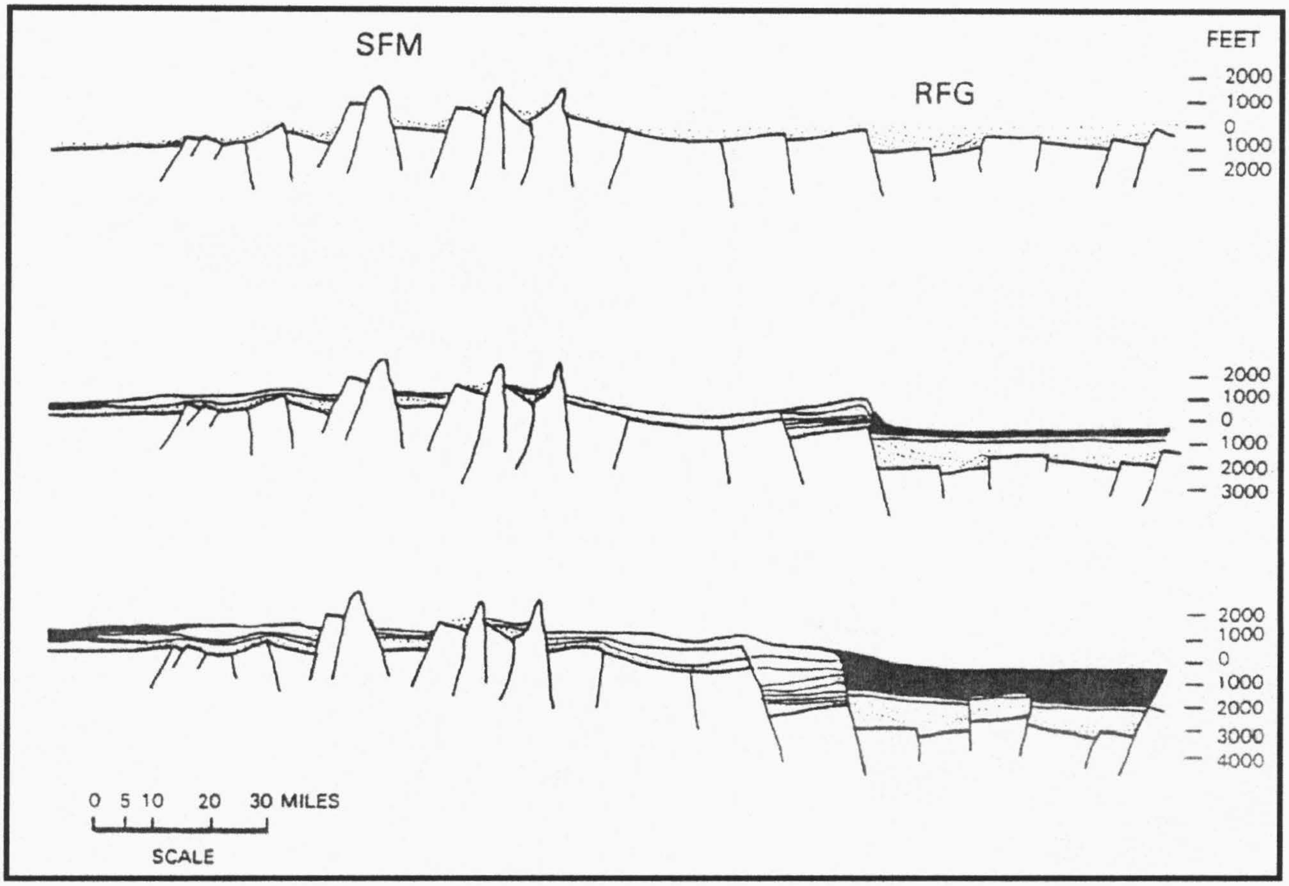
Figure 9. Development of the Upper Cambrian shelf. A.) Shelf and a series of inferred Precambrian fault blocks prior to the initial marine transgression. B) Shelf during the middle Dresbachian when a portion of the southeast shelf was subaerially exposed and karsted. C) A fault block adjacent to the full apparent graben of the Reelfoot Graben (RFG) that probably subsided 2000 ft. more than the comparable southern Ozark sequence by early Franconian. KH = Kansan highlands; GB = Greenfield Basin; LA = Lebanon Arch; CMB = Central Missouri Basin,; SFM = St. Francois Mountains; and RFG = Reelfoot Graben.

SUMMARY AND CONCLUSIONS

Upper Cambrian rocks in southern Missouri comprise a series of small- and large-scale depositional cycles that were controlled largely by a failed-rift tectonic framework that extended at least 150 miles from the failed Reelfoot Rift. Rift related thermal uplift and back tilting of faulted basement blocks, probably in a series of half grabens, created the St. Francois highlands which may be separated from the Reelfoot graben by a series of border faults. Uplift of these basement blocks may have exceeded 2500 feet. The alluvial fan sediments in the basal part of the Lamotte coincide with this early rift stage. Back basin formation resulted in the Central Missouri basin and the Greenfield basin which began as a broad plain where fluvial sediments were deposited between regional uplifts.

Three regional transgression in the upper Cambrian may be related to eustatic events, but other depositional cycles may be related to alternating activations in rift border faults. Intrashelf basin formation did not occur with the initial marine transgression. Instead intrashelf basin formation followed somewhat later regional shelf drowning episodes during the early Dresbachian and at the Dresbachian-Franconian boundary. The presence of intrashelf basins themselves are indicative of passive margin settings and rimmed regional carbonate shelf margins (Markello and Read, 1981 and 1982; read, 1985). Rimming of the regional shelf at the Reelfoot Graben may have been controlled by uplifting fault blocks in the border fault system. Multiple episodes of paleokarsting occurred within the regional shelf and in extensions of the regional shelf such as the Lebanon Arch. The unconformable relationships between these depositional cycles and their location within a shelf trend paralleling the Reelfoot graben suggests that the rift failed at an advanced stage.

The intrashelf basins themselves appear to have large half graben shapes, and because carbonate ramps change morphol-



ogy along the strike of intrashelf basin-deep ramp margins may actually be a series of half grabens. Carbonate ramps were primarily homoclinal ribbon rock sequences during periods of gradual regression, but locally were distally over-steepened during transgression or in areas across active faults. Prograding ramps may have ooid-skeletal barrier complexes in their early stages but evolve to thrombolite-stromatolite fringing banks as they approach the deep ramp and onlap isolated thrombolite buildups. In back of fringing banks broad tidal flats have peritidal cycles of thrombolite-stromatolite and supratidal laminite. The Davis intrashelf basin probably shoaled completely during the early Trempealauan.

Finally, paleokarsted carbonates, originally reddened limestones, have mostly been reduced during burial to whiterock dolomites (cf. Howe, 1969), prior to regional MVT mineralization stages. The original rock types that were karsted included more facies than just the lime wackestones of the "Taum Sauk." The cyclic nature of brown dolomite-whiterock paleokarst dolomites are related to border fault activation, because they reflect local uplift of a magnitude that is not reflected at the deep ramp margin, in scale or number. This indicates that the Reelfoot Rift greatly influenced regional-scale sedimentation and basement features.

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EARLIEST PALEOZOIC STRATIGRAPHY AND FACIES, REELFOOT BASIN AND ADJACENT CRATON

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ABSTRACT

Subsurface data from the northern Mississippi embayment reveal the presence of a rift basin (Reelfoot basin) that apparently contains strata older than any on the craton of the midcontinent. The "Reelfoot arkose," which rests nonconformably on Precambrian basement, is restricted to the Reelfoot basin and probably represents alluvial fan sedimentation during active formation of the rift basin. The overlying "St. Francis formation" is a carbonate and calcareous sandstone that is restricted to the rift basin. It was deposited during initial inundation of the rift basin by marine water. The Lamotte Sandstone extends from the craton, where it rests nonconformably on Precambrian basement, into the rift basin, where it grades into a marine shale that overlies the St. Francis formation. The lower Bonneterre Formation, a carbonate which overlies the Lamotte on the craton, also grades into a marine shale in the rift basin. These Cambrian strata reflect the influence of early Paleozoic rifting, combined with rising Cambrian sea level, on stratigraphy and facies distribution in the southern midcontinent.

In southeastern Missouri, the Lamotte Sandstone records the initiation of sediment accumulation on the craton and the inundation of the region by Cambrian seas. Peripheral to the ancestral St. Francois Mountains, the Lamotte is a blanket of distantly derived, quartzose sand that was deposited on a braided alluvial plain. The braided fluvial system aggraded from relatively proximal to relatively distal in nature as base level rose in response to rising Cambrian sea level. Near the end of Lamotte deposition, the alluvial plain evolved into a braid-delta as marine waters inundated the region. Within the ancestral St. Francois Mountains, the Lamotte is a locally derived arkose that was deposited on alluvial fans within valleys eroded into Precambrian basement. An upward gradation to shoreline and shallow marine facies records marine inundation of the ancient valleys.

Because the Lamotte was deposited by onlap onto an irregular erosional surface, and because Lamotte lithologies vary according to source rock composition, the nonmarine to marine facies transition at the top of the formation is the only reliable stratigraphic datum that can be used for correlation.

INTRODUCTION

Basal Paleozoic strata in the midcontinent region have historically been considered to be a blanket of Upper Cambrian sandstone that rests nonconformably on Precambrian basement. This sandstone is called the Lamotte in Missouri and Arkansas, the Mt. Simon in Illinois, Wisconsin, Minnesota and Iowa, and the Reagan in Oklahoma, Kansas and Nebraska. This regionally extensive sandstone is exposed only in the St. Francois Mountains of southeastern Missouri and in the upper Mississippi Valley of Wisconsin and Minnesota. However, lateral continuity of the sandstone has been demonstated by penetration by numerous boreholes throughout the midcontinent region. Integration of recent work indicates that it is part of a time-transgressive blanket of basal sandstone that covers much of the North American craton (e.g., Howe et al., 1972; Hereford, 1977; Houseknecht and Ethridge, 1978; Driese et al., 1981; Cudzil an Driese, 1987).

During the past several years, drilling in the northern Mississippi embayment has revealed the presence of sedimentary strata that appear to be older than the Lamotte Sandstone (see Grohskopf, 1955 for historical perspective). These strata are restricted to buried rift basins, the Reelfoot basin and Rough Creek graben (Schwalb, 1969), that apparently formed during the latest Precambrian or earliest Cambrian. In the Reelfoot basin, these rift strata include a basal arkose, an overlying carbonate formation, and a younger shale that is interpreted to be equivalent, at least in part, to the Lamotte Sandstone.

The general structure configuration of the region has been presented by Schwalb (1982 a, b) and a more detailed understanding will probably require the release of proprietary seismic data by the oil industry (e.g., Howe and Thompson, 1984). Of particular note is the presence of a broad uplift (Pascola arch; See Wilson, 1939) that results in an angular unconformity beneath Cretaceous strata of the northern Mississippi embayment. Strata as old as the Lamotte Sandstone subcrop beneath Cretaceous sediments in the vicinity of the Missouri bootheel. A subcrop map of the Pascola uplift has been presented by Schwalb (1982 a, b).

Even though information in the area is sparse and structural relationships are complex, generalized interpretations of stratigraphic relationships and depositional facies of lowermost Paleozoic strata have been completed. The objective of this paper is to summarize the stratigraphic and depositional relationships that exist in these earliest Paleozoic strata deposited in southeast Missouri, southern Illinois, and the Reelfoot-Rough Creek rift basins. The results presented herein are based on non-proprietary wire-line logs and cuttings from wildcat wells, and research performed on outcrops and mineral exploration cores located in the St. Francois Mountains of southeast Missouri. The correlations and facies relationships presented should be considered tentative, as no biostratigraphic research has been performed as part of this work. Nevertheless, the correlations presented herein are in good agreement with those of Schwalb (1969 1982a 1982b). The Reelfoot-Rough Creek results are part of a M.S. thesis completed by Paul Weaverling (1987) and some of the Lamotte results are based on a M.S. thesis completed by Bill Yesberger (1982), both under the direction of the author.

STRATIGRAPHIC RELATIONSHIPS

Figure 1 illustrates the distribution of petroleum exploration wells from which wire-line logs were used to establish physical stratigraphic relationships, and Table 1 provides critical information for each well shown in Figure 1. Since completion of these correlations by Weaverling (1987), two additional wells have been drilled in the embayment of Amoco Production Company; one is located in Mississippi County, Arkansas, near well 32 on Figure 1 and the other is located in Dunklin County, Missouri, southwest of well #29 on Figure 1.

Throughout most of the map area, a "normal" midcontinent, stratigraphic succession is present. That is, the Upper Cambrian Lamotte (Mt. Simon) Sandstone rests nonconformably on Precambrian basement rocks except where the Lamotte is absent because of non-deposition on topographic highs on the underlying erosional surface. However, along a relatively narrow trend

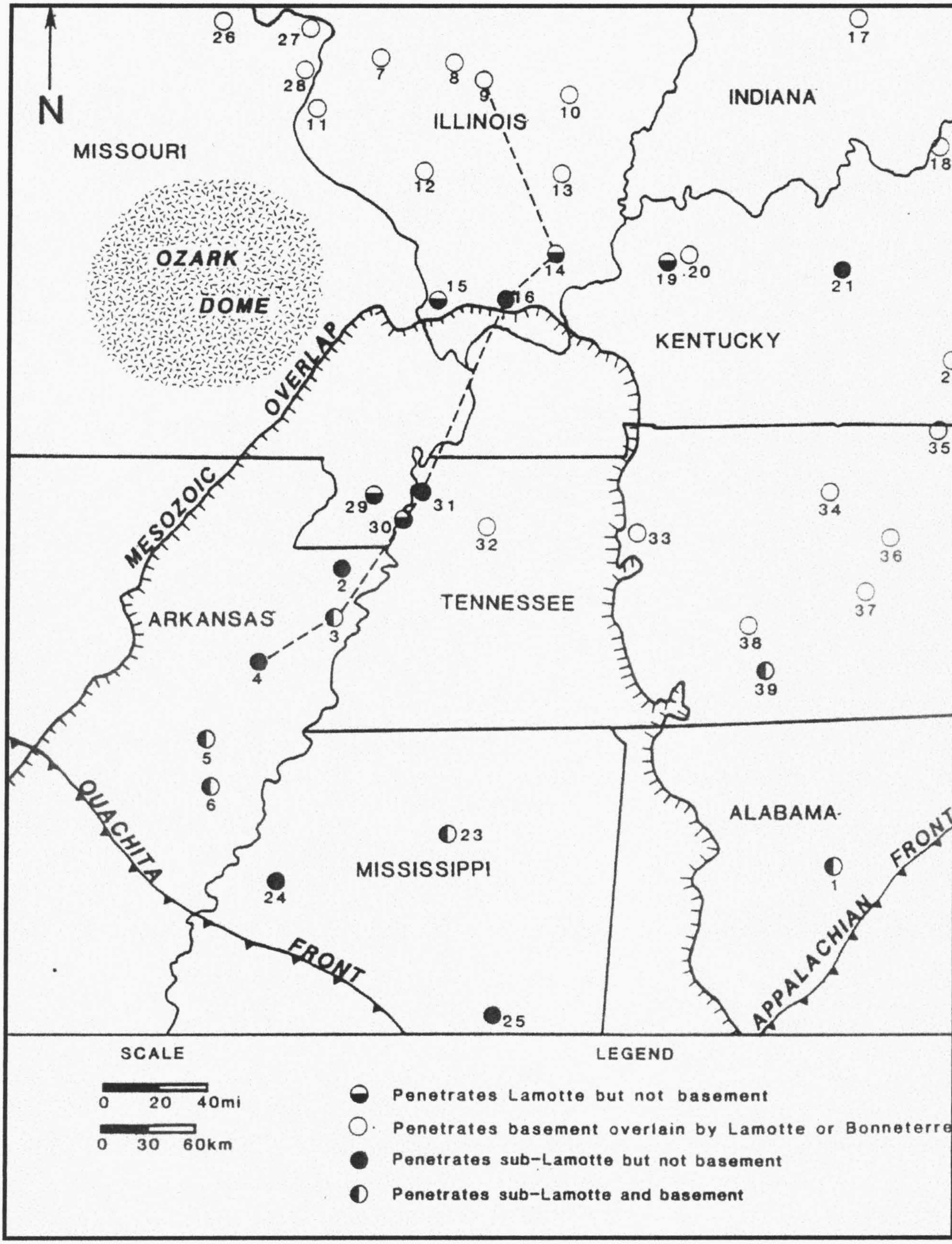

Figure 1. Map of northern Mississippi embayment showing wells used for stratigraphic correlation and lithofacies mapping. Wells are identified in Table 1 by well number.

WELL NUMBER	COUNTY	LOCATION	COMPANY	WELL NAME
		ALABAMA		
1	Culllman	29-9S-2W	Shenandoah & Occidental	#1 Smith
		ARKANSAS		
2	Mississippi	28-15N-10E	Dow Chemical	#1 Garrigan
3	Mississippi	14-12N-9E	Dow Chemical	#1 Wilson
4	Cross	36-9N-4E	Houston Oil & Min.	#1 Singer
5	St. Francis	4-4N-1E	Cockrell Corp. & Consolidated Gas	#1 Carter
6	Lee	36-2N-1E	Cockrell Corp. & Consolidated Gas	#1 Bunch
		ILLINOIS		
7	Madison	27-3N-6W	Mississippi Riv. Trans.	#S-1 Kircheis
8	Clinton	33-3N-1W	Brehm	#1 Herninghaus
9	Marion	6-1N-2E	Texaco	#1 Johnson
10	Wayne	3-1S-7E	Union	#1 Cisne Com.
11	Monroe	35-1S-10W	Miss. River Fuel	#A-15 Theobald
12	Perry	28-5S-3W	Beeson	#1 Poiter
13	Hamilton	6-6S-7E	Texaco	#1 Cuppy
14	Pope	2-11S-6E	Texaco Pacific Oil	#1 Streich
15	Union	21-13S-2W	Humble	#1 Pickell
16	Johnson	34-13S-3E	Texas Pacific Oil	#1 Farley
		INDIANA		
17	Lawrence	20-5N-2E	Texas (IN Farm Bur.)	#2614 Brown
		KENTUCKY		
18	Jefferson	10-V-44	E.I. DuPont	#1 Wad Fee
19	Webster	5-M-22	Exxon	#1 Duncan
20	Webster	23-N-24	Exxon	#1 Bell
21	Grayson	10-L-36	Texas Gas Trans.	#1 Shain
22	Metcalfe	16-F-46	Benz Oil	#1 Nunnally
		MISSISSIPPI		
23	Lafayette	18-17S-1W	Pruet & Hughes	#1 Dunlap
24	Coahoma	36-27N-3W	Texaco & Exxon	#1 Ivey
25	Oktibbeha	33-19N-12E	Exxon	#1 Fulgham
		MISSOURI		
26	St. Charles			
27	St. Louis	31-45N-7E	St. Louis City Sanitarium	#1 Fee
28	St. Louis			
29	Pemiscot	33-18N-13E	Killam	#1 Pattinson
30	Pemiscot	24-19N-11E	Strake Petroleum	#1 Russell
		TENNESSEE		
31	Lake	3-4S-1E	Benz Oil	#1 Merritt Est.
32	Gibson	19-55-6E	Big Chief Drilling	#1 Taylor
33	Humphreys	14-6S-19E	E.E. DuPont de Nemours	#2 Fee
34	Davidson	16-3S-35E	E.I. DuPont	#1 Fee
35	Macon	12-A-43	Houghland & Hardy	#2 Good
36	Wilson	10-7S-39E	Texaco	#1 Haynes
37	Rutherford	13-10S-37E	Gordon Street	#1 Holden
38	Maury	16-12S-28E	Staufer Chemical	#1 Fee
39	Giles	4-15S-29E	California Co.	#1 Beeler

 Table 1. Well data used in regional correlations. Well numbers keyed to figures.

extending from eastern Arkansas to southern Illinois (approximately parallel to the Mississippi River), and along a west-east trend from southern Illinois into western Kentucky, wells have penetrated strata that are apparently older than the Lamotte Sandstone (Fig. 1). These trends correspond to the Reelfoot basin and Rough Creek graben, as defined on the basis of subsurface data (Schwalb, 1969, 1982a, 1982b) and confirmed by geophysical methods in a number of recent publications (Ervin and McGinnis, 1975; Soderberg and Keller, 1981; Kane et al., 1981; Braile et al., 1982, 1986; Ginzburg et al., 1983; Mooney et al., 1983; Hildenbrand, 1985; Sexton et al., 1986).

Cross section A-A' illustrates correlation of Bonneterre and older strata southward from the Illinois basin into the Reelfoot basin (Fig. 2). The cross section is hung on a stratigraphic datum in the Bonneterre Formation; this shaly interval within Bonneterre carbonates is a fairly persistent key bed throughout the region. The cross section illustrates several important aspects of lower Paleozoic stratigraphy: (1). The lower portion of the Bonneterre Formation grades southward from mostly carbonate in well #9 to mostly shale in well #4. (2). The Lamotte Sandstone grades southward from mostly sandstone in well #9 to mostly shale in well #4. (3). In well #9, the Lamotte Sandstone rests directly on Precambrian granitic basement; in contrast, wells #16, 31, 3 and 4 appear to penetrate strata that are older than the Lamotte and well #3 additionally penetrates Precambrian granitic basement. One or more graben-bounding normal faults are inferred to be present between wells #9 and 16, as indicated in Figure 2. (4). In wells #31 and 3, the strata immediately underlying the Lamotte is a finely crystalline carbonate (labeled B in Figure 2) that appears to be equivalent to a calcareous sandstone in well #16. (5). In wells #16, 31, and 3, unit B is underlain by a thick arkosic sandstone (labeled A in Figure 2) that, in turn, rests on crystalline basement in well #3.

Units A and B of Figure 2 are possibly older than any recognized formations in the midcontinent. For this reason, and for convenience of discussion, they have been given informal names by Weaverling (1987) which are used here. The thick arkose is referred to as the Reelfoot arkose to signify its restricted occurrence within the Reelfoot basin, although it may also be present in the Rough Creek graben. The Reelfoot arkose varies considerably in thickness in those few wells that have penetrated its total thickness. It is 2573 feet thick in well #3 whereas it is less than 100 feet thick in well #6. As its name implies, the Reelfoot arkose is mostly medium to coarse grained, locally conglomeratic, feldspathic sandstone although siltstones and mudstones are also present locally. In well #3, the Reelfoot arkose is mostly red from basement up to about 500 feet below the base of the overlying carbonate. At that depth, the red color grades upward to gray over about 30 feet of section.

The carbonate stratum (unit B of Figure 2) is referred to as the St. Francis formation because its first and thickest penetration to date is in well #5 in St. Francis County, Arkansas. In that well, the St. Francis comprises 1044 feet of light to dark gray, crystalline, dolomitic limestone that is locally oolitic. The St. Francis formation has only been identified in wells #3, 5 and 6, although calcareous sandstones in well #16 are tentatively correlated as lithostratigraphic equivalents.

In addition to correlating these lithostratigraphic units within the Reelfoot and Rough Creek basins and documenting their relationships to strata outside those rift basins, Weaverling (1987) also tentatively correlated the Reelfoot arkose and St. Francis formation with lower Paleozoic strata in the southern Appalachians via deep wells in Mississippi and Alabama (Figure 1). These correlations suggest that the Reelfoot arkose and St. Francis formation occupy the approximate lithostratigraphic positions of the Lower Cambrian Rome and Middle Cambrian Conasauga Formations, respectively,

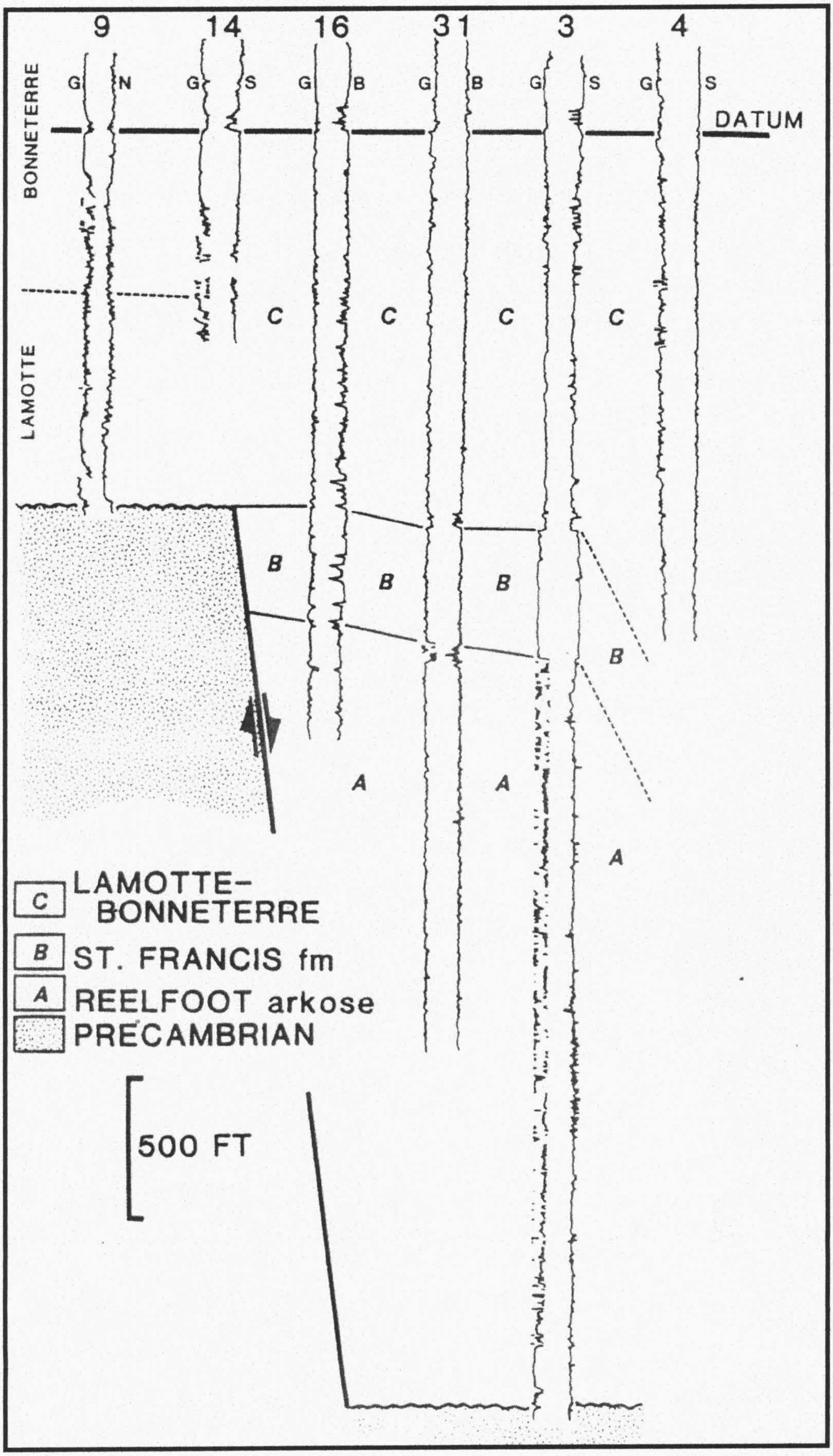

Figure 2. Cross section A-A' showing correlation of major stratigraphic untis based on wire-line long responses. Line of cross section is shown on Figure 1. Key to log types: G = gamma ray; N = neutron; S = sonic; and B = bulk density.

of the southern Appalachians (see Mellen, 1977). It is emphasized that these correlations are extremely tentative and based on lithostratigraphic criteria; no biostratigraphic control has been established.

REGIONAL DISTRIBUTION AND INFERRED FACIES

Assuming that the correlations discussed above are valid, four distinct lithostratigraphic "formations" can be mapped in the region. Figures 3 through 6 illustrate the distribution of predominant lithologies (sandstone, shale, carbonate) in the Reelfoot arkose, St. Francis formation, Lamotte Sandstone, and Bonneterre Formation, respectively. On each map, the locations of key wells that establish the presence/absence and lithology of specific strata are shown as black dots; outcrop observations and mineral exploration core data were also used to establish these relationships in southeast Missouri and northern Arkansas. On these maps, aeromagnetic anomalies were used to define the approximate edges of the Reelfoot and Rough Creek rift basins because well control is too sparse to accurately locate the boundaries of individual graben and half-graben sub-basins.

Individually, these maps reveal the distribution of sediment types that were deposited as Paleozoic sedimentation was initiated in the midcontinent region. Collectively, these maps depict the onlap of marine environments onto the midcontinent craton during the eustatic rise in sea level that occurred during the Cambrian Period.

Reelfoot Arkose

Figure 3 depicts the distribution of predominat sediment types in the Reelfoot arkose. In the area of primary interest, sedimentation was restricted to the rift basins and mostly sand was deposited. Four wells are inferred to document the presence of arkosic sandstones in the Reelfoot basin; the arkose has apparently not been penetrated

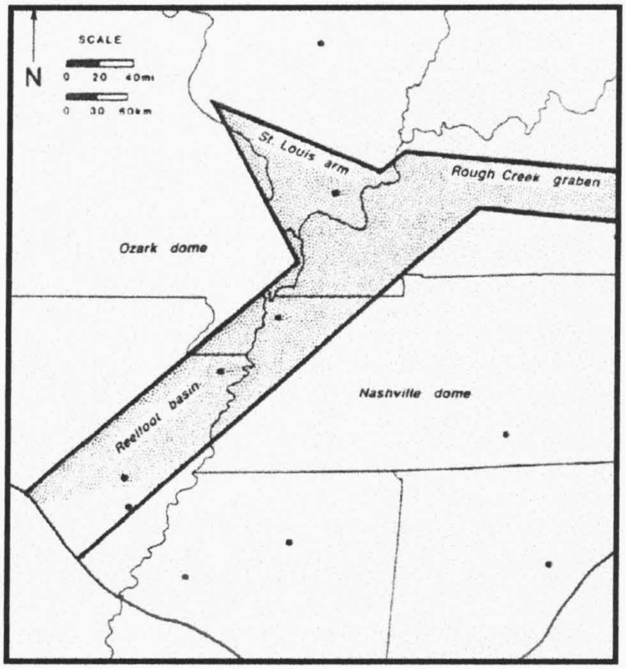

Figure 3. Distribution of predominant lithologies in the Reelfoot arkose, as defined in text. Map area is same as Figure 1. Conventional sand and shale patterns are used; white denotes areas of erosion (i.e. no correlative strata present).

in the Rough Creek graben, but it is suggested that arkose is probably present in the depths of that basin (Fig. 3). Outside the rift basins to the north and on the ancestral Nashville dome, no sediment was being deposited as erosion of Precambrian basement was taking place. At the south end of the Reelfoot basin, it appears that sandstones grade into shales as the predominant sediment type and shales are predominant in the Rome Formation through Mississippi and Alabama.

The predominance of red, conglomeratic, arkosic sandstones restricted to graben basins strongly suggest non-marine deposition of sediment locally derived from the Precambrian basement. Even though insufficient evidence exists to interpret specific depositional environments, it is likely that sedimentation occurred on alluvial fans and in associated braided fluvial environments. Locally distributed siltstones and mudstones may represent sedimentation in lakes or on floodplains associated with fluvial systems. The conspicuous upward gradation from red to gray arkoses near the top of the formation in well #3 may reflect the initial inundation of the Reelfoot basin by marine waters, and the accompanying change from oxidizing to reducing conditions.

The distribution of shales at the southern end of the Reelfoot basin and along the southern margin of the ancestral Nashville dome probably approximate the distribution of marine conditions during deposition of most of the Reelfoot arkose and Rome Formation.

St. Francis Formation

Figure 4 depicts the distribution of predominant sediment types in the St. Francis formation. In the northern half of the map area, sedimentation continued to be restricted to the riftbasins. In the area of juncture between the Reelfoot and Rough Creek basins, mostly sandstone was deposited. The sand may have been eroded from exposed Precambrian rocks north and west of this juncture; that sand may have been funnelled into the rift basins via the "St. Louis arm" of the graben system. Southward within the Reelfoot basin, sandstone is inferred to grade into carbonates in the vicinity of the Missouri bootheel. Carbonates are predominant through the southern part of the Reelfoot basin and extend eastward along the southern margin of the ancestral Nashville dome to the southern Appalachians. In the Rough Creek graben, thick shales that have been penetrated by two wells are correlated with the St. Francis formation.

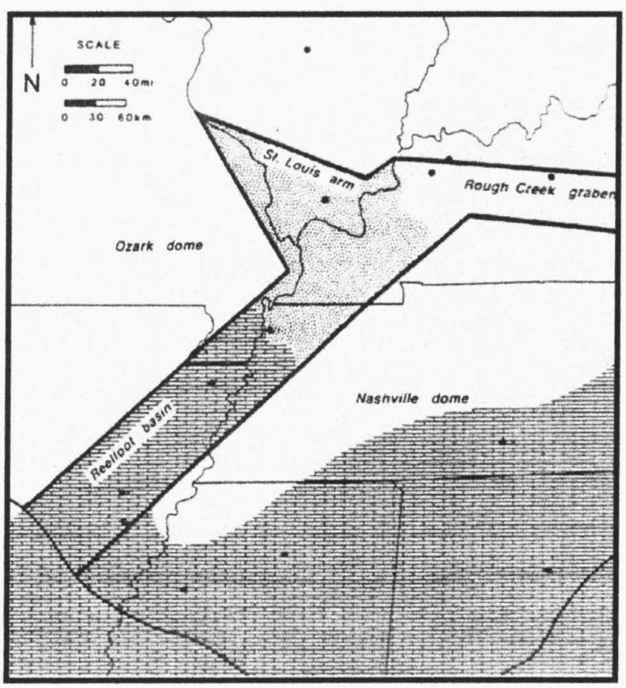

Figure 4. Distribution of predominant lithologies in the St. Francis formation, as defined in text. Map area is same as Figure 1. Conventional sand, shale, and carbonate patterns are used; white denotes areas of erosion (i.e., no correlative strata present).

The presence of oolite-bearing carbonates restricted to the Reelfoot basin suggests that shallow marine water invaded the basin from the south as Cambrian sea level rose. Alternatively, the oolites could have been derived from the shelf and deposited as turbidites. The apparent continuity of the St. Francis carbonates southward and eastward toward the southern Appalachians supports this interpretation. The distribution of predominantly carbonate lithologies along the southern margin of the ancestral Nashville dome probably approximates the distribution of marine conditions during St. Francis deposition. It appears that rising sea levels resulted in onlap of Cambrian strata onto the southern margin of the ancestral Nashville dome, as is suggested by a comparison of Figures 3 and 4.

The predominance of sandstone at the juncture of the Reelfoot and Rough Creek basins and the continuation of erosion immediately north and west of that juncture suggest influx of sand from fluvial systems. Deposition of sand may have occurred in fan delta environments as suggested by limited distribution of sandstone along the graben margins and fairly abrupt gradation southward into carbonates and eastward into shales.

Even though shale is the predominant lithology in the Rough Creek graben, that shale contains arkosic sandstone beds and oolitic limestone beds and has yielded Middle Cambrian fossil fragments (Schwalb, 1982, b). This evidence, together with the lateral association with sandstone and carbonate, suggest that the Rough Creek graben evolved into a restricted marine arm of the rift system, which may have been open to normal marine conditions only at the southern end of the Reelfoot basin.

Lamotte Sandstone

Figure 5 depicts the distribution of predominant sediment types in the Lamotte Sandstone and its inferred stratigraphic equivalents. During Lamotte deposition, crystalline basement throughout the map area was completely covered by sediment (except for local topographic highs on the erosional surface) for the first time in the Paleozoic Era. North of the rift system and at the juncture of the Reelfoot and Rough Creek basins, the Lamotte is mostly quartzose sandstone. In northern Arkansas, west of the Reelfoot basin, the Lamotte apparently grades southward into carbonates. In the Reelfoot basin, quartzose sandstone grades southward into predominantly marine shale in the vicinity of the Missouri bootheel (refer to Fig. 2). A similar gradation from quartzose sandstone to predominantly marine shale occurs eastward into the Rough Creek graben in western Kentucky. On the south side of the rift system, carbonates were deposited across the ancestral Nashville dome during Lamotte deposition.

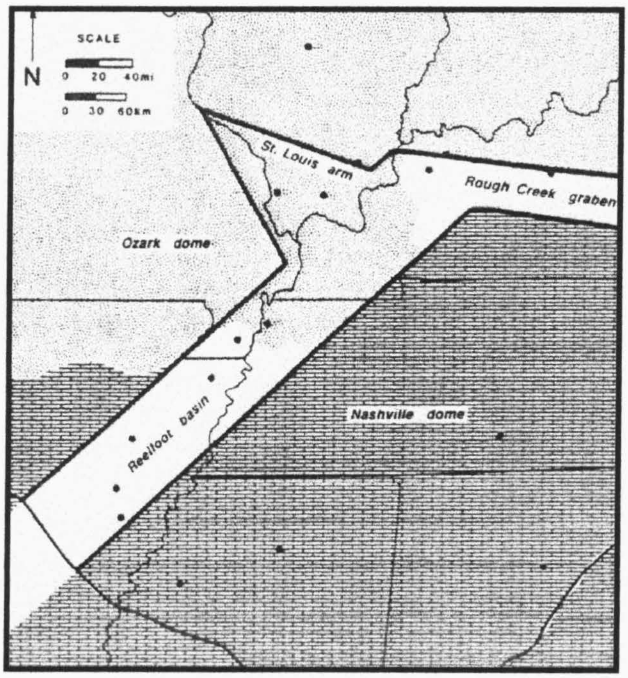

Figure 5. Distribution of predominant lithologies in the Lamotte Sandstone and correlative strata. Map area is same as Figure 1. Conventional sand, shale, and carbonate patterns are used.

In and around the St. Francois Mountains of southeastern Missouri, the Lamotte grades vertically upward from fluvial to marginal marine facies (Houseknecht and Ethridge, 1978), and the characteristics of these facies are discussed in a subsequent section. Well log character and subsurface samples from the Reelfoot and Rough Creek basins indicate that the Lamotte grades laterally into marine shale in those grabens, suggesting that rates of subsidence and water depths were greater within the grabens than in surrounding areas. Thus the Lamotte reflects continuation of the onlap induced by rising Cambrian sea level (compare Figs. 3, 4 and 5).

Bonneterre Formation

Figure 6 depicts the distribution of predominant sediment types in the lower half of the Bonneterre Formation and its inferred stratigraphic equivalents. During Bonneterre deposition, the entire map area was blanketed with carbonates except for the southern part of the Reelfoot basin, where marine shales were deposited. This overall pattern of sedimentation reflects continued onlap of marine conditions onto the craton in response to rising sea level during the Cambrian.

Bonneterre carbonates were deposited in a spectrum of marine environments that are discussed in other papers in this volume. The shales in the southern part of the Reelfoot basin are gradational from underlying "Lamotte shales" to overlying carbonates that "prograded" totally across the Reelfoot basin during deposition of the upper half of the Bonneterre. As such, they

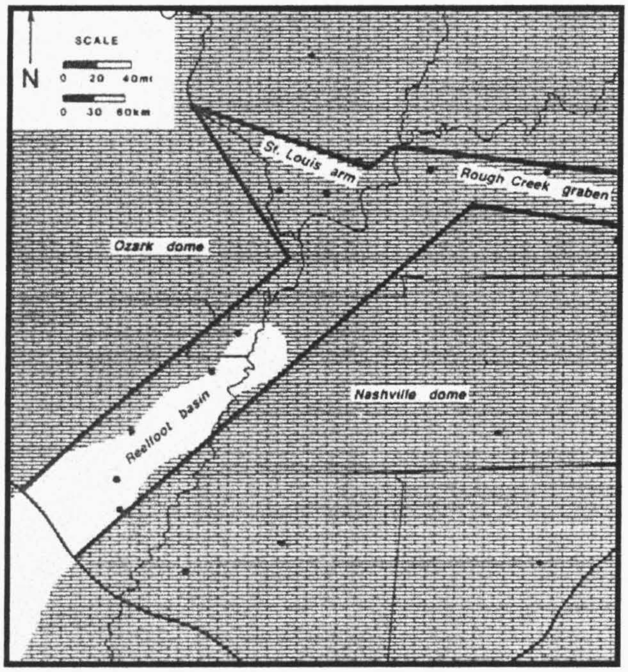

Figure 6. Distribution of predominant lithologies in the Bonneterre Formation and correlative strata. Map area is same as Figure 1. Conventional shale and carbonate patterns are used.

probably represent somewhat deeper marine conditions than those in which Bonneterre carbonates were deposited in.

TECTONIC AND SEDIMENTARY EVOLUTION

Figure 7 summarizes the lithostratigraphic correlations and generalized interpretations of depositional environments discussed above. The Reelfoot arkose is restricted to the Reelfoot basin (and probably the Rough Creek graben) and most likely represents alluvial fan and braided fluvial sedimentation that occurred during active graben development. It is similar in distribution and lithology to alluvial facies that have been documented in numerous graben basins, including, for example, lower Mesozoic strata of the Newark basin (Arguden and Rodolfo, 1986). The abrupt gradation upward from red to gray arkoses near the top of the formation may signify initial invasion of the graben basin by marine waters as sea level rose during the Cambrian.

The St. Francis formation is also restricted to the Reelfoot basin, although marine shales inferred to be stratigraphic equivalents are present in the Rough Creek graben. Throughout most of the Reelfoot basin, the St. Francis represents shallow marine carbonate facies (Fig. 7). At the north end of the Reelfoot basin, at the juncture with the Rough Creek graben, the St. Francis is apparently a calcareous sandstone that is tentatively interpreted as a fan delta deposit. Thus, the St. Francis represents a non-marine through marine facies sequence deposited during inundation of the graben system by marine water, while subaerial erosion of Precambrian basement continued outside the graben basin.

The Lamotte Sandstone is the oldest formation that was deposited outside the boundaries of the graben basins. The distribution of lithologies discussed above suggests that the Lamotte represents a widespread transition from non-marine to marine deposits. North of the graben basins, the Lamotte is mostly a braided fluvial deposit that grades vertically upward to braid-delta and shallow marine facies. Within the confines of the graben basins, the Lamotte apparently grades laterally into a shallow marine shale. These interpretations imply that a lateral transition from mostly braided fluvial facies to mostly marine basin facies is present in the northern part of the Reelfoot basin (Fig. 7).

The Bonneterre Formation signifies establishment of widespread marine conditions throughout the southern midcontinent region resulting from the Cambrian sea level rise. In the lower half of the formation, a southward gradation from carbonates to shales implies a transition from a clear water marine shelf environment to a deeper, muddy marine environment. However, the upward gradation from shale to carbonate in the southern part of the Reelfoot basin (e.g., well #3 in Figure 7) implies that the carbonate "shelf" prograded across the deeper basin as Bonneterre deposition proceeded. By the end of Bonneterre deposition, carbonates were being deposited across the entire map area; the establishment of

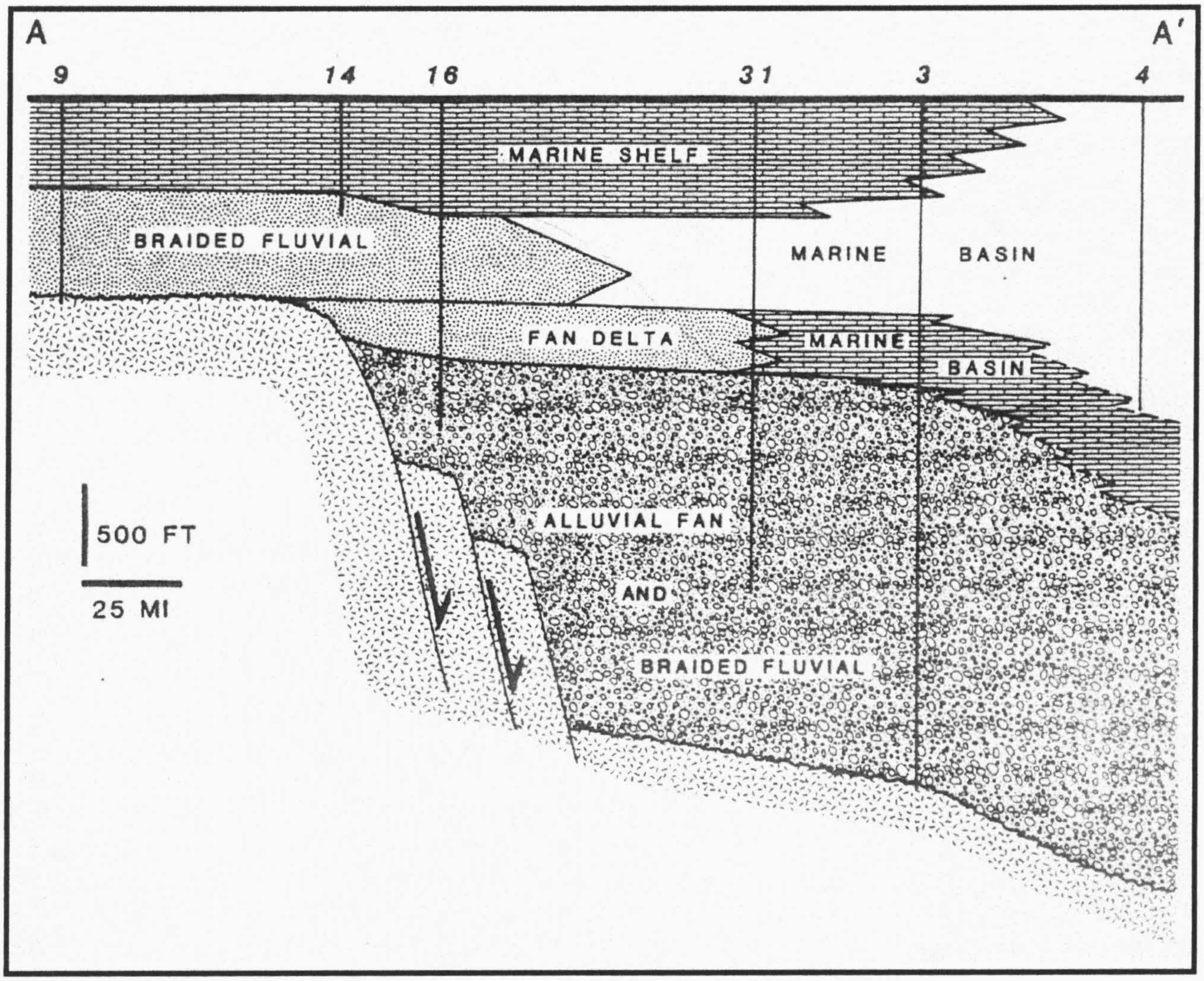

Figure 7. Cross section A-A' showing inferred stratigraphic and facies relationships discussed in text. See Figure 2 for wire-line log responses.

the Arbuckle-Knox carbonate platform had been completed.

The distribution and thickness of inferred facies discussed above can also be used to reconstruct a generalized subsidence history of the Reelfoot basin. Figure 8 illustrates three distinct phases of basin development. The first phase involved development of graben and half-graben basins during active normal faulting (Figure 8A), probably associated initiation of rifting (e.g., Ervin and McGinnis, 1975). During this phase of basin development, Arkosic detritus was eroded from uplifted fault blocks and locally deposited in the down-faulted basins, thereby accounting for the extreme variations that have been observed in its thickness. Based on comparisons with alluvial arkoses in other graben basins, the rates of subsidence and sedimentation were probably very high. The age of this phase of basin development cannot be established, but the correlations discussed previously imply that it may have occurred during the early Cambrian. If the inferred non-marine origin of the Reelfoot arkose is correct, it is unlikely that an accurate age will ever be determined because of a lack of faunal control.

The second distinct phase of basin evolution is represented by deposition of the St. Francis formation (Fig. 8B). Observed thicknesses of the St. Francis formation suggest that the Reelfoot basin was subsiding as a single basin, rather than as individual graben and half-graben basins. For

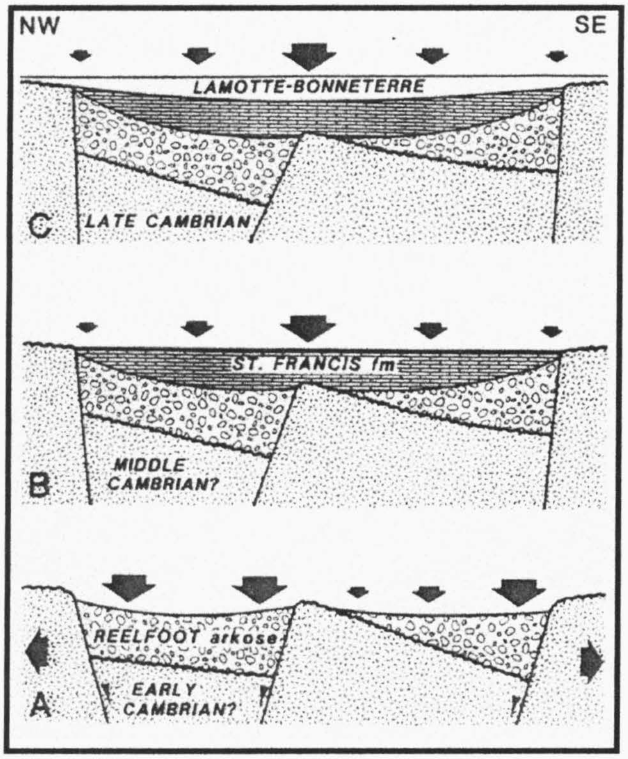

Figure 8. Hypothetical northwest-southeast cross sections showing sequential development of the Reelfoot basin. A. Phase of active faulting and deposition of Reelfoot arkose. B. Phase of St. Francois formation. C. Phase of coupled regional subsidence, rising sea level and initial deposition of sediment outside limits of rift basin. Early part of third phase would involve deposition of Bonneterre. Within each phase, arrows pointing downward depict relative subsidence rates. However, absolute subsidence rates were highest in A, lower in B, and lowest in C.

example, wells #5 and 6 (Figure 1) penetrated thick St. Francis carbonates above very thin Reelfoot arkoses before penetrating basement. This implies that areas that were relatively high during active graben formation (deposition of thin Reelfoot arkose) became relatively low during later subsidence (deposition of thick St. Francis carbonates), as illustrated near the center of Figure 8A and 8B. Based on lithostratigraphic relationships, a tentative middle Cambrian age is inferred for the St. Francis formation. An accurate age will probably be established because the St. Francis likely contains marine microfauna that will allow biostratigraphic correlations.

The third distinct phase of basin evolution is represented by deposition of the Lamotte and Bonneterre Formations. As Cambrian sea level rose and marine water spilled out of the Reelfoot and Rough Creek grabens to cover the adjacent craton (Figure 8C), these basins apparently became more coupled with regional basement and followed the general subsidence pattern of the entire southern midcontinent. Despite this general trend, most lower and middle Paleozoic formations appear to thicken into the Reelfoot basin, suggesting that the buried rift remained an axis of relatively greater subsidence throughout much of the Paleozoic Era.

In summary, the stratigraphic sequence of Reelfoot arkose through Bonneterre Formation in the Reelfoot basin represents the initiation and abandonment of a rift basin, contemporaneous with the major eustatic rise in sea level that occurred during the Cambrian Period.

LAMOTTE SANDSTONE FACIES IN THE ST. FRANCOIS MOUNTAINS

Exposures of Lamotte Sandstone in the St. Francois Mountains (Figure 9) provide a rare glimpse of the basal Paleozoic sandstone that blankets most of the North American craton. The Lamotte has been the subject of numerous studies that sought to reconstruct the nature of early Paleozoic sedimentary environments. Wallace (1938) and Ojakangas (1963) concluded that most of the quartzose sand in the Lamotte was derived from distant sources to the north and northwest, and that the Lamotte was deposited mostly in marine environments. Houseknecht and Ethridge (1978), and Yesberger (1982) agreed that most of the quartzose sand was derived from distant north or northwestward sources, but concluded that the Lamotte was mostly deposited in fluvial environments, and that only the uppermost portion of the formation was deposited in marine influenced environments. This section summarizes the facies characteristics of the Lamotte and relates these to the larger scale stratigraphic framework proposed in the earlier sections of this paper.

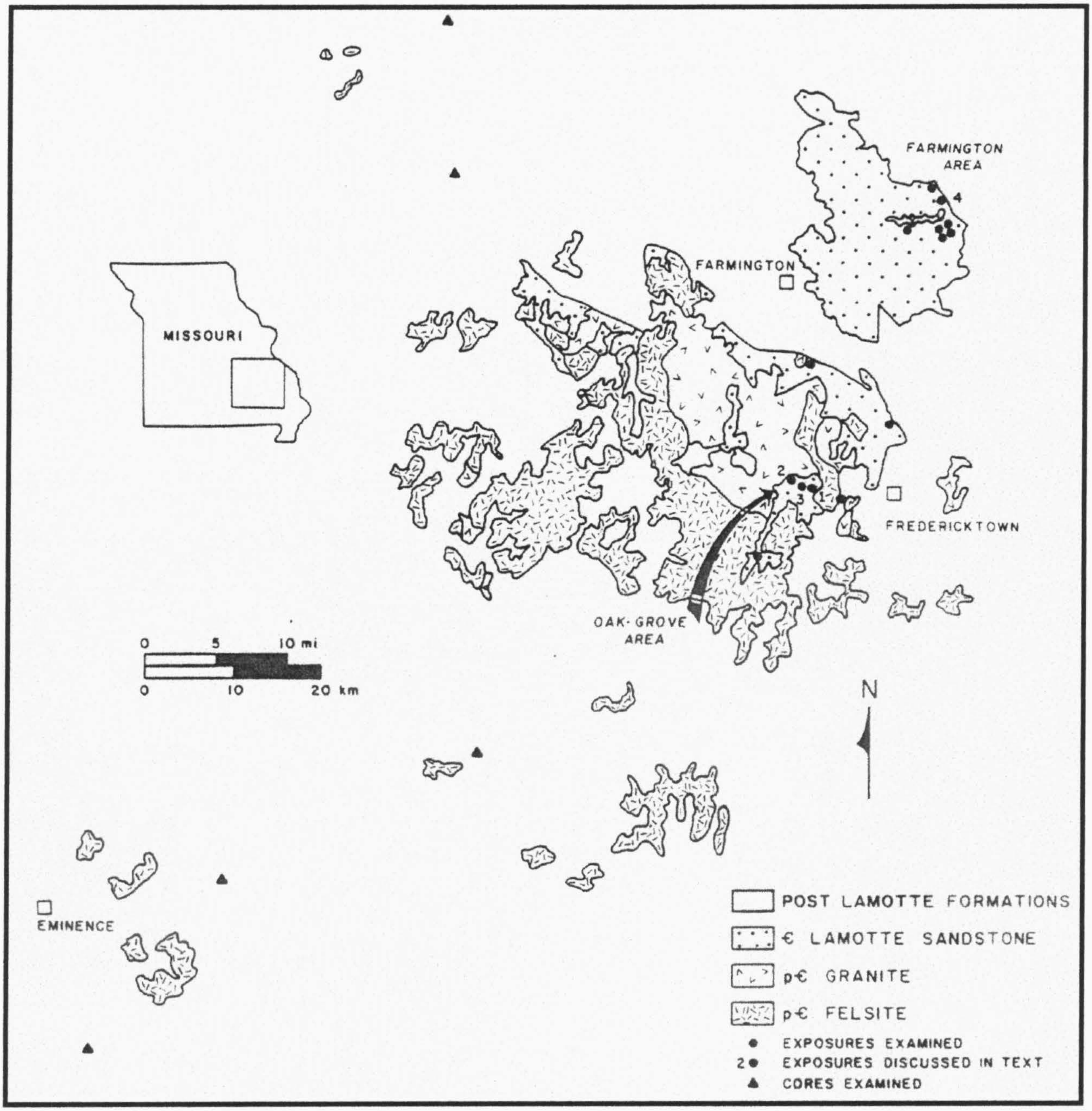

Figure 9. Generalized geologic map of the St. Francois Mountains area showing locations of Lamotte Sandstone exposures discussed in text.

Lamotte Depositional Settings

Figure 10 is a schematic illustration of the ancestral St. Francois Mountains showing various settings in which Lamotte sediment was deposited. Regionally, the Lamotte is a blanket of quartzose sandstone (represented by the dotted pattern in Fig. 10) that onlapped and partly buried the ancestral St. Francois Mountains, which were characterized by rugged erosional relief. Lamotte outcrops that are peripheral to the Precambrian core of the ancestral St. Francois Mountains are part of that regionally extensive blanket of quartzose sandstone; the best exposures of that type of Lamotte are on the Farmington anticline, located northeast of the core of the mountains (Fig. 9). Within the ancestral St. Francois Mountains, sediment locally derived from Precambrian crystalline rocks was deposited in valleys on the erosion sur-

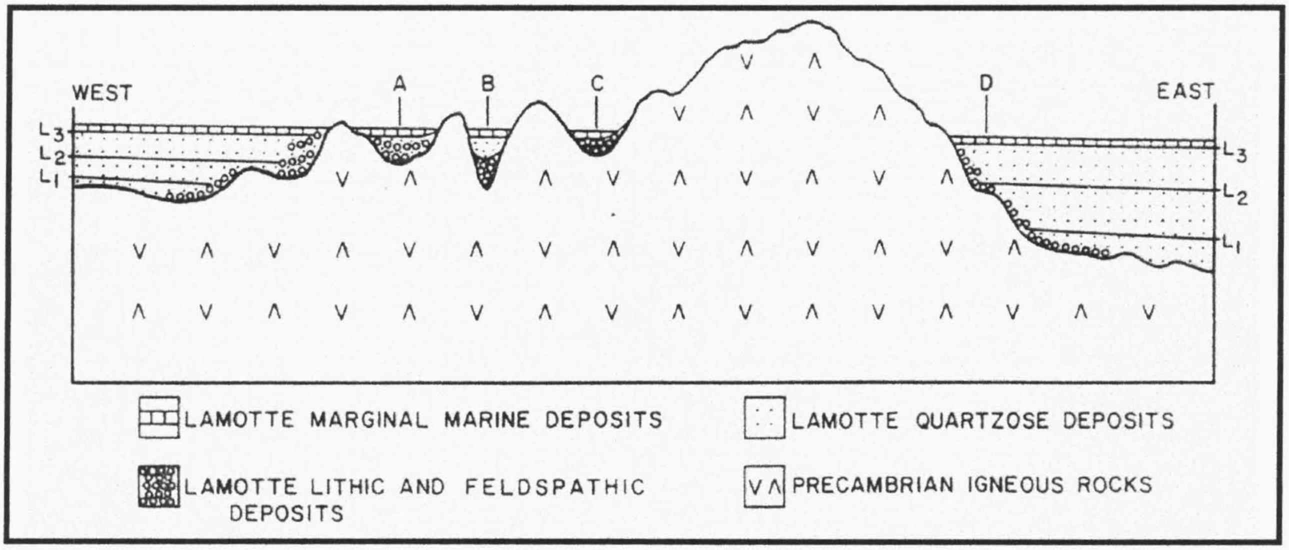

Figure 10. Hypothetical west to east cross section through the ancestral St. Francois Mountains at the end of Lamotte deposion. Lines L1, L2, L3 represent successive levels of the alluvial plain as it buried the flanks and lower knobs of the mountains. A, B, C, and D represent depositional settings of (A) interbedded arkosic and quartzose deposits; (B) arkosic deposits overlain by quartzose deposits; (C) arkosic deposits with no associated quartzose deposits; and (D) quartzose deposits with arkosic deposits present only at base of section.

face (represented by the open circles in Figure 10) and this type of Lamotte is arkosic; the best exposures are located in exhumed valleys within the St. Francois Mountains proper (e.g., Oak Grove area of Figure 9). As depicted in Figure 10, the Lamotte is variable in composition depending upon the relative proportion of distantly vs. locally derived sediment that was deposited in a particular setting. The following sections provide descriptions of lithology and depositional facies in two end-member types of settings.

Farmington Area

The Farmington area is peripheral to the rugged igneous core of the St. Francois Mountains and is underlain by a granitic surface of relatively gentle relief. Precambrian basement is exposed in this area only where streams have eroded through the Lamotte. For these reasons, this area may be more representative of the regional characteristics of the Lamotte than other exposures in the St. Francois Mountains.

Non-marine facies. – The Lamotte is typically 200 to 250 feet thick in the Farmington area, and all but the upper 30 to 50 feet is interpreted as non-marine. In the basal part of the section, the Lamotte is medium to coarse grained (locally pebbly), arkosic to quartz arenite that displays a predominance of trough cross bedding and crude horizontal stratification. These characteristics grade up section into fine to medium grained, quartz arenite that displays a predominance of planar cross bedding. The overall upward decrease in grain size is accompanied by a decrease in bed thickness, from 2 to 6 feet near the base of the section to generally less than 1 foot in the upper part of the non-marine facies. Throughout this sequence, cross bedding indicates unidirectional sediment dispersal to the east-southeast (Houseknecht and Ethridge, 1978; Yesberger, 1982). Sediment finer than sand is virtually absent throughout this section; only rarely are lenses of siltstone or claystone observed.

Houseknecht and Ethridge (1978) interpreted this vertical sequence as the deposits of a braided fluvial system, with more proximal braided facies at the base of the section grading to more distal braided facies at the top. Yesberger (1982) refined this interpretation and compared Lamotte sedimentary structures and facies sequences to modern braided river facies models. He found that the lower part of the Lamotte section most nearly resembles the Donjek and South Saskatchewan models of Miall (1977, 1978). In those rivers, most sediment is deposited on longitudinal bars and/or transverse (cross-channel bars). Using these analogues, Yesberger (1982) determined that the lower Lamotte braided fluvial environment was characterized by high flow energy, rapid fluctuations in flow velocity, and depths that averaged 5 to 6 feet.

The upward gradation in braided fluvial style was an apparent response to aggradation of the fluvial system, which was probably induced by rising sea level. As the fluvial system aggraded, the erosional topography that had been established on the Precambrian basement surface was gradually buried and replaced by a more level alluvial plain. Braided rivers that had been confined to incised valleys during deposition of the lower Lamotte evolved into braided rivers that were relatively unconfined on a broad braid-plain. With no vegetation to stabilize the system, the Lamotte braid-plain probably resembled modern glacial outwash plains, with numerous, shallow channels characterized by rapid lateral switching of water flow.

Locally, the broad plain of alluvial sand was apparently reworked by eolian processes. In several outcrops, Yesberger (1982) identified beds and lenses of sandstone that is finer grained and better sorted than adjacent beds of apparent fluvial origin. These beds display horizontal bedding, low angle cross stratification, small scale trough cross bedding, and ripple cross bedding. Paleocurrent indicators suggest highly variable sediment transport directions within these beds and lenses. These characteristics, together with a total absence of trace or body fauna, suggest local reworking of fluvial sand by eolian proceses. However, the fine grain size and limited bed thickness suggests that the competence of winds was relatively low and that variability in wind direction was considerable.

Marine facies. – The uppermost 30 to 50 feet of Lamotte in the Farmington area was deposited in environments that were either marine-influenced or totally marine. Integration of the work of Houseknecht and Ethridge (1978) and Yesberger (1982) suggests that the uppermost Lamotte represents shoreline and shallow marine facies of a braid-delta.

Outcrops of the uppermost Lamotte that are laterally equivalent display significantly different lithologies and sedimentary structures. Some outcrops are predominantly sandstone and display a wide variety of sedimentary structures, including massive bedding, trough and planar cross bedding, horizontal bedding, and low angle cross stratification. Paleocurrent indicators suggest highly variable sediment transport directions. Locally, phosphatic shell fragments are present in carbonate cemented sandstone beds. Other outcrops at the same stratigraphic horizon display approximately equal volumes of sandstone and mudstone arranged into coarsening upwards, bioturbated sequences that are locally incised by channel-shaped lenses of sandstone.

These characteristics are interpreted to represent lateral variation along the shoreline of an active braid-delta. At locations of active fluvial channel flow, the shoreline would have protruded seaward, where wave energy would naturally be concentrated. Interaction of fluvial and wave energy would explain the association of sand-dominated sediment, a large variety of sedimentary structure types, and highly variable paleocurrent indicators. Laterally along the shoreline, areas that were not sites of active fluvial channel flow would tend to be embayments where tidal processes would be concentrated and where wave energy would be lower. In such embayments, barrier bars incised by tidal channels could result in the coarsening upward, mud and sand sequences observed in several Lamotte outcrops. Thus, the variable facies characteristics displayed by the uppermost Lamotte probably reflect sedimentation at various locations along the shoreline of a braid-delta.

Oak Grove Area

The Oak Grove area (Fig. 9) illustrates "Lamotte" sedimentation within topographic low areas within the rugged, ancestral St. Francois Mountains, physically removed from the alluvial plain where quartzose sand was deposited (i.e., the Farmington area). This ancient valley, which is now exhumed, is bordered on the east and south by rugged granitic terrain. In a narrow corridor to the southeast, the Lamotte dips into the subsurface beneath the Bonneterre (Fig. 9).

The exposures of sandstone and conglomerate in the Oak Groe area highlight a stratigraphic problem that is common throughout the region. In the absence of fauna in non-marine facies that are not in physical continuity with strata of known stratigrahic affinities, it is impossible to determine whether these deposits are older than, equal in age to, or younger than the Lamotte Sandstone regionally. They have been mapped as Lamotte on the basis of lithology, but their true age is unknown.

These deposits are virtually identical to the lithologies observed in cuttings of the Reelfoot arkose from the Reelfoot basin because they were derived from Precambrian basement rocks and transported only a short distance to sites of deposition. Thus, even if their age is equivocal, they do provide an opportunity to examine the sedimentological characteristics of facies similar to those of the Reelfoot arkose.

Non-marine facies. – The exposures in the Oak Grove area are mostly "red beds" interpreted to have been deposited on alluvial fans (Houseknecht and Ethridge, 1978). On the east side of the valley, an exposure of boulder conglomerate onlaps felsitic basement rocks. Angular to rounded rhyolite porphyry clasts, which range from pebble sized to 10 feet in diameter, are randomly distributed in a red to brown matrix of clay and sand. Distinct, irregular contacts are visible within the conglomerate due to variation in color and texture of the matrix. This conglomerate is interpreted to be the deposit of multiple debris flows which were probably of high viscosity as suggested by the random distribution of boulders. The debris flows were obviously shed off the adjacent felsitic mountains and probably formed an alluvial fan along the valley wall. Lenses of horizontally bedded sandstone and mudstone within the conglomerate were probably deposited in ponds or in small streams that developed on the surface of the alluvial fan between major debris flow events.

On the west side of the valley, an exposure of red and white, cross bedded, feldspathic sandstone onlaps granitic basement rocks. Two distinct subfacies are present. The "background" facies is a sheet-like deposit of hematitic sandstone that displays small scale trough cross bedding. The trough cross bed sets are only about 18 inches wide and 6 inches thick. Incised into this background facies are several broad, thin, channel-shaped bodies of white sandstone. Each of these channel-sandstones fines upward, becomes better sorted upward, and displays a consistent bedding sequence upward from trough cross beds to planar cross beds to horizontal beds that grade into the overlying background facies. These two subfacies are interpreted to be sheetflood and incised fluvial channel deposits of a sand-rich alluvial fan.

Marine facies. – In the center of the valley, between the two exposures described above, strata that display a gradation upward from non-marine to marine facies are exposed. Cross bedded sandstones like those described in the preceding paragraph grade upward into horizontally bedded, finer grained, calcareous sandstones, siltstones, and mudstones. At the top of the section, a calcareous siltstone contains abundant brachiopod (Micromitra sp.) fossils. This facies sequence was deposited along a transgressive shoreline in back-bar, bar, and foreshore environments (Houseknecht and Ethridge, 1978) and represents the gradation into the overlying Bonneterre Formation.

Summary of Lamotte Facies

As implied in Figure 10, Lamotte facies vary both vertically and laterally depending on location relative to the rugged topograhy of the ancestral St. Francois Mountains and the erosional configuration of the underlying basement. Peripheral to the St. Francois Mountains, the Lamotte was deposited in braided rivers that became more unconfined through time as the fluvial system aggraded and buried the irregular topography that characterized the top of basement. Rising Cambrian sea level not only caused aggradation of the fluvial system, but also eventually flooded the braided alluvial plain, resulting in deposition of braid-delta facies.

Within the ancestral St. Francois Mountains, sedimentation in isolated valleys was dominated by alluvial fan processes. Where rhyolite was the predominant source of sediment, matrix-supported debris flows formed alluvial fans composed mostly of conglomerates. Where granite was the predominant source of sediment, aggrading fluvial systems formed alluvial fans composed mostly or arkosic sandstones. Rising sea level eventually flooded these isolated valleys, resulting in deposition of facies that record the gradation from non-marine to marine processes.

In other locations in and around the St. Francois Mountains, Lamotte lithologies and facies suggest variable amounts of mixing between sediment sources and depositional processes discusssed above. As the regionally distributed blanket of quartzose sand onlapped the ancestral St. Francois Mountains, various valleys were inundated by quartzose detritus at different times, depending on their elevation. Hence, lithology cannot be used as a reliable criterion for correlation, even across relatively short distances. The relatively abrupt upward gradation from non-marine to marine facies at the top of the Lamotte correlates with rising Cambrian sea level, and is probably the only criterion that can be used for lateral correlation within the Lamotte.

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SEDIMENTARY FACIES, DIAGENESIS, AND ORE DISTRIBUTION IN THE BONNETERRE FORMATION (CAMBRIAN), SOUTHEAST MISSOURI

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ABSTRACT

The Bonneterre Formation is the lowest unit of an Upper Cambrian platform-carbonate sequence that developed around the St. Francois Mts. Major lithological facies in the Bonneterre include an algal stromatolite "reef" and associated grainstone banks that was deposited on the platform edge, a back reef facies consisting primarily of interbedded cryptalgalaminates and lagoonal mudstones that were deposited shoreward of the reef, and an offshore, intrashelf basin facies consisting of interbedded limestones and shales. The platform edge and most of the back reef carbonates have been dolomitized. Much of the dolomitization is believed to have occurred during early diagenesis due to contact with seawater possibly modified by evaporation or mixing with fresh water. The Bonneterre underwent late diagenetic alteration, associated with Mississippi Valley-type (MVT) mineralization, including brecciation, carbonate cementation, and epigenetic dolomitization.

The Bonneterre is the primary host for the lead-zinc-copper ores of the southeast Missouri MVT district. Ore grade mineralization is largely restricted to the platform edge facies although minor and trace mineralization occurs in all of the facies as well as in overlying and underlying units. The chemical and hydrological conditions that lead to ore precipitation in certain facies are not yet clearly understood.

INTRODUCTION

This paper gives a brief description of the facies and diagenetic history of the Bonneterre Formation (Cambrian) of southeastern Missouri and some of the latest ideas concerning the origin of the Bonneterre lithologies and their relationship to mineralization. A large part of this paper is an update of an earlier paper by the authors (Gerdemann and Gregg, 1986) with additional unpublished material. Much of the new information is based on preliminary studies conducted by the authors at the St. Joe Minerals Corporation Geological Research Laboratory in Viburnum, MO between its establishment in 1982 and the sale of the company in 1986. The purpose here is to encourage further research on sediment hosted Mississippi Valley-type (MVT) ore deposits of southeastern Missouri and elsewhere.

Geological Setting

Southeastern Missouri is part of the stable cratonic interior region of North America. The principal geological feature of the area is the Ozark Uplift which is bounded on the northeast by the Illinois Basin, on the northwest by the Forest City Basin, and on the south by the Arkoma Basin and Ouachita Mountains. The regional tectonic setting and the distribution of major MVT districts (including those of southeastern Missouri) are shown in Figure 1.

Major facies relationships in the Bonneterre were first described by Ohle and Brown (1954). Numerous studies since have added greatly to our knowledge of the sediment hosted MVT districts of southeastern Missouri (e.g. Snyder and Odel, 1958; Snyder and Gerdemann, 1968; Gerdemann and Myers, 1972; and especially Society of Economic Geologists, 1977). The Bonneterre Formation, which forms the lower part of an Upper Cambrian platform-carbonate sequence in southeast Missouri, is the primary host of (MVT) lead-zinc-copper sulfide ore bodies of this area. The sediments were deposited in a shallow sea surrounding the St. Francois Mountains (Fig. 1) which are composed mostly of silicic Precambrian volcanic and intrusive rocks. These were areas of high relief and islands during Late Cambrian time. The Bonneterre is conformably underlain by the Lamotte Sandstone, which unconformably rests on the Precambrian basement. The Lamotte consists primarily of quartz arenites, although it commonly is arkosic and/or conglomeratic near Precambrian highs (Houseknecht, this volume). The Bonneterre may rest directly on igneous basement rocks near the Precambrian highs where local "pinch-outs" of the Lamotte occur. The Bonneterre is overlain by interbedded carbonates, and shales of the Davis Formation. The sediments thicken southward and eastward and are locally displaced by normal faults that trend in a general northwesterly direction.

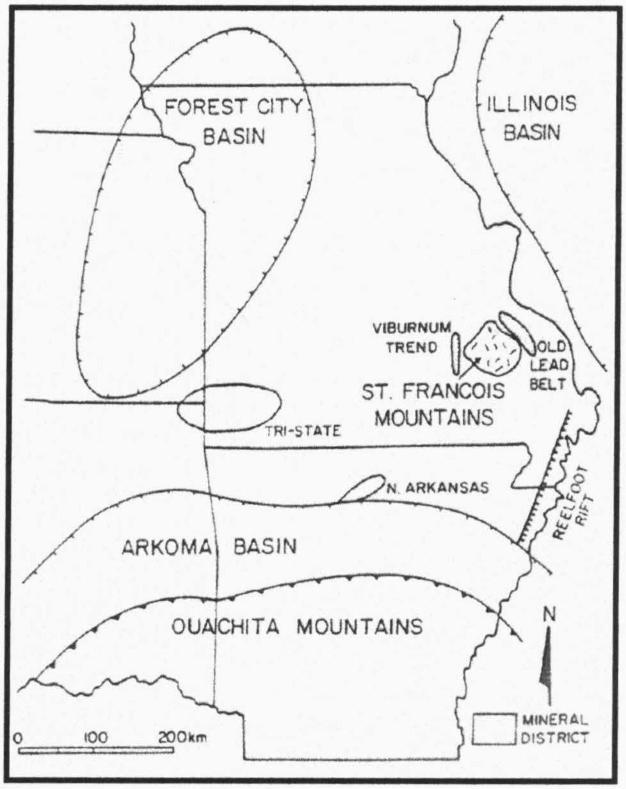

Figure 1. Regional tectonic setting of the southeastern Missouri MVT district showing major sedimentary basins and other MVT districts.

FACIES RELATIONSHIPS IN THE BONNETERRE

Facies relationships in the Bonneterre and nearby units are illustrated in Figure 2. The Bonneterre Formation contains three basic facies: 1) An offshore intrashelf basin facies composed of lime mudstones interbedded with green shales. This facies is discussed in further detail by Palmer and Gregg (this volume; also Gregg, 1985, 1988). 2) A platform edge facies composed of an algal stromatolite "reef"-grainstone bank complex that developed around the St. Francois mountains. 3) A restricted platform "back reef" facies that was deposited adjacent to and within the St. Francois Mts.

The platform edge carbonates can be divided into three informal members which

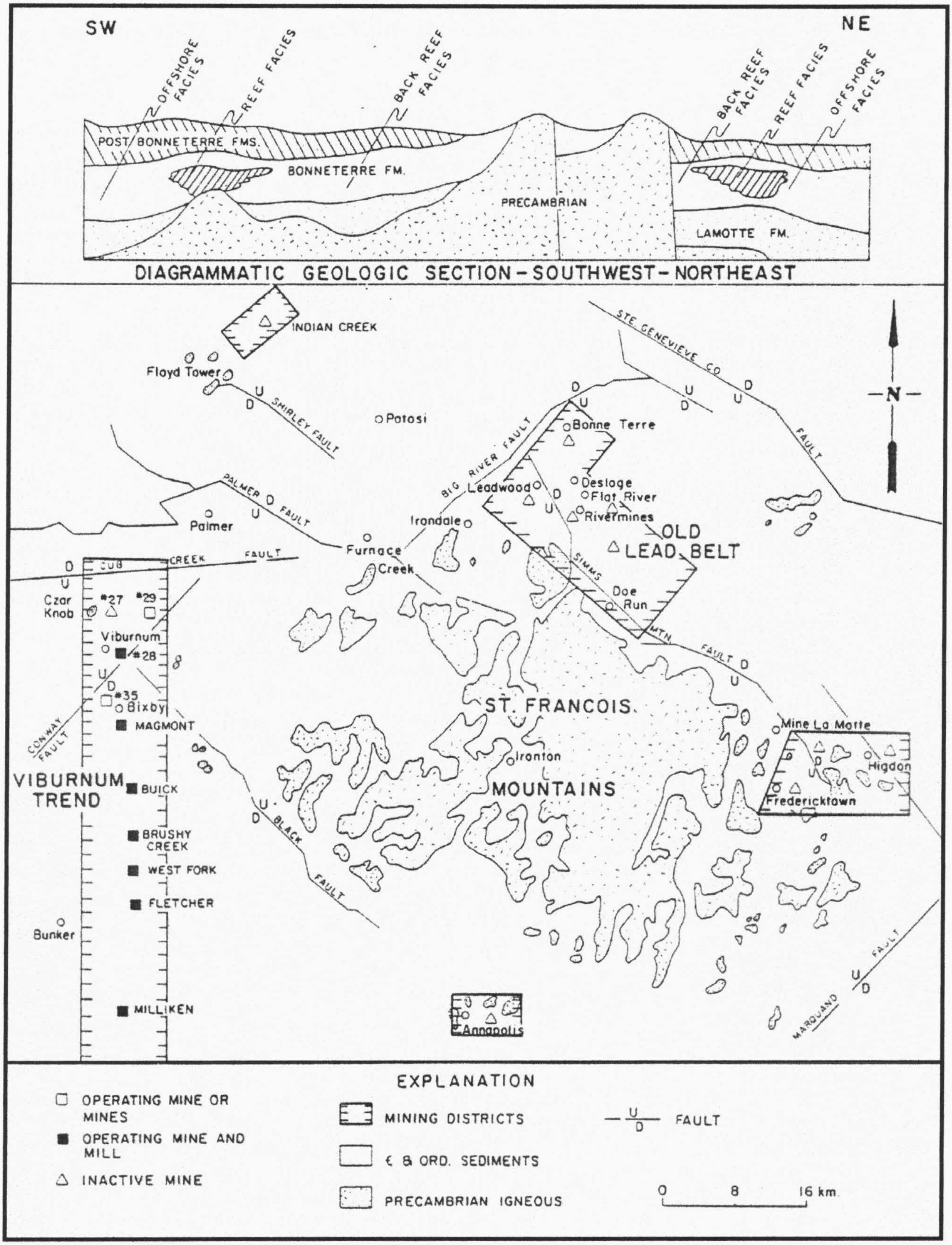

Figure 2. Major geologic features of southeast Missouri showing locations of mines, major towns, and Precambrian outcrops. Diagramatic geologic section shows major facies relationships in the Lamotte and Bonneterre Formations (modified from Snyder and Gerdeman, 1968).

are referred to in ascending order as: the lower Bonneterre, the algal stromatolite bioherm or reef, and the upper Bonneterre. Sedimentation of the platform edge complex began with glauconitic mudstones, packstones and wackestones that were deposited in moderately deep to shallow water, low energy environments. Occasionally, the lower Bonneterre contains oolitic grainstone bars that parallel the ancient shoreline. The oolitic beds represent a higher energy environment, probably above wave base. An algal "reef" or bioherm overlies the lower beds or occasionally rest directly on Precambrian igneous knobs where the lower beds are missing. The algal bioherms are made up of digitate stromatolites and interdigitate oolitic, skeletal, and algal debris (Fig. 3a). Interbedded with the algal bioherms are grainstone channels also composed of oolites, skeletal fragments, and algal clasts.

The reef was probably deposited in the nearshore surf environment as indicated by the presence of interstromatolitic grainstones. The reef-grainstone bank carbonates are predominantly brown, but locally bleached beds are encountered (Fig. 3b), which commonly have sharp upper contacts with brown rock and gradationally pass downward into the underlying brown carbonates. In some cases several bleached sequences may be encountered in a single drill core; they are interpreted as resulting from periodic subaerial exposure that caused oxidation of organic material in the rocks.

The upper Bonneterre contains a thick sequence of oolitic and skeletal grainstones (Fig. 3c) that commonly show prominent cross-bedding. The grainstones were deposited as a series of shoals and offshore bars in a shallow water, high energy setting and are commonly interbedded with wackestones containing soft sediment deformational features such as contorted bedding and slumps, and edgewise conglomerates. The wackestones probably represent lower energy lagoons that existed between the grainstone bars. These beds are followed by transgressive siltstones and mudstones conformably overlain by the interbedded carbonates and shales of the Davis Formation. On the basis of paleontology (Kurtz, 1986), an unconformity has been postulated to exist between the grainstone facies and the overlying transgressive beds.

Shoreward of the platform edge facies a restricted platform or back reef facies was deposited in quiet lagoons and peritidal flats that existed among islands formed by the igneous St. Francois Mts. The back reef, or "white rock", facies, as it is referred to by mining geologists in the region, is largely composed of two distinct lithologic types: bleached lagoonal mudstsones and cryptalgalaminates (Fig. 3d) (Howe, 1968). At some back reef locations, however, bleached digitate stromatolites, grainstones, and other lithologies are observed. The mudstones were deposited in protected, shallow water inter-island lagoons. The cryptalgalaminate beds were deposited in shallow water, as cyanobacterial (blue green algae) mats that were periodically subaerially exposed. The bleached appearance of the back reef rocks is probably due to oxidation during the periods of subaerial exposure. Sandstones composed of quartz, feldspars, and rock fragments eroded from the nearby igneous highs commonly form channel cuts and clastic wedges that are interbedded with the carbonates (see Houseknecht, this volume).

DOLOMITIZATION

The platform edge facies of the Bonneterre, including the lower Bonneterre, algal bioherms, and upper Bonneterre have been pervasively dolomitized. The back reef beds, with the exception of some of the lagoonal mudstones have also been dolomitized. Either evaporative reflux (Adams and Rhodes, 1960) or mixing zone dolomitization (Badiozamani, 1973; Folk and Land, 1975) mechanisms may be used to explain most of the dolomitization (Fig. 4). A source of hypersaline brines may have been the back reef facies if evaporite conditions were

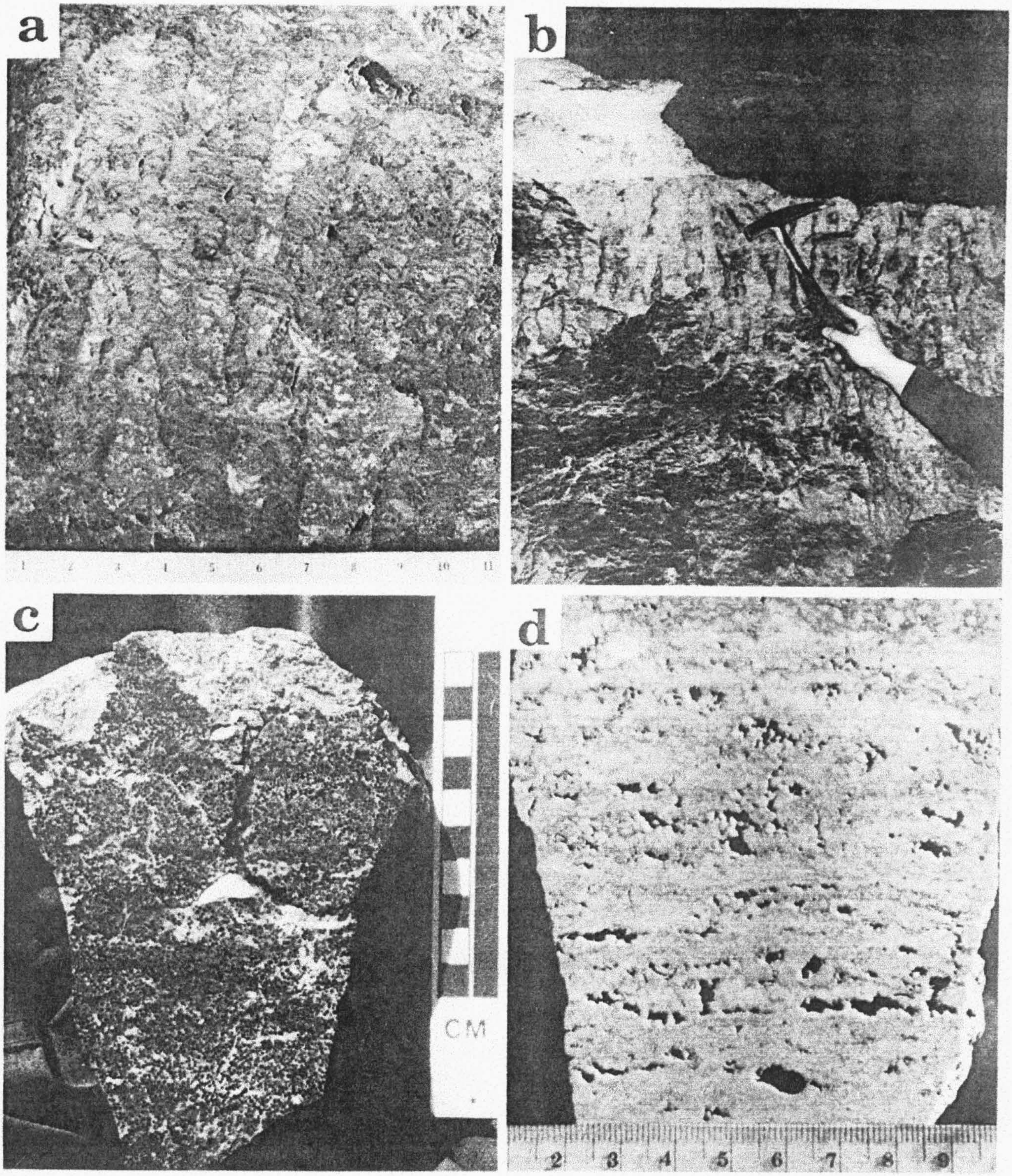

Figure 3. Lithofacies of the Bonneterre Formation: a) Polished slab showing digitate stromatolites from the platform edge facies in the Viburnum 27 mile; scale in inches. b) Contact between a bleached digitate stromatolite bed and an overlying brown grainstone bed in Fletcher mine. c) Polished slab showing dolomitized oolitic grainstone from the platform edge facies in the Casteel mine; scale in centimeters. d) Polished slab showing dolomitized cryptalgalaminates from the back reef facies of the Bonneterre; scale in inches.

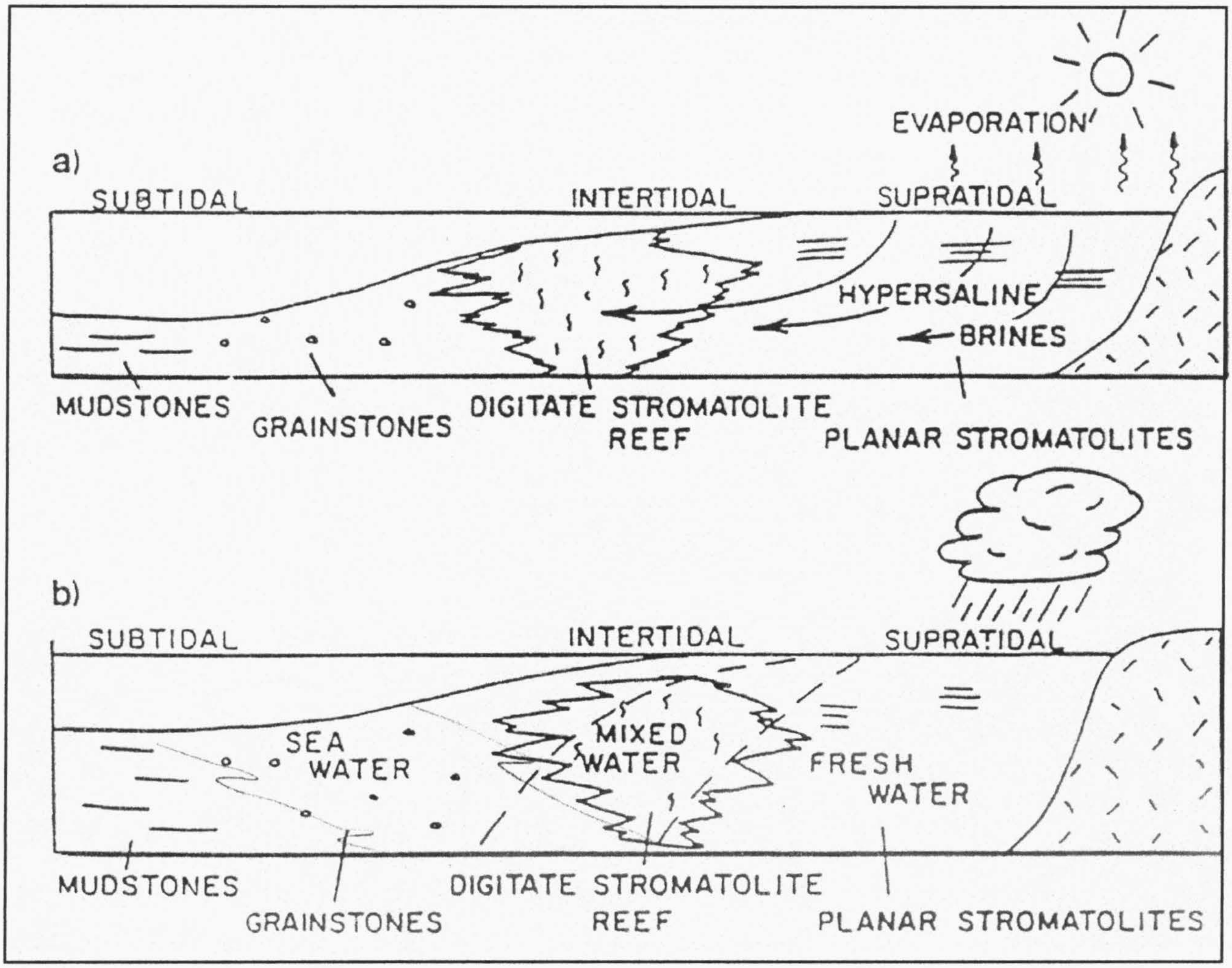

Figure 4. Possible early diagenetic mechanisms for the dolomitization of the Bonneterre Formation: a) Evaporative reflux model and b) dorag or mixing zone model.

widespread there. However, direct evidence for evaporite conditions, such as gypsum or halite molds, have not been found in the Bonneterre. Additionally, structures such as tepees and solution breccias, which are common in hypersaline conditions, are absent in the Bonneterre back reef. A mixing zone mechanism may be postulated for the reef-grainstone facies but the origin of the dolomites in the back reef facies remains a problem. Petrographic and stable carbon and oxygen evidence suggest that early diagenetic dolomite in the back reef facies formed from fluids near Cambrian seawater composition, possibly slightly modified by evaporation (Gregg and Shelton, in preparation). A similar mechanism was postulated for the formation of Holocene dolomites in supratidal sediments on Ambergris Kay, Belize (Mazzulo et al., 1986).

Understanding the origin of the Bonneterre dolomites is complicated by the epigenetic hydrothermal events associated with MVT mineralization. Many, if not most, of the early dolomites appear to have been texturally and geochemically altered, even where far removed from known ore bodies, making interpretation of early diagenetic events difficult (Gregg, 1985; Gregg and Shelton, in preparation). The late mineralizing event may also have resulted in dolomitization of beds that had been unaffected by early diagenetic dolomitization.

BRECCIATION, CEMENTATION, AND POROSITY EVOLUTION

Brecciation is usually associated with carbonate hosted MVT mineralization (Anderson and Macqueen, 1982). Brecciation is an important control on ore distribution in some mines in the Viburnum Trend (e.g. Sweeney et al., 1977). However, almost all of the ore east of the St. Francois Mts. and a large percentage of the ore in the Viburnum Trend (Fig. 2) is disseminated and its distribution controlled by facies relationships (see discussion below). Possibly carbonate dissolution, associated with brecciation, increased porosity and permeability allowing increased circulation of fluids during some stages of mineralization. Limited karst development is thought to have occurred in the Bonneterre prior to mineralization in southeastern Missouri. The karst may have served as conduits for epigenetic brecciation accompanying mineralization in the Viburnum Trend subdistrict (Voss et al., in press).

Epigenetic dolomite cement was precipitated, concurrently with sulfide minerals, in southeastern Missouri. The dolomite cement displays a distinctive cathodoluminescent (CL) growth stratigraphy (Fig. 5) that has been correlated throughout the mineral district and southern Missouri (Voss and Hagni, 1985; Gregg, 1985); Rowan, 1986; Voss et al., in press). Dissolution surfaces visible in the cement using CL can be correlated with postulated early karst and the later periods of brecciation (Voss et al., in press). CL petrography has revealed that the cement occurs in virtually all pore space in the Bonneterre, including microscopic intercrystalline porosity and much of the fracture porosity. Isotope and trace element data from individual CL growth zones and host replacement dolomite suggest that the dolomite cement was precipitated by distinct pulses of fluids (Braunsdorf and Lohmann, 1983; Frank and Lohmann, 1986), which probably came from southern (Arkoma) as well as northern (Illinois) basinal sources (Gregg and Shelton, 1989). CL petrography has also revealed that the same epigenetic dolomite cement is a volumetrically important open space filling in carbonate units throughout southern Missouri and northern Arkansas, occurring as high in the section as the Lower Ordovician (Gregg, 1985 and Rowan, 1986). This indicates that the mineralizing fluids permeated rocks far removed from sites of sulfide precipitation and that the event was regional in extent rather than restricted to a few mining districts where sulfide minerals occur in abundance.

Following dolomite cementation calcite was precipitated in open spaces, throughout southeastern Missouri, during one of the last pulses of basinal fluid. Druses of large

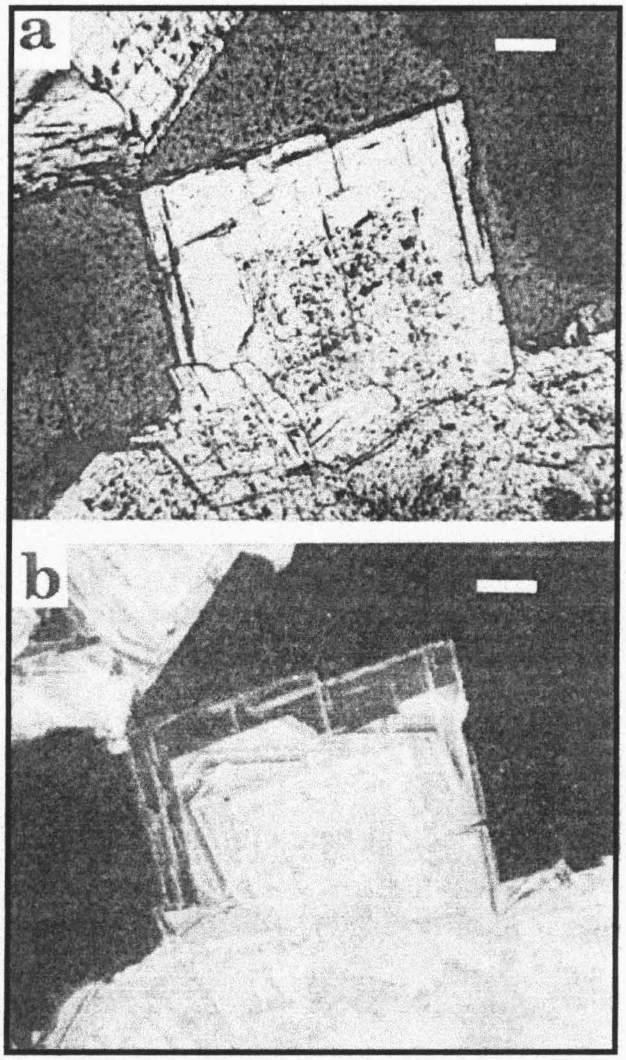

Figure 5. Dolomite cement from the Viburnum Trend: a) plane light, b) cathodoluminescence showing distinctive growth stratigraphy. Scale bar = 0.1 mm.

(up to 1 m or more) "dogs-tooth" and "nail-head" calcite crystals are commonly found in large cavities in the Bonneterre Formation. Smaller crystals of epigenetic calcite cement, although not as common as epigenetic dolomite cement, are encountered, filling vug and intercrystalline porosity throughout southeastern Missouri.

Primary porosity in carbonate rocks commonly ranges from 40% to 70% (Bathurst, 1976). Presumably porosity and permeability was high in the Bonneterre prior to mineralization, in order for the unit to transmit the large volume of fluid necessary for ore emplacement. This, despite early diagenetic pressure solution and cementation. The few petrophysical measurements that have been made on the Bonneterre indicate that porosity and permeability is now low (Perry, 1958; Ellison, 1977). Porosity is generally less than 5% (Fig. 6) and permeability is mostly less than 2 millidarcies (Fig. 7). Sulfide minerals occlude some of the porosity in and near ore bodies, but this represents only a small fraction of the volume of the Bonneterre. Most of the original porosity as well as porosity created by dissolution appears to have been destroyed by precipitation of carbonate (particularly dolomite) cement. The relationship between MVT mineralization and porosity development due to carbonate dissolution, as well as porosity reduction due to precipitation of epigenetic carbonate cements, should be of interest to petroleum geologists working in regions that have been affected by basinal water as has southern Missouri.

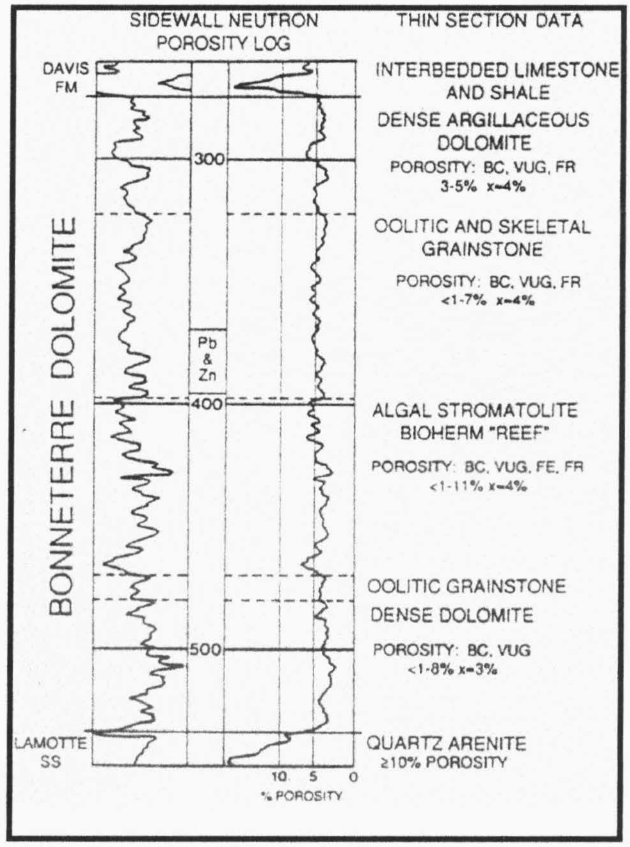

Figure 6. Gamma Ray-Sidewall Neutron Porosity log through the Bonneterre Dolomite in the Viburnum Trend. Porosity scale is adjusted for dolomite. Ore grade sulfide mineralization occurs just above the 400 ft. depth line. Sulfide mineralization eslewhere in the section is minimal. Thin section data on right describes general lithology and porosity types using the classification of Choquette and Pray (1970). Porosity types where determined by examining both thin sections and several subsurface cores. Precent porosities were determined by point counting 200 or more points on `50 thin sections representing all of the described lithologies.

RELATIONSHIP OF FACIES TO ORE MINERALIZATION

MVT mineralization is largely restricted to dolomitized facies of the Bonneterre Formation, the lower parts of the Davis Formation (usually associated with fractures), and to the upper portions of the Lamotte Sandstone, usually in "dirty" or arkosic facies near its pinch out onto Precambrian basement. Nearly all ore is in the Bonneterre Formation. It occurs from the base to the top of the formation and in all dolomitized lithologies. The preferred stratigraphic position varies with geographic location. The platform edge stromatolitic reef-grainstone facies is host for the vast majority of ore in the Viburnum Trend, the Old Lead belt, and Indian Creek mine areas.

Figure 8 is a detailed east-west section across the Viburnum Trend, located about midway between the Fletcher and Brushy Creek mines, showing the major facies. Figure 9 shows the location of the major facies

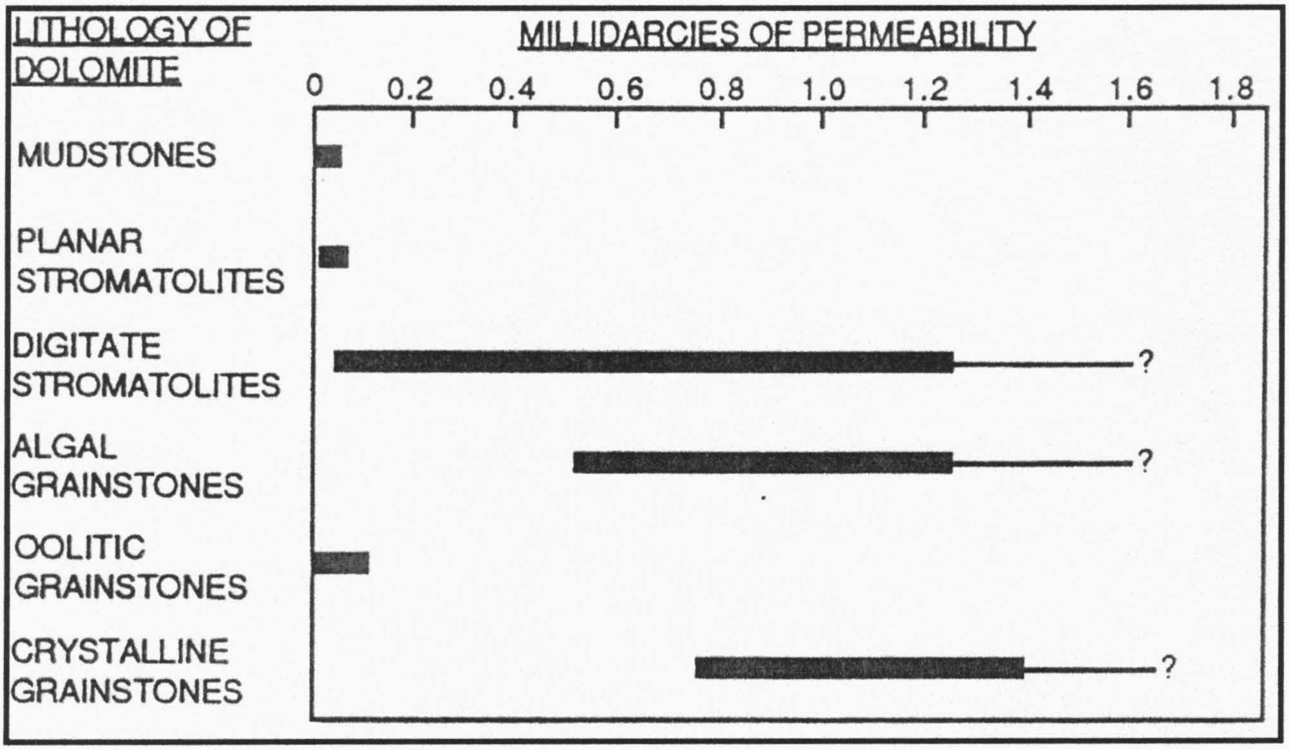

Figure 7. Permeability ranges in Bonneterre dolomite lithologies. Values are calculated from data of Perry (1959). These data were collected on a "homemade" permeameter and not originally expressed in millidarcies. They should therefore, be regarded as approximate.

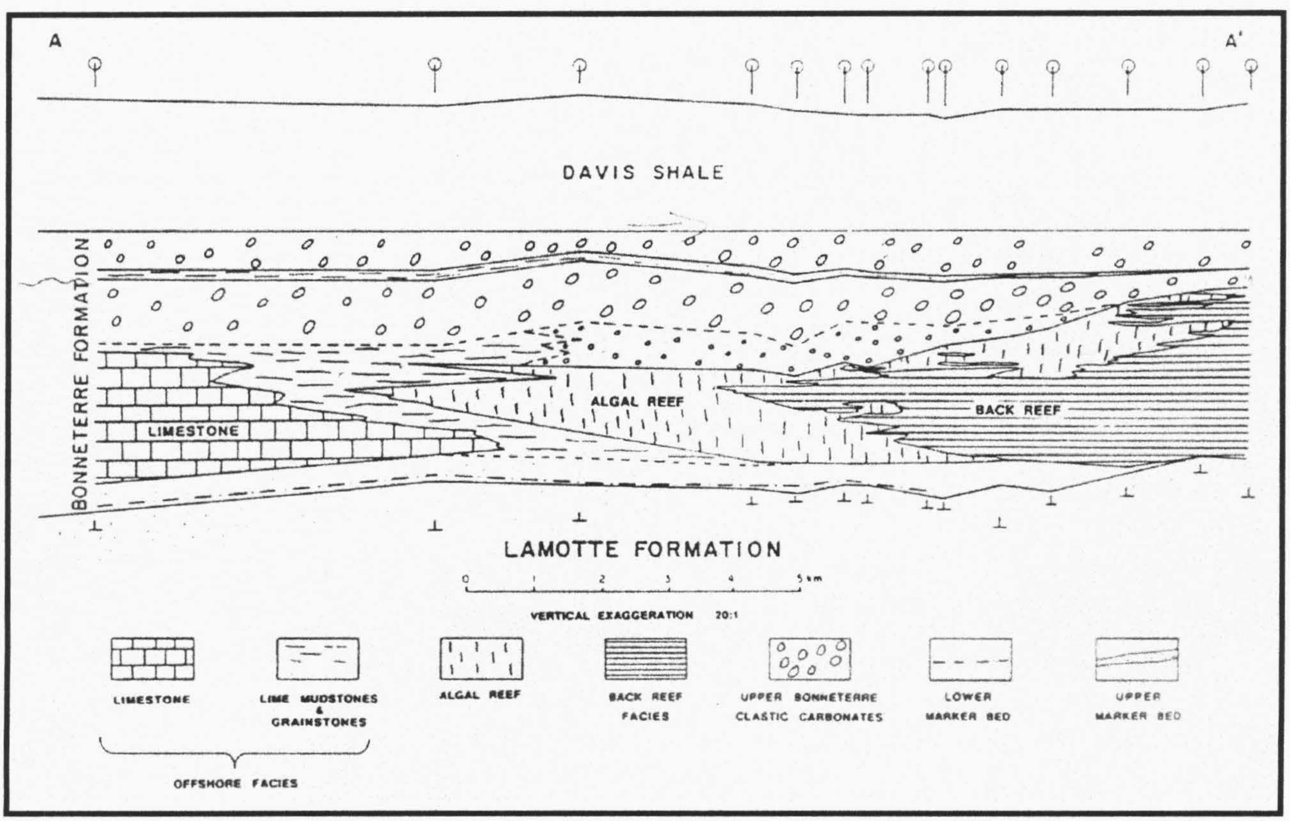

Figure 8. Detailed section across the platform edge facies of the Bonneterre Formation showing the relationship between major lithological types (modified from Gerdemann and Myers, 1972).

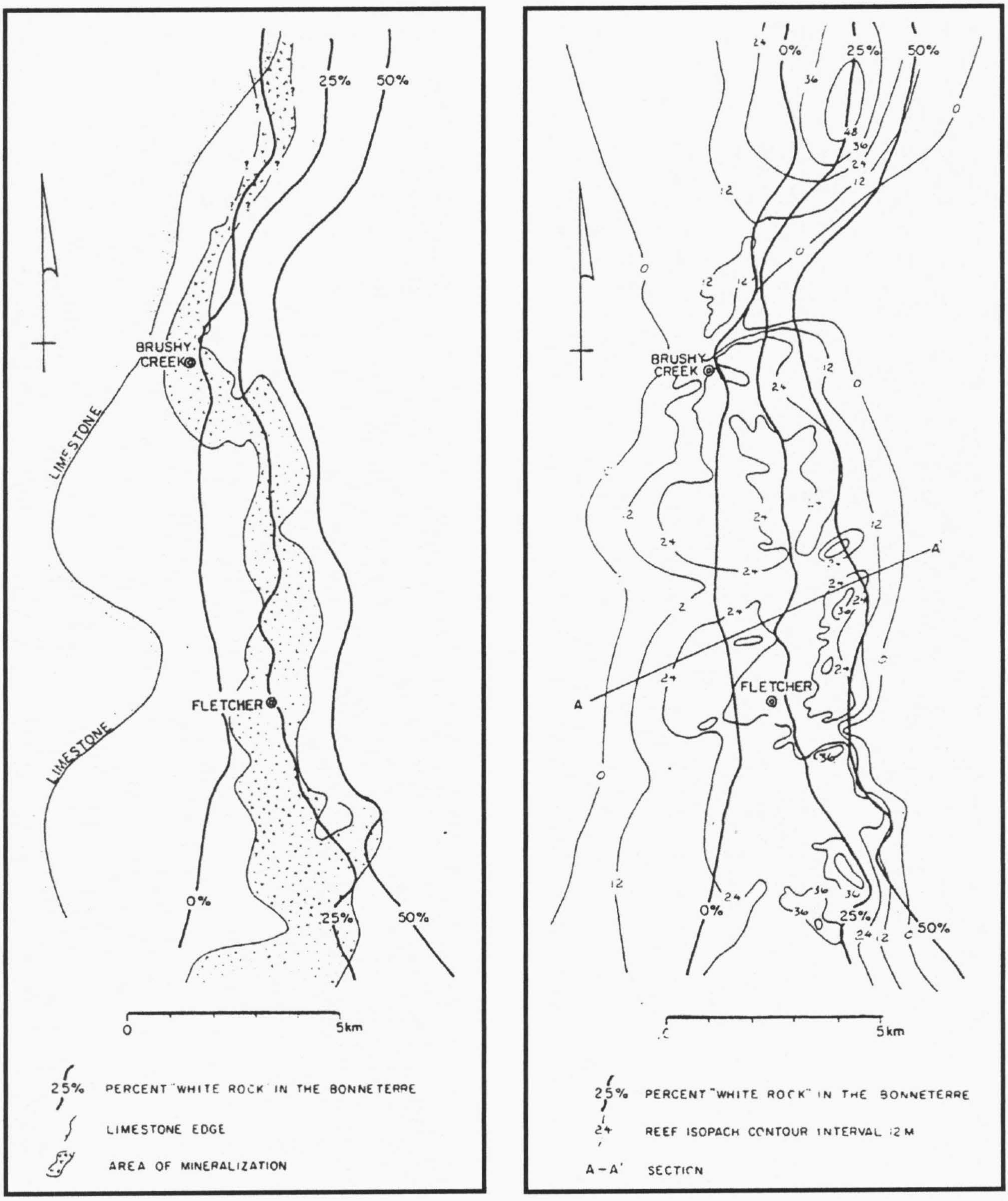

Figure 9. a) Map showing position of mineralization, offshore facies (limestone), and back reef facies (expressed as percent "white rock") within the Bonneterre Formation. b) Map showing "white rock" pinching out against stromatolitic reef within the Bonneterre Formation. Section A-A' is shown in Figure 8 (from Gerdemann and Myers, 1972).

along strike, as well as the distribution of mineralization. The relationship of mineralization to facies patterns illustrated here represents the predominant regional situation in southeast Missouri. There are significant variations in detail in different locations, but the major relationships persist regionally.

Small tonnages of ore-grade mineralization are in the back reef "white rock" facies. In the Annapolis, Missouri area, 29,000 tons of lead metal were produced between 1915 and 1931 (Wharton, 1975) from the "white rock" facies. In addition, there are numerous other locations in southeastern Missouri where scattered trace mineralization and even small ore grade concentrations of mineralization are in the back reef facies, but none have been or promise to be significant ore producers.

In the main production areas, ore occurs in certain preferred stratigraphic positions. In the Mine Lamotte-Fredericktown area ore is restricted to the lower beds of the Bonneterre and upper Lamotte Sandstone. In the Flat River-Leadwood-Bonneterre area, it is distributed throughout the entire Bonneterre Formation and upper Lamotte. In any particular mine or part of a mine, in this very large area (referred to collectively as the 'Old Lead Belt"), a particular stratigraphic position may be the favored ore horizon. Overall, however, most ore was mined from beds below the reef. In the Viburnum Trend, ore is generally restricted to beds from mid-reef to the top of the Bonneterre. At the Indian Creek mine most ore was mined from the reef-grainstone facies, particularly along the steeply dipping reef front where algal stromatolite bioherms intertongue with oolitic grainstones. At the northeastern end of the mine, ore was confined to the lower Bonneterre and the upper portion of the Lamotte Sandstone.

In most cases it is undetermined why a particular stratigraphic position was more favorable for mineralization. There is evidence that ore fluids traveled upward and laterally (Viets et al., 1983; Gregg and Shelton, in press). Some beds with limited permeability acted as barriers to upward movement, and ore is present only beneath these units, except where they are fractured or brecciated. In such occurrences ore is distributed in the fractures and breccia and often spreads out in overlying unbrecciated rocks.

The importance of proximity of the back reef, or "white rock" to ore has been stressed by some authors (Davis, 1977). However, important examples of ore deposits, such as the Indian Creek Mine, many miles from the "white rock" area greatly diminishes its importance to ore genesis. Indian Creek, however, is associated with a platform edge, algal stromatolite reef-grainstone bank. The reason for the important association of ore and mineralization with the platform edge facies is unknown. If ore fluids migrated through the Lamotte, the increased permeability of this facies of the Bonneterre, compared to the shaley offshore facies, would permit much greater fluid movement. However, this fact does not explain why ore minerals were preferentially precipitated here rather than in other rocks of the Lamotte or Bonneterre. Because the relationship is so strong, it is suggested that a complex relationship between hydrologic and chemical conditions in these rocks caused localization of mineralization. The nature of these conditions is, as yet, unknown.

SUMMARY

The Bonneterre Formation (Cambrian) was deposited on a carbonate platform surrounding the Precambrian igneous St. Francois Mts. in southeastern Missouri. The Bonneterre is composed of three major facies which are, from nearshore to deep water: a back reef, restricted platform facies, an algal bioherm (reef) grainstone, platform edge facies, and a deeper water intrashelf basin facies. The platform edge and back reef facies were pervasively dolomitized during both early diagenetic and epigenetic events.

The Bonneterre is the primary host of the Mississippi Valley-type lead-zinc-copper deposits of southeastern Missouri. These ores probably were precipitated by fluids expelled from nearby sedimentary basins. Ore grade mineralization is mostly restricted to the platform edge facies, although minor and trace mineralization occurs throughout southeastern Missouri.

ACKNOWLEDGEMENTS

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SEDIMENTOLOGY AND DIAGENESIS OF THE BONNETERRE DOLOMITE IN THE VIBURNUM TREND, SOUTHEAST MISSOURI

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ABSTRACT

The Bonneterre Dolomite of the Viburnum Trend consists of forereef, stromatolitic reef, and back-reef facies that record transgression, regression, and transgression. Shallow-water features are abundant. Stabilization of presumed aragonite and multiple dolomitization episodes have resulted in complex fabrics. Effective porosity appears to be facies controlled, but local differences reflect discontinuous dolomitization.

INTRODUCTION

Gerdemann and Myers (1972) were the first to delineate sedimentary facies of the Bonneterre Dolomite in a comprehensive manner. Since their landmark paper, a number of theses and published articles have contributed to further understanding of this important sulfide-host-rock. The purpose of our paper is to draw together some of the information developed by students at the University of Missouri, specifically reports dealing with Bonneterre sedimentology, dolomitization, and porosity development. Details can be examined in theses by Lyle (1973), Ellison (1977), and Medary (1986).

GENERAL GEOLOGY

The Bonneterre is a complex limestone-dolostone unit within the Upper Cambrian of Missouri, which, like other North American Cambrian cratonic successions, is a transgressive interval resting upon rocks of Precambrian age (Fig. 1). In the vicinity of the St. Francois Mts. the underlying Lamotte Sandstone pinches out on the flanks of erosional highs within the Precambrian igneous terrane so that, in places, Bonneterre carbonates rest directly upon Precambrian rocks. Bonneterre and other Paleozoic sedimentary rocks dip outward in all directions from the St. Francois Mtns., the structural core of the Ozark Dome. Surface exposures of the Bonneterre are dolostone, with the exception of a restricted up-dip facies called the Taum Sauk Limestone. Within the subsurface Bonneterre dolostone generally grades down-dip into limestone, but the exact distribution of limestone vs. dolostone depends in part on the occurrence of sedimentary facies. Algal stromatolites, oolites, intraclasts, mudcracks, disconformities, and cross-beds reflect shallow-water deposition for surface and shallow subsurface parts of the Bonneterre.

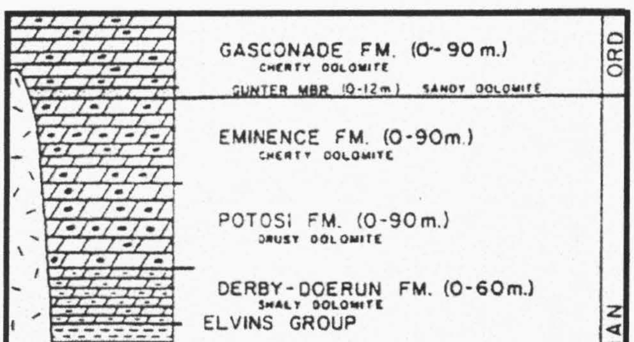

Figure 1. General stratigraphy of Precambrian and lower Paleozoic rocks of southeast Missouri (from Houseknecht and Ethridge, 1978).

SEDIMENTOLOGY

As might be expected from its economic importance, much has been written over the past several decades about the general stratigraphy and sedimentology of the Bonneterre; and, there is a sizeable body of literature addressing its history of mineralization. However, surprisingly few papers have dealt with the petrography of this important unit. As late as 1973, the thesis by Lyle, which was later published in Economic Geology, was the first to illustrate Bonneterre rocks in thin-section.

In southeast Missouri's sulfide district (Fig. 2), the Bonneterre consists of three

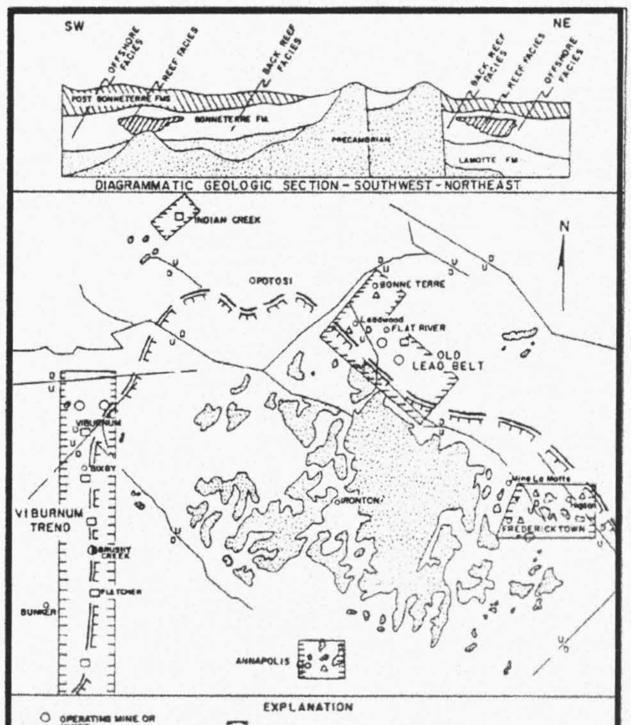

Figure 2. General geology of the sulfide district of southeast Missouri (from Gerdemann and Myers, 1972). Broad subdivisions of the Bonneterre in this area include offshore facies, reef facies, and black reef facies.

dominant facies disposed in symmetrical fashion about the St. Francois Mtns.: the offshore facies, the reef facies, and the back reef facies. Lyle (1973, 1977), subdivided the Bonneterre of the Viburnum Trend even further (Fig. 3). Lyle's cross-section demonstrates a Late Cambrian transgression, followed by a regression, followed by a second transgression. The resultant facies mosaic is most evident in the wedge-like distribution of the stromatolitic boundstone of figure 3.

DIAGENESIS

Bonneterre sediments exhibit the effects of conversion of aragonite to calcite and of dolomitization. Petrographic evidence indicates a complex history of diagenesis, with some dolomite being later than some calcite and other dolomite being earlier than other calcite. An example of the latter is poikilotopic calcite cement that occurs in what was earlier a porous idiotopic dolostone. In this case the calcite cement is clearly younger than the dolomite. Dedolomitization favored the cores of dolomite rhombohedra. Microprobe study of neighboring dolomite rhombs without dedolomite suggests that the cores of dolomite rhombohedra were more susceptible to dedolomitization because of their higher iron content. Figure 4 is a diagram (modified from Lyle, 1977) illustrating the disposition of diagenetic facies within the Bonneterre of the Viburnum Trend. Distributions of the poikilotopic calcite cement and the dedolomite suggest that the two reflect the activity of a common fluid. That is, it appears that the fluid has emplaced the

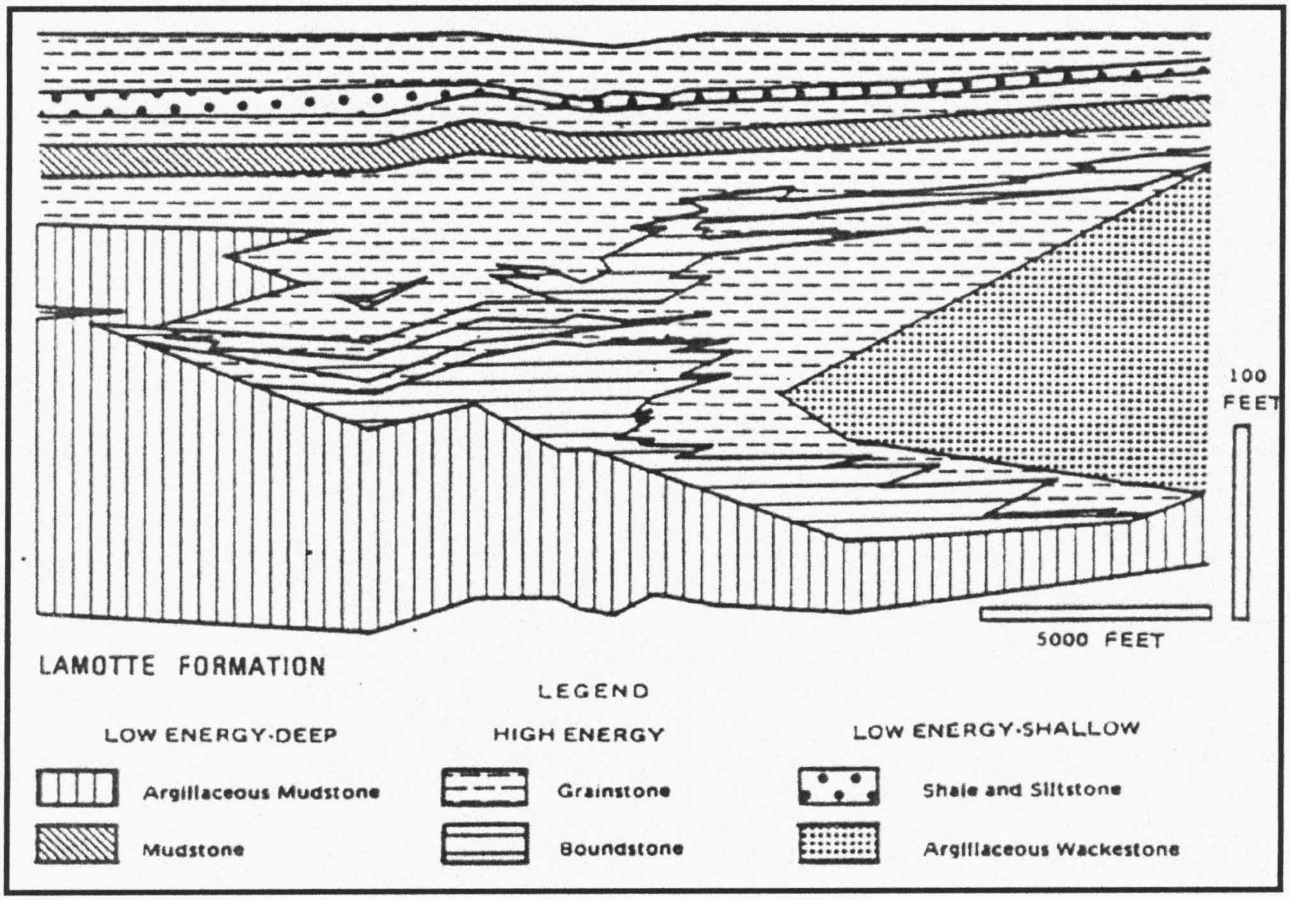

Figure 3. West to east cross-section across the Viburnum Trend (from Lyle, 1977). This section is based on 9 cores. The wedge-like distribution of the stromatolitic boundstone best reflects a transgression followed by a regression followed by a second transgression.

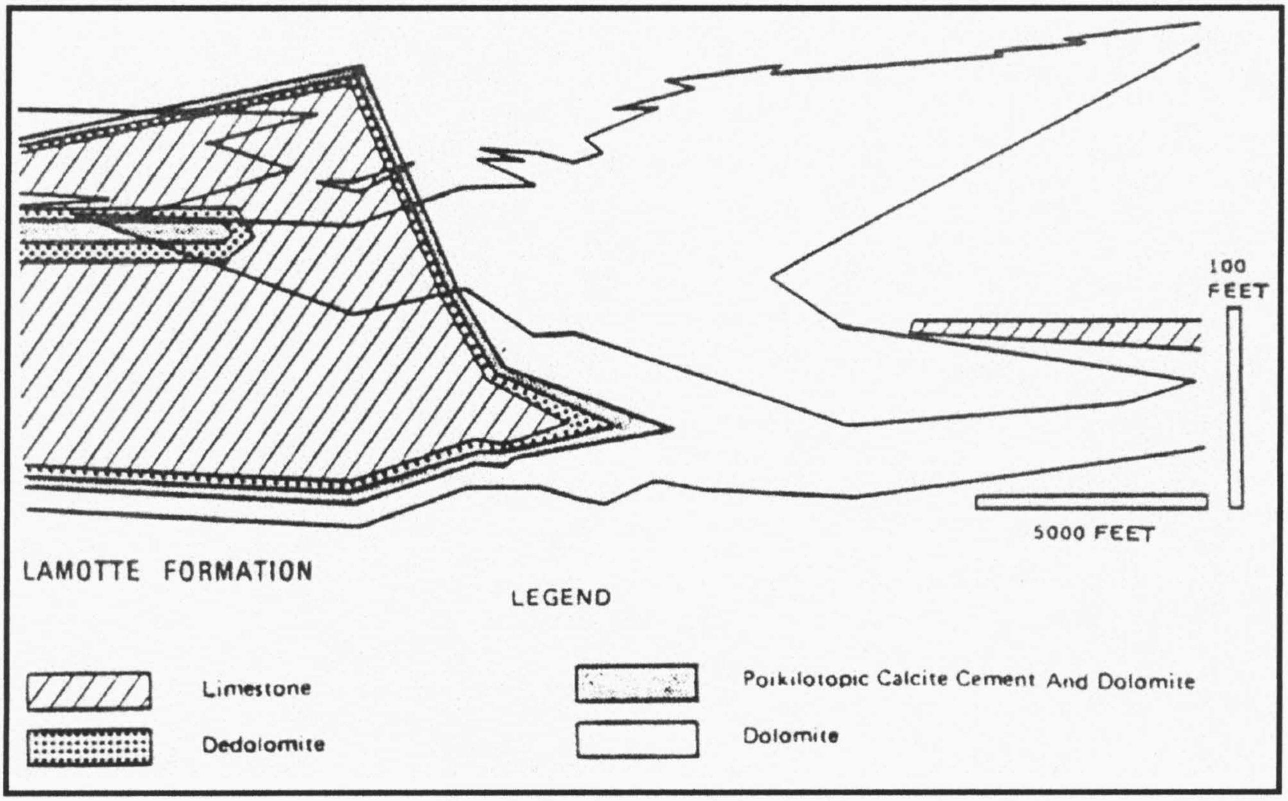

Figure 4. Distribution of diagenetic facies within the Bonneterre of the Viburnum Trend (modified from Lyle, 1977).

poikilotopic calcite cement did, at the same time, dedolomitize the centers of contiguous dolomite rhombohedra.

REDOLOMITIZATION

Not only does the Bonneterre reflect a complex history of calcite diagenesis and dolomitization but it also records an interesting case of redolomitization. Medary (1986) showed through careful petrographic study that an earlier ferroan dolomite was redolomitized by a non-ferroan event. The compelling evidence consists of ghosts of ferroan dolomite crystals "floating" within non-ferroan dolomite crystals.

POROSITY DEVELOPMENT

Ellison (1977) investigated the Bonneterre of the Viburnum Trend with a mercury porosimeter in an effort to delineate the distribution of effective porosity. Specifically, he sought to determine to what extent Bonneterre porosity is coincident with sedimentary and diagenetic facies delineated by Lyle (1973). Table 1 shows the range of porosities that exists among the dominant sedimentary facies of the Bonneterre.

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Facies	Lithology	Porosity Type	Porosity Value (%)
backreef	coarsely crystalline dolostone	mesointercrystal	3-13
reef	digitate stromatolite	mesointerparticle	<5
forereef	fossiliferous dolomitized mudstone	microinterparticle	<4
	dolomitized mudstone	channel	<5
	fossiliferous dolomitized mudstone	breccia	9-15
offshore-shelf	oolitic dolomitized grainstone	oomoldic-vug	4-14
	dolomitic quartz siltstone	microintercrystal	11-14
	dolomitized mudstone-grainstone	shelter-vug	7-11
	lime mudstone	microinterparticle	<2
	lime grainstone-packstone	oomoldic	2-4

Table 1. Distribution of porosity within Bonneterre (Ellison, 1977). Terminology from Choquette and Pray (1972).

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LITHOFACIES OF THE EAU CLAIRE (BONNETERRE) FORMATION IN ILLINOIS

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ABSTRACT

The Bonneterre Dolomite (Eau Claire Formation in Illinois) has produced hundreds of millions of tons or ore spatially related to Precambrian knobs in southeastern Missouri adjacent to southern Illinois. Isopach maps illustrate pinchouts of the Eau Claire Formation and underlying Mt. Simon Sandstone against Precambrian paleotopographic highs in southern and western Illinois. Stratigraphic pinch-outs and limestone-to-dolomite facies changes present in Illinois are similar to those known to be associated with ore deposition in southeastern Missouri. Exploratory drilling will doubtless help to locate the position of the pinch-outs and facies changes.

An abrupt increase in regional thickness of the Eau Claire Formation is suggested along the eastern, downwarped flank of the Du Quoin Monocline in south-central Illinois. The Eau Claire consists of a siliciclastic-rich facies in the northern half of the state and a predominantly carbonate-rich facies in the southern half. Dolomite is generally the carbonate mineral that occurs in the silici-clastic facies. Limestone is the dominant rock type in the area south and east of the Sparta Shelf. All penetrations on the Sparta Shelf of southwestern Illinois encounter the dolomite facies of the Eau Caire where it lies directly on or a short distance above the Precambrian crystalline basement. The limestone facies of the Eau Claire may be preserved off-structure or up-section from the pinchout of the Mt. Simon (Lamotte) Sandstone in the Sparta Shelf region.

INTRODUCTION

Purpose

The Eau Claire Formation in Illinois is considered the stratigraphic equivalent of the Bonneterre Dolomite of Missouri and some adjacent states (Buschbach, 1975; Fig. 1). Hundeds of millions of tons of ore hosted by the Bonneterre have been mined in southeastern Missouri. Much of this ore, especially in the Old Lead Belt, was situated near Precambrian paleotopographic highs where the facies boundary between dolomite and limestone and windows through the overlying confining shales of the Davis Formation permitted metal-bearing fluids to migrate upward. As a first step in evaluating the potential for the occurrence of similar ore deposits in Illinois, a set of lithofacies maps and an isopach map were compiled for the Eau Claire Formation. Examination of these maps indicates several areas where more detailed work to evaluate base-metal potential may be warranted.

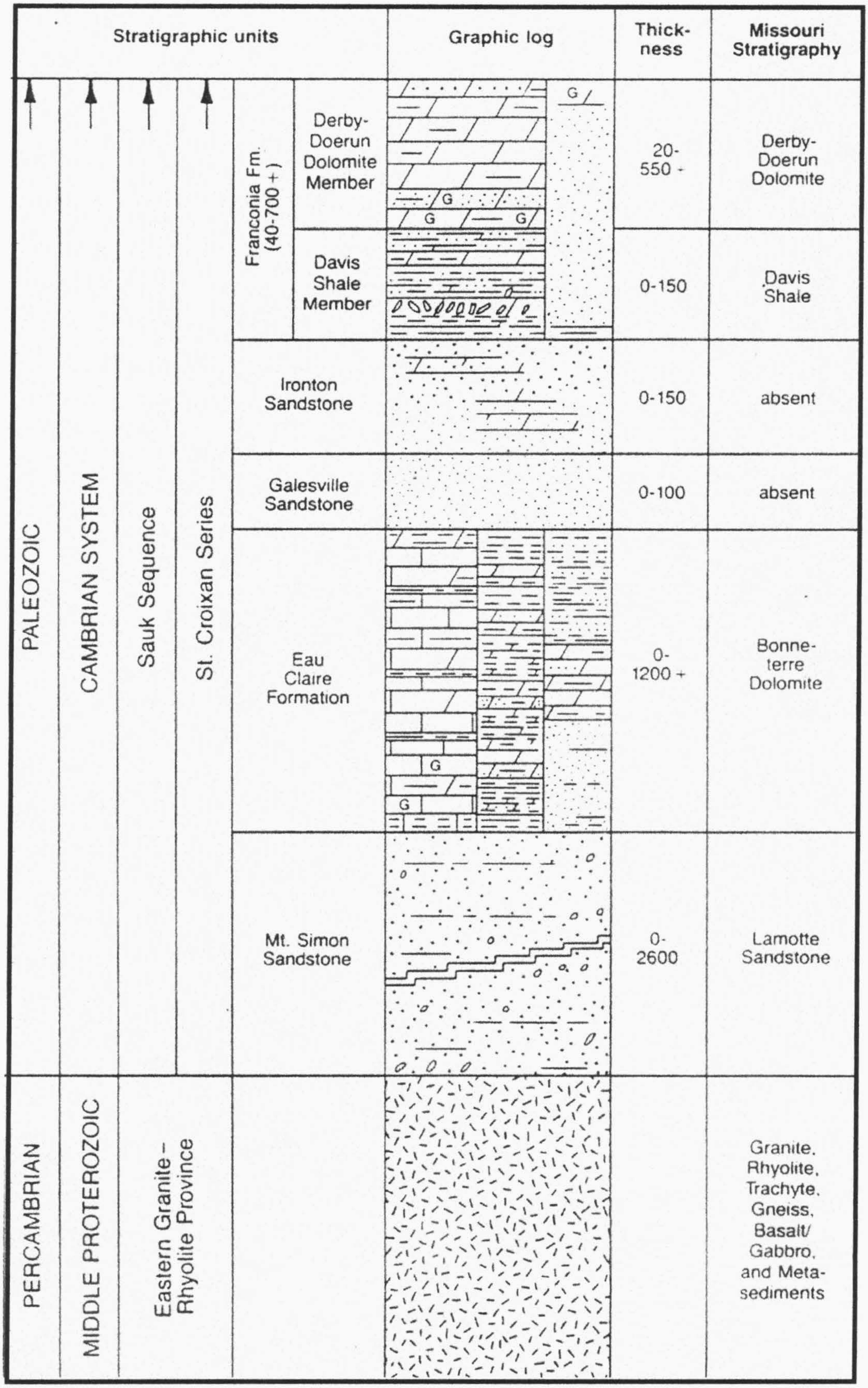

Figure 1. Columnar section of the Eau Claire Formation and related units in Illinois (Modified from Buschbach, 1975).

Background

The Eau Claire Formation was named for the city of Eau Claire, Eau Claire County, Wisconsin, where 100 feet of fossiliferous, partly shaly, thin-bedded, fine-grained, quartz sandstone constitute the type section (Ulrich, 1914). The Eau Claire Formation, as used by Buschbach (1964, 1975), occurs in the subsurface throughout all of Illinois, except an isolated location in Perry County where a knob of Precambrian crystalline rock formed an island in the Cambrian sea until post-Eau Claire time. The Eau Claire conformably overlies and is gradational with the coarser, unfossiliferous Mt. Simon Sandstone, except where Mt. Simon was not deposited and the Eau Claire was deposited directly on Precambrian crystalline basement. In approximately the northern half of Illinois where it can be identified, the Eau Claire Formation underlies the Galesville Sandstone, an unfossiliferous, fine- to medium-grained quartz arenite. South of approximately 40° N. latitude, the Galesville grades to a carbonate facies that is included in the upper part of the Eau Claire. At the type locality of the Galesville Sandstone, and elsewhere in the Wisconsin and the upper peninsula of Michigan, the contact between the Galesville and Eau Claire is unconformable (Ostrom, 1970), but, in Illinois, the relationship between the two formations is often lithologically gradational, and considered to be conformable (Buschbach, 1975).

In the area south and west of the limit of Galesville deposition, the Eau Claire Formation is conformably overlain by the Franconian Formation. In part of this area, the Davis (basal) Member of the Franconia ranges up to 150 feet thick and is composed of silty, finely sandy, argillaceous dolomite (Buschbach, 1975). In southeastern Illinois, the Davis Member was not deposited, and the Derby-Doerun Member rests directly on the Eau Claire (Stevenson et al., 1975).

The type Eau Claire Formation is entirely siliciclastic, whereas the Bonneterre Formation is typically a medium- to fine-grained partly glauconitic and shaly dolomite that is locally a limestone. The name Eau Claire historically has been applied to all facies of these strata in Illinois and will be so applied in this report. The two names have been used for their respective litho-facies in reports on eastern Iowa, northeastern Missouri, and western Illinois (Howe et al., 1972; McKay, 1988). These reports have used cross sections to illustrate the vertical succession of strata and intertonguing relationships of the facies, an essential procedure in determining the proper formation assignment. Because a complete examination of the succession of strata and construction of cross sections are beyond the scope of this report, reassignment of the carbonate lithofacies in Illinois to the Bonneterre Formation must await future studies.

METHODS AND DISCUSSION

An isopach map was prepared using more than sixty penetrations of the Eau Claire Formation (Fig. 2). These are essentially all penetrations of the formation in Illinois, except where numerous injection/withdrawal wells occur in clusters on underground gas-storage structures. In such cases, single wells with the best data available were chosen from each cluster. Lithofacies and thickness data were compiled from sample studies on file in the Illinois State Geological Survey's records. Wireline logs were used to pick formation boundaries and to refine sample-study information.

Eau Claire thickness ranges from less than 200 feet along the Mississippi River in northwestern Illinois to more than 1200 feet in south-central Johnson County in extreme southern Illinois. No other Eau Claire sections have been drilled in areas adjacent to Johnson County that would permit tracing the extent of this thickened

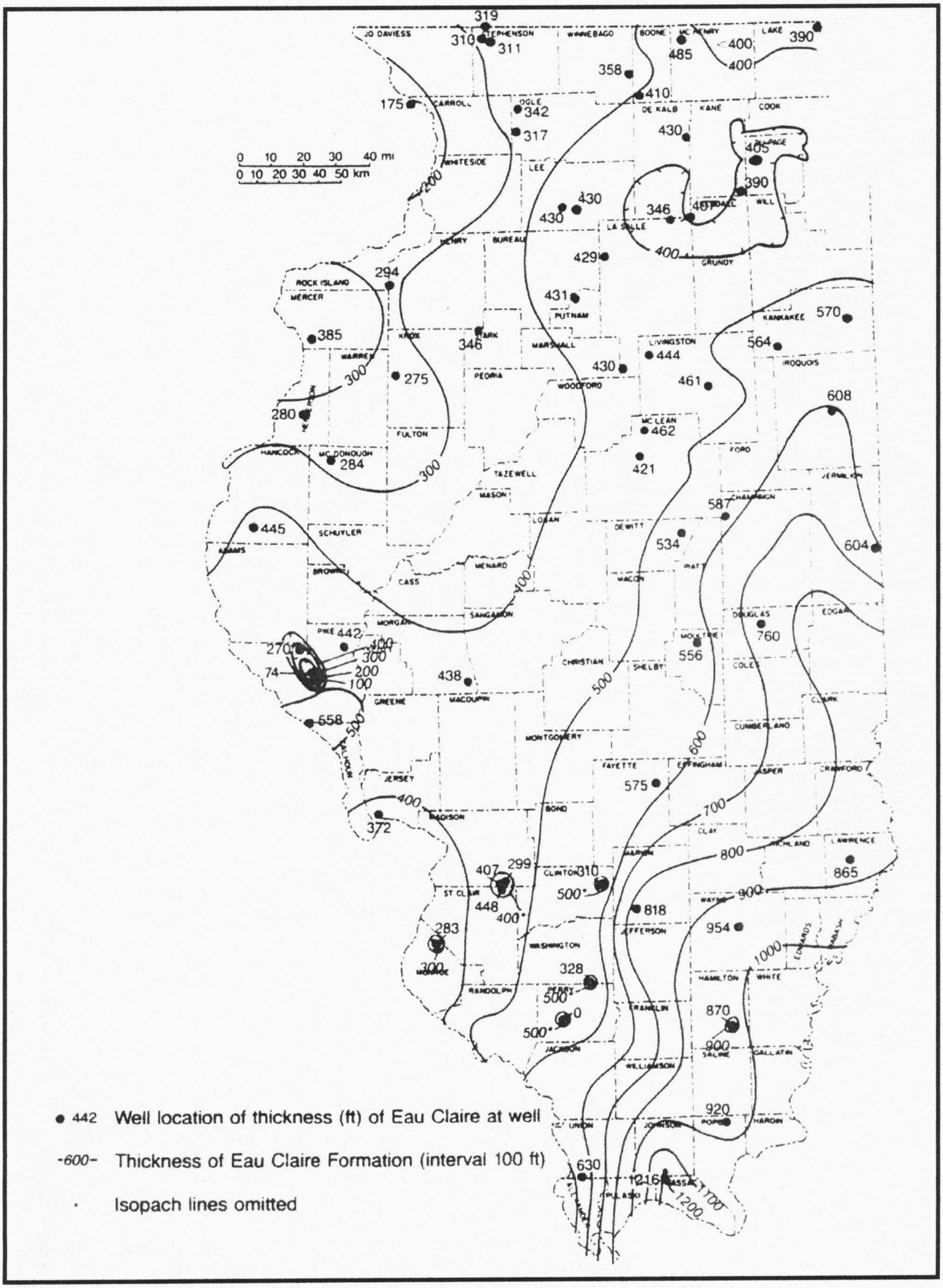

Figure 2. Thickness of the Eau Claire Formation in Illinois (Modified from Buschbach, 1964; 1965).

carbonate section. It appears to continue to thicken into the Rough Creek Graben in western Kentucky. The regional trend of increasing thickness is from northwestern to southeastern Illinois. However, an area of increased thickness in westernmost Illinois is indicated by a well at the northwestern tip of Calhoun County and a few nearby wells. Here the Eau Claire is more than 100 feet thicker than the regional trend. This trend apparently extends into northeastern Missouri from the southern part of the west-central Illinois.

Other anomalous features on the thickness map, mostly in southwestern Illinois, are the thin spots that occur where the lower part and, in one place, all of the Eau Claire pinches out over Precambrian paleotopographic highs. The best documented of these features occurs in southeastern Madison County where the morphology of a paleotopographic high has been demonstrated with three wells (Fig. 3). On the top of this high, the Eau Claire is less than 300 feet thick and rests unconformably on Precambrian basement. The formation thickens to nearly 450 feet to the southwest where it conformably overlies 58 feet of Mt. Simon Sandstone. A third well, which is located between the others, has 407 feet of Eau Claire above 44 feet of Mt. Simon.

Five other wells in western and southwestern Illinois (in Pike, Monroe, Clinton, Washington and Hamilton Counties) penetrated incomplete sections of the Eau Claire resting directly on basement. A sixth well, located in Perry County, has no Eau Claire; the upper part of the Derby-Doerun Member of the Franconia Formation rests directly on Precambrian. The size of these areas is exaggerated for mapability. The Madison County Precambrian knob appears to be less than two miles across. The others are probably similar in scale.

A full section of 818 feet of the Eau Claire overlying Mt. Simon Sandstone is present in the Marion County well (Fig. 2), south-central Illinois just east of the Du Quoin Monocline (Fig. 4). Thickness variations suggest that the monoclinal structure may have been active at this time and exerted some influence on Eau Claire sedimentation. The Eau Claire Formation thins westward across the Fairfield Basin approximately 4 feet per mile in 33 miles between the Wayne County and Marion County wells. West of the monocline it thins approximately 9 feet per mile in the 41 miles from the Marion County well westward to the thickest Madison County test.

LITHOFACIES RELATIONSHIPS

Lithofacies mapping for this study was carried-out according to procedures used in the USGS Strategic and Critical Minerals (SCM) mapping program. Carbonate-to-siliciclastic ratios were partitioned at 0.25:1 (20% carbonate, 80% siliciclastic) and 2.0:1 (67% carbonate, 33% siliciclastic). A 1.0:1 (50% carbonate, 50% siliciclastic) isopleth, not used in the SCM program, has been added to more clearly show where the dominant rock type changes (Fig. 5).

General lithofacies relationships of the Eau Claire in Illinois were illustrated on a map that showed areas of sandstone, siltstone and shale, and dolomite and limestone (Buschbach, 1975). Additional data have permitted the resolution of more details of the facies transition between siliciclastics and carbonates. The results of this study show the same general pattern of lithofacies with siliciclastics being the dominant rock type in somewhat more than the northern half of the state (Fig. 5).

In nearly all areas where siliciclastics are dominant, dolomite is the associated carbonate. The only limestone documented within the area dominated by siliciclastics occurs interbedded with dolomite in the Lombard Member of the Eau Claire Formation in northeastern Illinois (Kane and Du Page Counties; Buschbach, 1964).

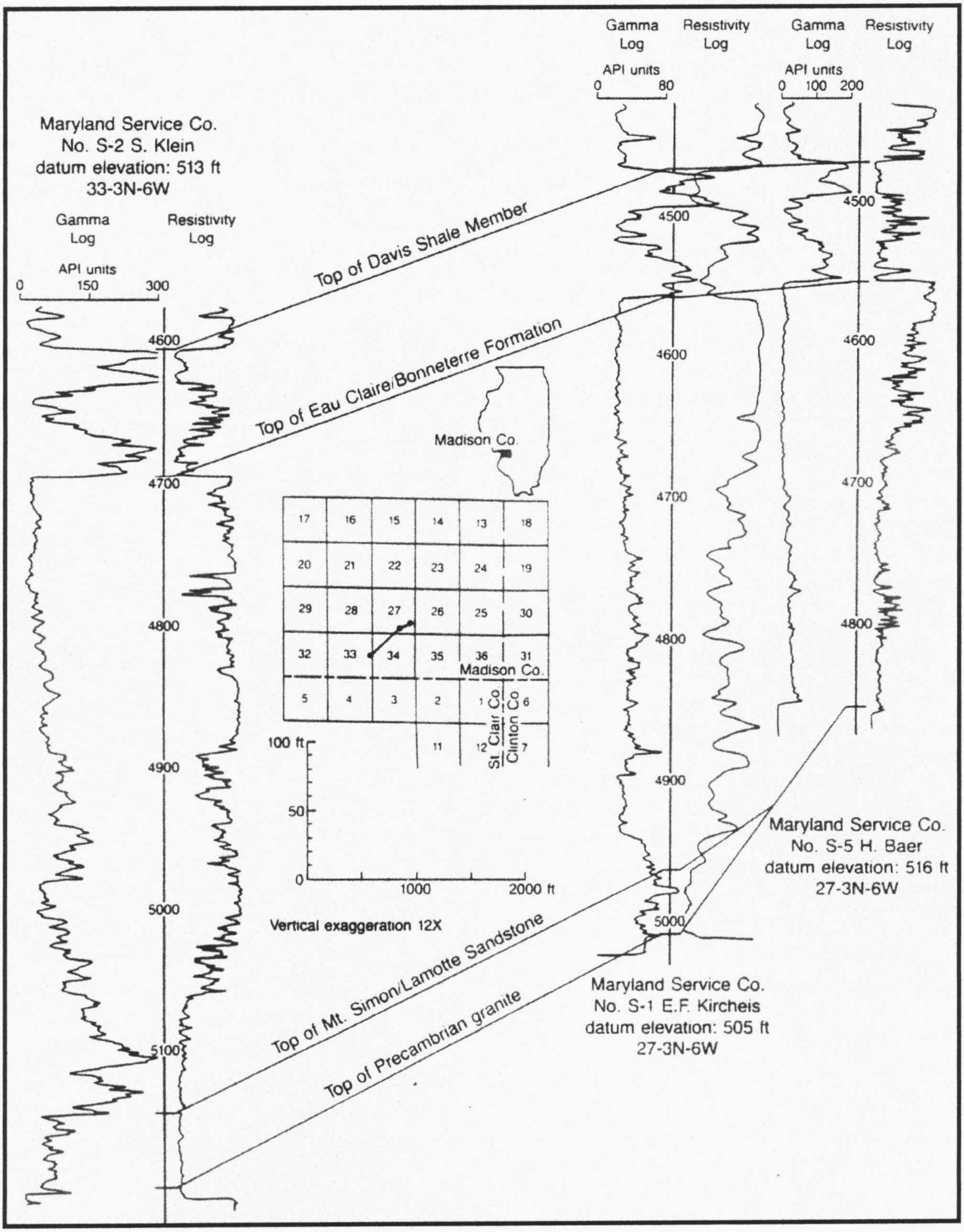

Figure 3. Cross section of Eau Claire Formation and related strata over Precambrian granite knob in southeastern Madison County, Illinois.

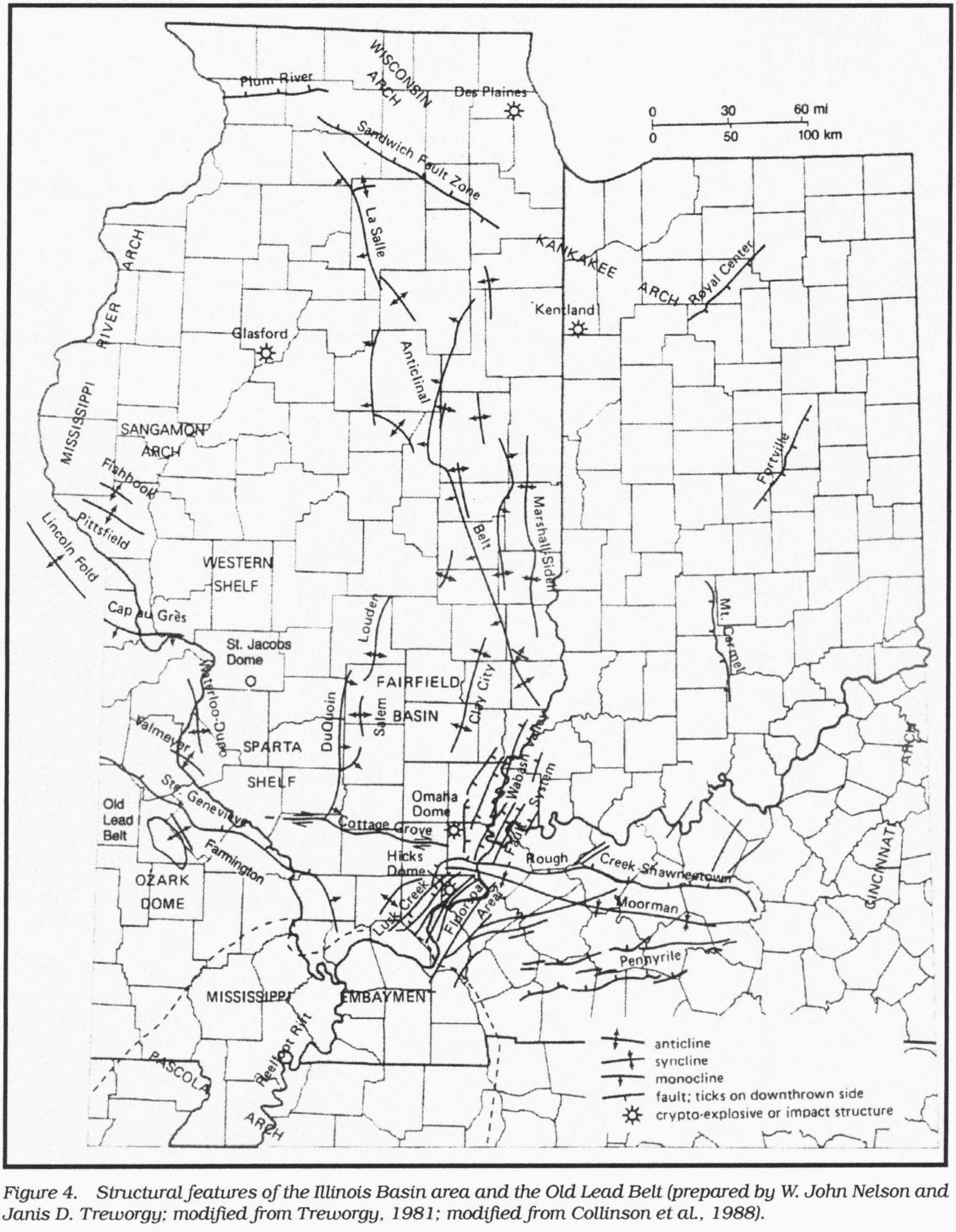

Figure 4. Structural features of the Illinois Basin area and the Old Lead Belt (prepared by W. John Nelson and Janis D. Treworgy; modified from Treworgy, 1981; modified from Collinson et al., 1988).

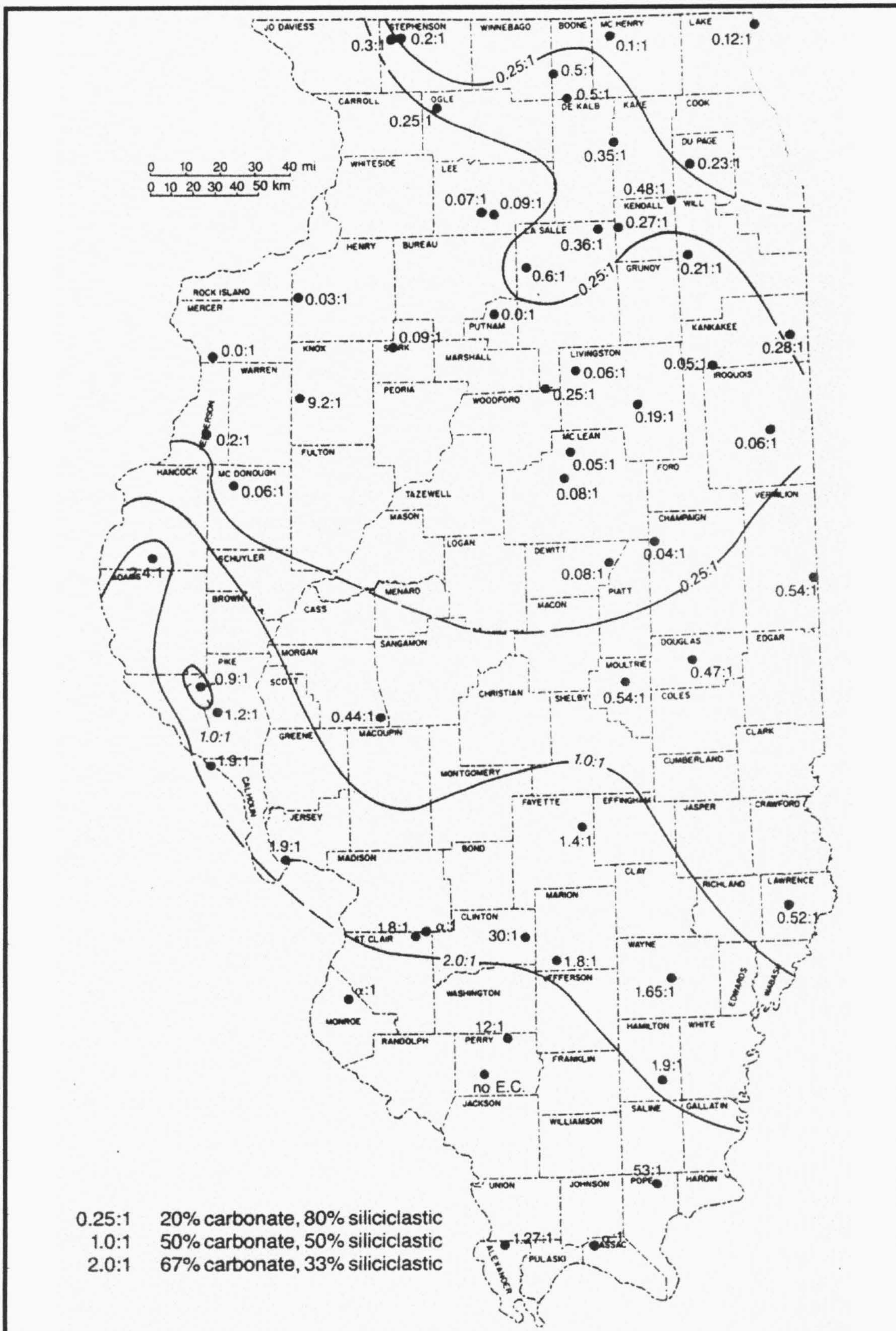

Figure 5. Carbonate-to-siliciclastic ratios of the Eau Claire Formation in Illinois.

The carbonate facies occurs to the southwest of the sinuous, southeast-trending 1.0:1 isopleth, which extends from Hancock County in western Illinois to Wabash County, southeastern Illinois (Fig. 5). This trend is approximately normal to the isopach lines in the Fairfield Basin. Although not well constrained, the carbonate facies appears to occur farther north in the deepest part of the Fairfield Basin, and the siliciclastic facies occurs farther to the south on the western flank of the basin. Wells penetrating full sections of the Eau Claire in extreme western Illinois, (Hancock, Calhoun, and Jersey Counties, adjacent to northeastern Missouri) also encountered the carbonate facies.

The two wells in central Pike County penetrated sections of Eau Claire strata in which the carbonate-to-siliciclastic ratios were strongly influenced by a positive basement feature. The southeastern well encountered a thinned section of the Eau Claire where it had been deposited directly on basement. Except for the uppermost 74 feet, the formation pinches-out against a basement knob. The well to the northwest penetrated 270 feet of Eau Claire resting on Mt. Simon Sandstone. The strong influence of the basement structure is indicated by this well having 172 feet less Eau Claire and approxiately 150 feet less Mt. Simon Sandstone than a well approximately 14 miles east. Samples are not yet available from the eastern well to permit lithofacies comparisons. Other surrounding wells also penetrate much thicker sections of the Eau Claire. This anomalously thin Eau Claire section has a carbonate to clastic ratio of 0.9:1, which is substantially less carbonate than surrounding wells that have ratios of 1.9 to 2.4:1.

All penetrations of the Eau Claire Formation on the Sparta Shelf encountered rocks with high carbonate to siliciclastic ratios. The lowest ratio, 1.8:1, was observed in southeastern Madison County where the Eau Claire section is complete and overlies Mt. Simon Sandstone. Elsewhere on the shelf, the proportion of carbonate was increased where depositional pinchout eliminated the more siliciclastic strata in the lower Eau Claire over Precambrian paleotopographic highs. No limestone was observed in any of the wells in this area or in the Marion County test a few miles east of the Du Quoin Monocline, which forms the eastern edge of the Sparta Shelf.

Limestone-to-dolomite ratios were partitioned at 4.0:1, 1.0:1, an 0.25:1, which are equal to limestone percentages of 80, 50 and 20 respectively, of the carbonate strata in the formation. Drill cuttings were originally described for five or ten-foot intervals. A two-foot bed thickness was generally the minimum that could be resolved from a combination of sample descriptions and wireline logs. No previous attempt had been made to illustrate the dominant type of carbonate in the Eau Claire Formation. Limestone-to-dolomite ratios that were determined by this study could have important implications about where mineralization of the Eau Claire was most likely to have occurred.

Limestone-to-dolomite ratios are more than 4:1 in three wells in extreme southern Illinois and in two wells in the southern part of east-central Illinois. Oolitic limestones have been reported in the Eau Claire Formation in Indiana (Droste and Patton, 1985). The two wells in Moultrie and Lawrence Counties indicate an area in which the Eau Claire carbonate is nearly pure limestone. That area trends toward southwestern Indiana (Fig. 6 & 7). The long axis of this area is nearly parallel to the trend of maximum thickness (Fig. 2) that swings into southwestern Indiana from east-central Illinois.

Near the center of the Fairfield Basin (Fig. 3) and to the south (from Wayne County to Hamilton County), the limestone-to-dolomite ratios increases from slightly less than 1:1 to nearly 2:1. This trend continues southward into northern Pope County where the ratio is more than 4:1, in southern Johnson County, all the carbonate in the Eau Claire Formation is preserved as limestone. The trend toward pure limestone reverses to the west into Union County. As the thickness of the Eau Claire diminishes

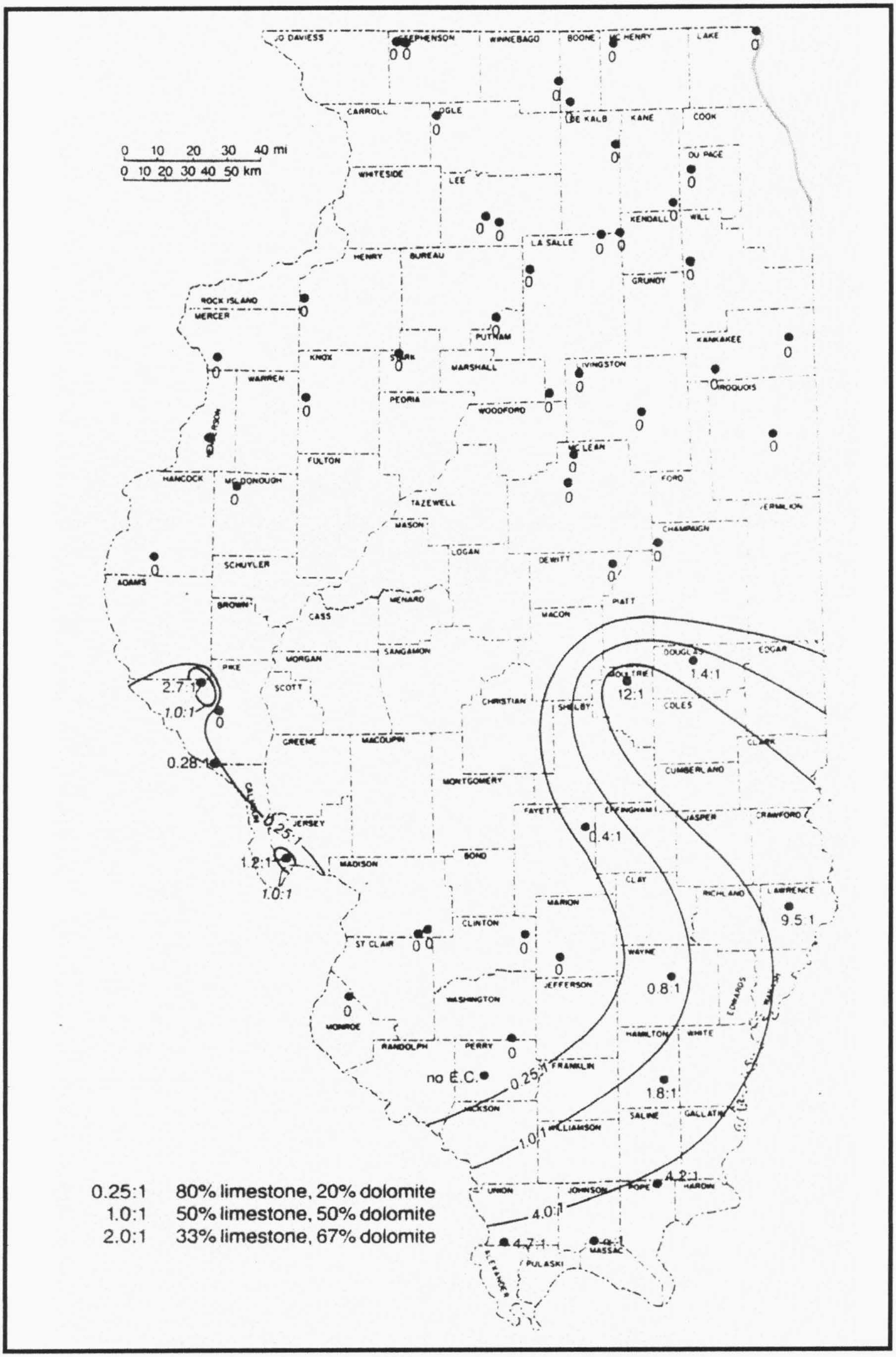

Figure 6. Limestone-to-Dolomite ratios of the Eau Claire Formation in Illinois.

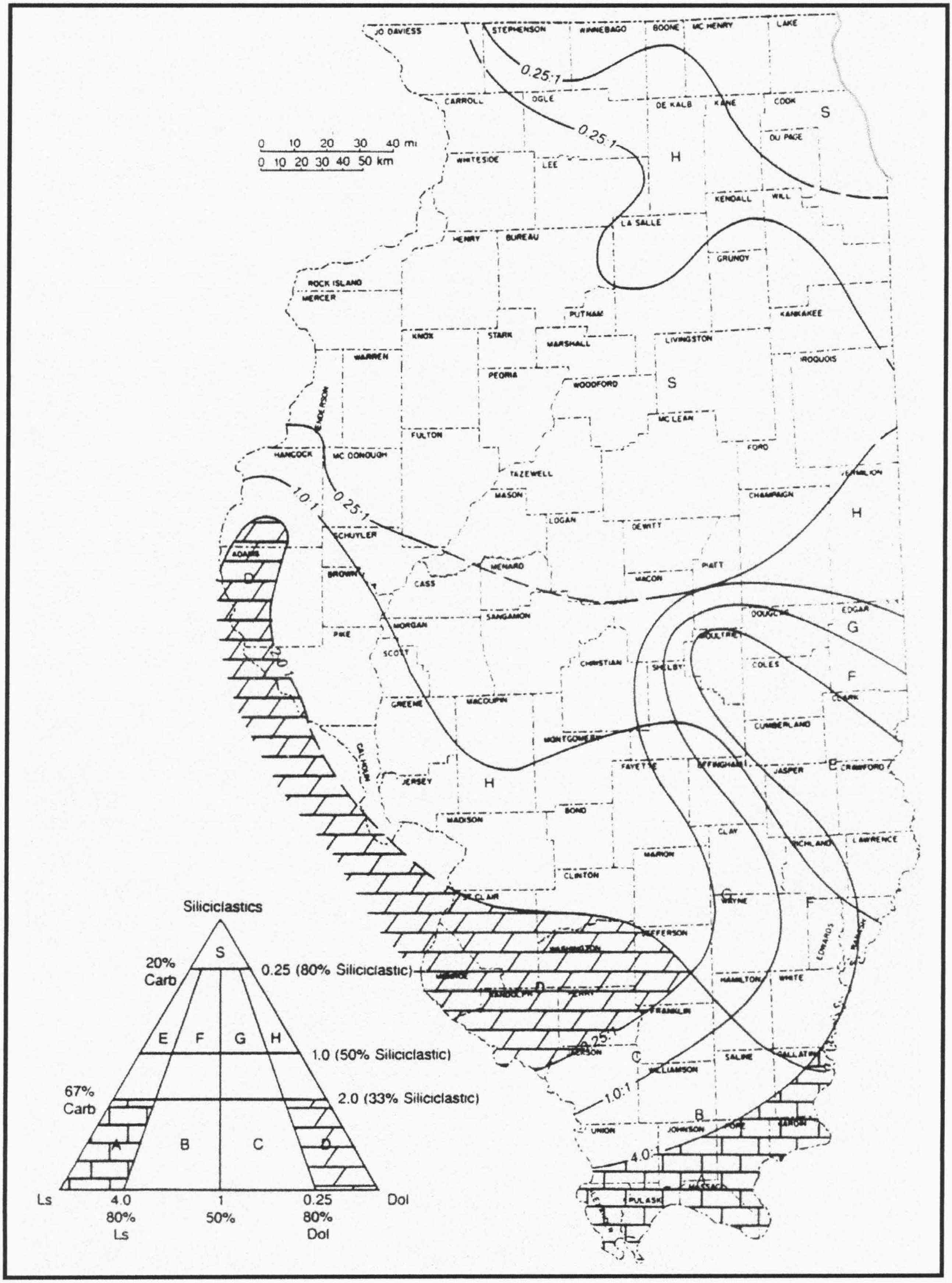

Figure 7. Combined ternary lithofacies relationships in the Eau Claire Formation.

from 1,216 feet in Johnson County to 630 feet in Union County toward the Ozark Dome, the ratio declines to slightly more than 4:1, which is similar to the ratio in northern Pope County. No data are available between the well in southern Washington County and the Union County test. In this area the Sparta Shelf seems to terminate at the Cottage Grove Fault Zone. The Ste. Genevieve Fault Zone, which truncates the north limb of the Farmington Anticline on the northeast edge of the Old Lead Belt (Fig. 3), crosses the Mississippi River into Illinois. These features may have influenced sedimentation and controlled the flow of mineralizing fluids, respectively, but no well penetrates the Eau Claire Formation closer to these structural features than the Union County test.

CONCLUSIONS

Geological features that are related to ore deposition in the Old Lead Belt of southeastern Missouri are also found in southern and western Illinois. These features include substantial amounts of carbonate in the Eau Claire (Bonneterre) Formation with facies changes from limestone to dolomite, and pinchouts of the underlying Mt. Simon (Lamotte) Sandstone and Eau Claire strata against basement paleotopographic highs.

Carbonate is the dominant rock type in the Eau Claire southwest of the zone shown as the 1.0:1 isopleth and continues to increase to much more than 2.0:1 toward the south and west (Fig. 5). Wells on the Sparta Shelf penetrated depositionally thinned Eau Claire that are nearly all carbonate.

Pinchouts of the Mt. Simon Sandstone and part or all of the Eau Claire are obvious from the "bull's-eyes" on the isopach map (Fig. 2). The Precambrian crystalline knobs that cause the depositional pinchouts are virtually impermeable and would divert the flow of ore-forming fluids being expelled from the Illinois Basin. These pinchouts, with the exception of the ones in Hamilton County and the northwesternmost Pike County test, occur where the Eau Claire carbonate is predominantly dolomite. The development of secondary porosity in these dolomites might have permitted the ore-forming fluids to be transmitted through the Eau Claire Formation. Dolomitization of the Eau Claire over these knobs may be anomalous. The primary limestone facies may be preserved in at least a part of the section here, as it is in most of the wells to the east. Most of these eastern wells were not drilled on Precambrian knobs and exhibit considerable amounts of limestone (Fig. 6 & 7). A dolomite/limestone interface could occur near wells drilled on the crests of knobs or close to the flanks of these structures, up section from the pinchouts of the Mt. Simon Sandstone and lower beds of the Eau Claire Formation.

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CORRELATION OF UPPER CAMBRIAN STRATA IN THE SUBSURFACE OF EASTERN MISSOURI

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ABSTRACT

Major lithofacies changes take place, and profound diachroneity of some formations occurs, in the Late Cambrian of Eastern Missouri. Tectonic effects spreading from the uplifted margin of the New Madrid rift produce sudden changes in water depths that simulate eustatic effects. The stratigraphic record is decipherable because of general parallelism between faunal zone boundaries, pseudoeustatic, and eustatic events.

A basal fluvial and an upper marine siliciclastic section persists in Eastern Misouri. Above this, a southerly carbonate dominated section passes northward into a deeper water siliciclastic section. The upper part of the Late Cambrian shows carbonates extending across Eastern Missouri, but with influxes of siliciclastics from the north.

INTRODUCTION

Correlations of Upper Cambrian strata in the subsurface of Missouri have been made between typical "Ozark" facies and out-of-state sections. Howe, Kurtz, and Anderson (1972) ran a cross section from the northwest flank of the St. Francois Mountains northward to Upper Mississippi Valley rocks and Kurtz, Thacker, Anderson, and Gerdemann (1975) correlated similar age rocks from the St. Francois Mountains westward across southern Missouri to Delaware County, Oklahoma and to southeastern Kansas. At that time the emphasis was on correlation. Since then additional subsurface data has been acquired, processed, and analyzed and better depositional models are available. Current emphasis by Cambrian workers is on depositional environments and how they relate to water depth and tectonics. The purpose of this paper is three fold:

1. Make a correlation between the two foregoing cross-sections.

2. Tie these two cross-sections to a third cross-section (Palmer, in preparation) via a common drill hole.

3. Bring more contemporary models especially those by Markello and Read (1982) to bear in solving problems involving correlation and depositional environments in the Late Cambrian of Missouri.

Emphasis is on the Dresbrachian and Franconian part of the section where faunal control is relatively good and original sedimentary fabric is mostly well preserved.

The three Missouri drill-holes used in this study are, from south to north: 1) St. Joe Mineral Corporation (TE-1), Texas County, NESE Sec. 25, T.32N., R.10W., 2) St. Joe Minerals Corporation (63-25), Audrain County, NENE Sec. 6, T.50N.,R.7W., and 3) St. Joe Minerals Corporation (SF-1), Clark County, Sec.5,T.65N.,R.6W. The Texas County hole is the common tie with Palmer's (in preparation) work. The reader is referred to Howe, Kurtz and Anderson (1972) for a description of the Ozarks surface section and the Upper Mississippi surface section. Formation names and member names are the same as in Kurtz, et. Al (1975). The Sullivan Siltstone Member and Whetstone Creek Member of the Bonneterre Formation were not introduced at the time the 1972 paper was written.

Figure 1 shows the location of the N-S and E-W cross sections and the cross section in this paper. Figure 2 is the cross-section. The datum is the occurrence of *Eoorthis remnicha* at the base of the *Eoorthis-Taenicephalus* Zone. *Eoorthis* was found in all three drill holes.

The drill holes on the south end of the north-south cross section and the east end of the east-west cross section are only about 18 miles apart. I have backed off the ends of the cross-sections to two cores (Texas and Audrain Counties) that have thick limestone sections, contain readily retrievable fossils, and are more basinal in character. This avoids the complexities shown in drill-holes closer in to the St. Francois Mountains. The third core (Clark County) is included to re-

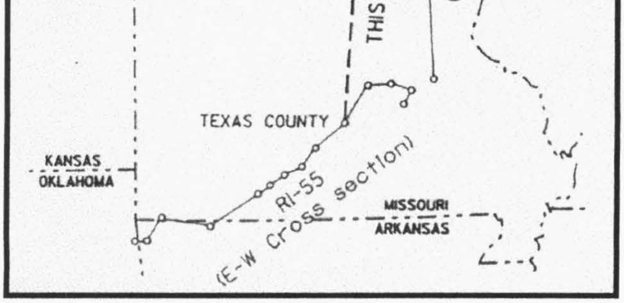

Figure 1. Locations of cross sections.

illustrate and re-correlate through the profound facies changes that take place northward from the St. Francis Mountains by reason of the influx of clastics from the shield and overall deeper water environment.

Lithostratigraphic information is derived from megascopic examination of cores, microscopic examination of churn drill cuttings and insoluble residues. Biostratigraphic information comes from body fossils of trilobites and brachiopods split from cores and from phosphatic-shelled inarticulate brachiopods freed from a carbonate matrix of selected core samples using formic or acetic acid.

The writer is especially indebted to James R. Palmer of the Department of Natural Resources, Division of Geology & Land Survey, State of Missouri for the many stimulating discussions involving depositional models that seemed particularly applicable to the Cambrian of Missouri and for days in the field where the models were put to the test.

GENERAL CONSIDERATIONS

Upper Cambrian lithofacies developed in an interior shelf basin in Missouri are similar to those found in the Nolichucky Formation, developed in an intrashelf basin in Southwest Virginia (Markello and Read, 1982) (Palmer, 1986). However, the rim separating each basin from the bordering geocline is quite different, peritidal carbonates in Virginia and an uplifted Precambrian igneous terrain bordering the Reelfoot Rift on the northwest in Missouri and Arkansas (Clendenin, 1989). The uplifted and maturely dissected block of igneous rocks affected both clastic and carbonate sedimentation (Palmer, this volume) (Houseknecht, this volume). The Missouri section is also different in that it passes northward to a largely siliciclastic and deeper water depositional environment. Although this paper deals with sedimentation in the intrashelf basin proper, the origins of the many discontinuities found in the basin and the basin margins, and water-depth related fa-

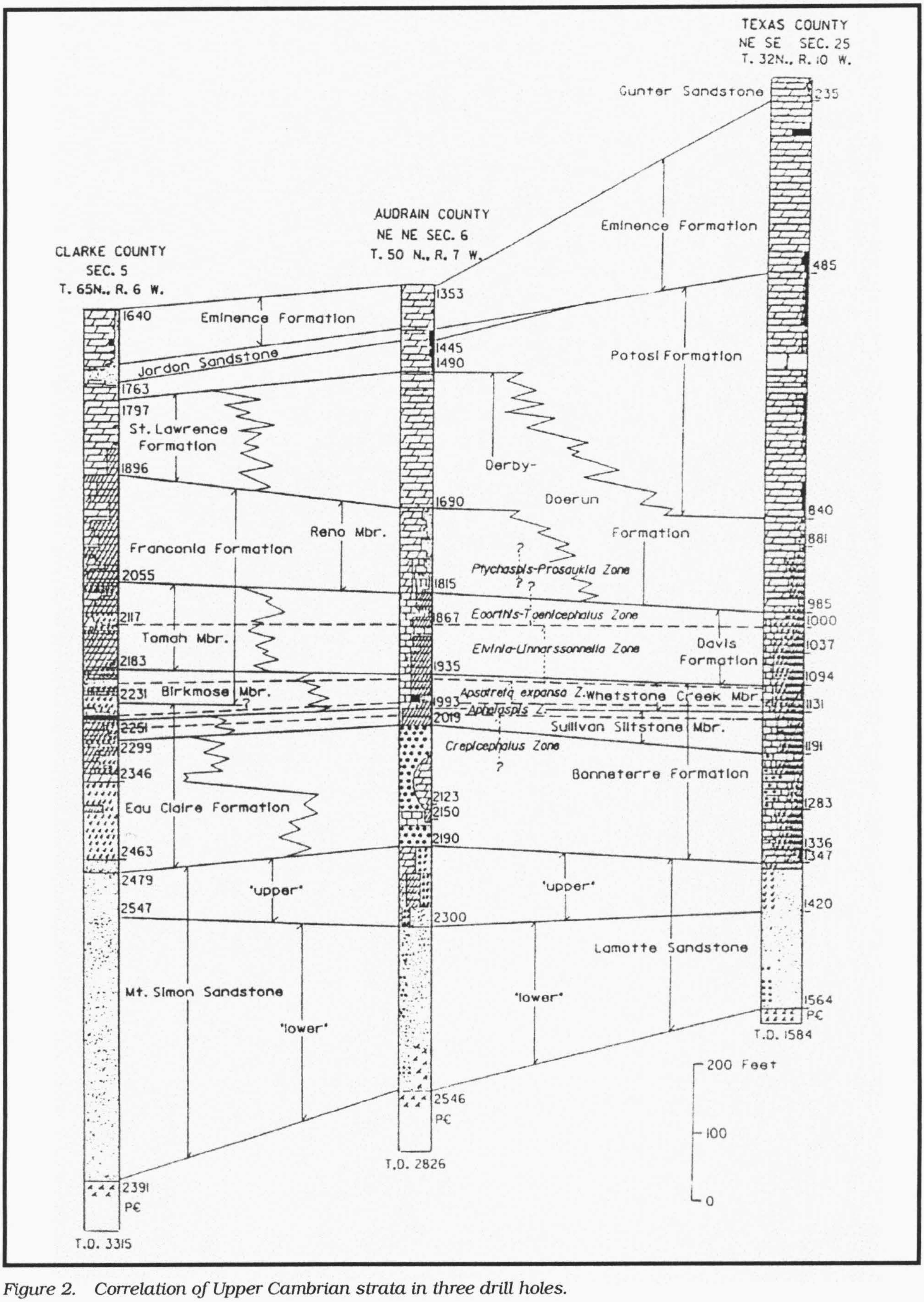

Figure 2. Correlation of Upper Cambrian strata in three drill holes.

cies relationships that are present within the formations relate directly to both the local tectonics (Clendenin, 1989) producing pseudo-eustatic effects, and world-wide eustatic events such as described by Miller (1987).

The terminology of Markello and Read (1982) is used where the original fabric is preserved in carbonate formations. I am following Palmer's (this volume) and Clendenin's (1989) interpretation of depositional environments in Missouri as follows:

Basin-shales, with thin layers of fine carbonates or clastics.

Lower ramp – "ribbon rock," usually of interbedded mudstone-wackestone and shales, deposited below storm wave base.

Upper ramp – mudstone-wackestone interbedded with skeletal and/or ooid grainstone, deposited below normal wave base, but above storm wave base.

Shoal – skeletal and/or ooid grainstone – packstone, deposited above normal wave base.

Palmer has described the Texas and Audrain county cores using Markello and Reads' (1982) terms and his descriptions are followed where applicable.

LITHOSTRATIGRAPHY REPRESENTATIVE OZARK FORMATIONS

Lamotte Sandstone

The Lamotte Sandstone overlies an eroded Precambrian igneous terrain and the thickness largely reflects the paleotopography of the buried igneous. The formation has been thoroughly studied by Houseknecht and Etheridge (1978). The bulk of the formation, is a non-marine, mostly fluvial, deposit made up of variably sorted quartz sandstone, usually crossbedded, and locally feldspathic and/or shaly. The upper part of the Lamotte is marine. The contact between the nonmarine and marine units is sharp and is marked by the presence of burrows and an increase in clay content. Glauconite and/or phosphatic debris from large-shelled inarticulate brachiopods is usually present. Some dolomite may be present, increasing in amounts toward the top of the unit.

Bonneterre Formation

"Lower Bonneterre"

The subsurface stratigraphy of the Bonneterre has been studied by a number of authors including Howe, Kurtz and Anderson (1972), Larsen (1977), Gerdemann and Meyers (1972), Palmer (1986, and this volume), Clendenin (1989). The various lithofacies making up the Bonneterre are described in detail by Palmer (this volume). The lower part of the Bonneterre is distinguished by two mutualy contiguous facies, a deeper water basinal shales and lower-ramp shale and mudstone wackestone ribbon rock facies, and an upper ramp to shoal, frequently glauconitic, skeletal to ooid wackestone-packstone to packstone-grainstone facies. These two facies are essential equivalents of the "micrite and shale facies" and "oolite facies" respectively of the Bonneterre as described in Kurtz, et. al. (1975). The contact with the overlying Sullivan Siltstone is sharp and is, in places, disconformable.

Sullivan Siltstone Member

The Sullivan Siltstone is a laminated calcareous siltstone with local intraclastic conglomerates, some burrowing, and minor amounts of glauconite. The origin for the quartz silt dominating this distinctive unit is unclear. The lamination probably originates as pulses of sedimentation caused by storms or by episodes of reworking by currents. Palmer (this volume) considers the depositional setting to be lower ramp.

Whetstone Creek Member

The Whetstone Creek is a unit consisting of mudstone-wackstones-grainstones, moderately glauconitic and interbedded with shale. Multiple micro-unconformities and hardgrounds suggest erosion by abrasion and/or resolution of carbonates on the sea floor. Palmer (this volume) suggests that the Whetstone Creek represents drowned platform sedimentation. Evidence from northern Missouri supports a time of slow siliciclastic sedimentation under starved basin conditions and in relatively deep water. In other words, absence of the *Dunderbergia* Zone in some cratonal sections may be due to absence of sediment due to lack of sediments brought to the area or by-passing rather than subaerial erosion at the Dresbachian-Franconian boundary.

Davis Formation

The Davis Formation is an overall shaly basin deposit which can change to ramp and shoal sediments toward the basin margins. Progradation of ramp and shoal facies further complicates the picture to the point that the Davis Formation, as exemplified in the type area can no longer exist. The effects of minor eustatic events and local pseudo-eustatic events can be obscured in the basin. A case in point is a newly recognized eustatic lowering of sea level that coincides with the appearance of the brachiopod *Eoorthis remnicha* (John Taylor, James Stitt and James F. Miller, personal communications). Basinal Davis sections show no change whereas in the more marginal section at Leadwood (see field trip guide [Stops 17 and 18], this volume) there is an abrupt change from basinal shales to a shoaling ooid skeletal packstone-grainstone. At this same Leadwood section, the Davis Derby-Doerun contact also shows a similar abrupt basin-to-shoal change but this is evidently a pseudo-eustatic event.

Derby-Doerun Formation

The Derby-Doerun is typically a ramp to shoal succession ranging from deep ramp ribbon carbonates to upper ramp packstone-grainstone and boundstones. The lower part of the formation is higher in quartz silts and shales, in contrast to the cleaner upper section. This contact can be correlated over wide areas in the Ozarks subsurface based on insoluble residues and is the "Top of the Cambrian Clastic" referred to in Kurtz, et. al. (1975).

Potosi and Eminence Formations

The Potosi Dolomite and overlying Eminence Dolomite formations in the subsurface are distinguished by insoluble residue characteristics. Much of the rock can best be described as "crystalline carbonate" (Palmer, 1986) in which original fabric has been destroyed. Present sedimentary fabric does show a general upper ramp shoal-lagoonal and peritidal complex (Palmer this volume) of wackestone-boundstones, packstones grainstones, "whiterock" dolostones and laminates.

Gunter Sandstone

The Gunter Sandstone Member of the Gasconade Formation rests unconformably on the Eminence. This unconformity is developed in response to the "Black Mountain Eustatic Event" (Miller, 1987) and is Early Ordovician in age as is the uppermost part of the Eminence Formation (Kurtz, 1981).

REPRESENTATIVE UPPER MISSISSIPPI VALLEY FORMATIONS

The influx of clastics from the shield so dominates the Cambrian section in northern Missouri that Upper Mississippi Valley rock units are best applied. The post-Mt. Simon section is a basinal section dominated by the deposition of laminated fine sandstones, siltstones and shales, variably glauconitic, and with subordinate amounts of carbonate. Most of the section is burrowed and the original laminations and body fossils contained therein have been destroyed. Regionally, near shore clastic wedges have pinched out basinward, some in the outcrop area, others in the subsurface so that only relatively deep basin sediments remain as far south as northern Missouri. (Berg, 1954; Nelson, 1956; Howe, Kurtz and Anderson, 1972, p. 26).

Mt. Simon Sandstone

The Mt. Simon and Lamotte are the same lithic unit with a lower fluvial section and an upper marine section. (See description of "Ozarks" formations).

Eau Claire Formation

The Eau Claire Formation is a unit of fine grained sandstones and shales, variably glauconitic and extensively burrowed. Unburrowed sediment is usually laminated suggesting relatively low energy levels of sedimentation. Basal sediments are coarse grained reflecting local derivation from the Mt. Simon. Most of the upper part of the Eau Claire has carbonate interbedded with clastics indicating proximity to the area dominated by carbonate generation to the south, the Bonneterre Formation. Uppermost Eau Claire sediments are entirely clastic.

Galesville and Ironton Sandstones

The Galesvile and Ironton sandstones are absent in northern Missouri by reason of basinward pinchout and the Birkmose Member of the Franconia Formation rests on the Eau Claire. It is possible that the Galesville is represented by a thin unit of basinal sandstones and shales termed the "Upper Eau Claire" in Howe, Kurtz and Anderson (1975).

Birkmose Member (Franconia Formation)

The Birkmose is a highly glauconitic, fine grained sandstone and shale unit. Burrowing has destroyed most of the original laminations. The unit is highly diachronous in that the age ranges from middle Franconian in the Upper Mississippi Valley outcrop area to lowest Franconian in northern Missouri.

Tomah Member (Franconia Formation)

The Tomah is pink-tan-grey colored fine grained sandstone and shale unit grading into green where glauconitic is present. K-feldspar grains can make up most of the sediment. Where not burrowed, the unit is laminated sand and shale. The upper part of the Tomah in northern Missouri contains carbonate, unlike surface exposures.

Reno Member (Franconia Formation)

The Reno is a glauconitic and mostly burrowed dolomitic sandstone, siltstone and shale. Laminations and crossbeds are present when not burrowed. The lower part of the formation contains more shale interbeds than does the upper part.

St. Lawrence Formation

The St. Lawrence is a shaly, silty, and variably glauconitic dolomitic unit that stands in contrast to the sandstones above and below.

Jordan Sandstone

A thin layer of sandstone between the Eminence and Potosi formations represents a tongue of Jordan in northern Missouri and was referred to as "Momence" in Howe, Kurtz and Anderson (1972). It is probable that a upper dolomitic sandstone unit, the Sunset Point, that has been included in the Jordan (Ostrom, 1966) is, in part, early Ordovician in age.

BIOSTRATIGRAPHY AND EVENT STRATIGRAPHY

It is generally agreed that faunas and faunal changes make biostratigraphy work and that many of the faunal zone boundaries do approximate time planes. Abrupt and pronounced faunal changes must be environmentally controlled, but the environmental cause may not be readily apparent in the rock record. This has been especially true for faunas and faunal changes in the Cambrian first described as Biomeres and Biomere boundaries by A. Palmer (1965). Evidence also suggests that some eustatic and pseudo-eustatic events are of short duration even to the point that they have the potential of better approximating time planes than do faunal changes. The point is, in deciphering geological history in a region, all potential isochronous or near-isochronous surfaces serve as references for interpretation of the sedimentary and environmental record.

The Upper Cambrian is divided into the Dresbachian, Franconian and Trempealeauian Stages. The Dresbachian in Missouri is represented by the *Cedaria, Crepichephalus, Aphelaspis,* and *Dunderbergia* Zones. Lochman (1940) and (1968) reported *Cedaria* and *Crepichephalus* Zone faunas respectively from surface sections of the Bonneterre Formation. Kurtz (1971) demonstrated the utility of using inarticulate brachiopods for zonation in the upper *Aphelaspis, Dunderbergia* and lower *Elvinia* Zones in Missouri. The biostratigraphy and lithologic framework of the Davis and Derby-Doerun Formations (Elvins Group) of Franconian Age from surface sections surrounding the St. Francois Mountains were described by Kurtz (1975). Trilobite faunas from the subsurface have not been described. Faunal zonations and in this report are the same as in Kurtz, et.al. 1975, unless otherwise noted.

The upper part of the *Crepichephalus* Zone begins in the lower part of the Bonneterre but extends into the lower part of the Sullivan Silstone in basinal sections. The *Crepichephalus-Aphelaspis* Zone boundary (base of the Pterocephaliid Biomere of A. Palmer) is sharp but shows no lithic evidence for the environmental change that caused the faunal change. The *Aphelaspis* Zone, in turn crosses the Sullivan Siltstone-Whetstone Creek Boundary and the overlying Dunderbergia Zone (=*Apsotreta-expansa* Zone of this report) falls within the Whetstone Creek in basinal sections, but can be demonstrated to also occur in basal Davis strata in marginal sections (Kurtz, 1986). The eustatic event that has marked the Dresbachian-Franconian boundary is supported by the thinning of the *Apsotreta stricta* subzone of the *A. expansa* Zone from basin to basin margin (Kurtz, 1986).

The lower part of the Franconian stage is well represented by the *Elvinia-Linnarssonella* Zone followed by *Eoorthis* and associated trilobites that mark the beginning of the Ptychaspid Biomere and the *Eoorthis-Taenicephalus* Zone. This sharp and extreme faunal change seems to coincide with a eustatic event best shown in marginal sections sensitive to sea level lowering (see discussion of the Davis formation this paper). This event was interpreted as a still stand of the sea at the end of *Elvinia* Zone time in the Upper Mississippi Valley (Howe, Kurtz, and Anderson, 1972, p. 26).

Faunal control above the Davis is poor. *Ptychaspis-Prosaukia* Zone fossils are found in the Derby-Doerun and suggests that the Franconian-Trempealeauian boundary occurs near the Derby-Doerun-Potosi contact in "typical" Ozark sections. No fossils have been found in the Trempealeauian age rocks of the subsurface. However, the uppermost 24-45 feet of Eminence from surface sections contains an Ibexian (Lower Ordovician or Canadian) conodont fauna (Kurtz, 1981). The Black Mountain Eustatic Event mentioned earlier in this paper was apparently a brief one judging from better faunal control elsewhere (Miller, 1987) than in Missouri. A parallel condition seems to exist in the Upper Mississippi Valley in which the uppermost Cambrian Formation, the Jordan Sandstone has an upper dolomitic unit, Sunset Point Member (Ostrom, 1966) containing both Late Cambrian and Early Ordovician fossils. The unit has since been assigned as a basal unit to the Early Ordovician Oneota Dolomite. (Ostrom, 1967, Davis, 1970).

CORRELATIONS

Lamotte (Mt. Simon) Sandstone

"Lower" Lamotte

Texas County. – The lower Lamotte overlies a badly weathered Precambrian "granite" at 1564 feet. The 1564-1531 foot interval is a poorly sorted sandstone with ferruginous red clay matrix cement. The basal 8 feet is a boulder conglomerate with specular hematite and red clay matrix cement. From 1531-1480 feet the formation exhibits banding or laminations of clean and ferruginous layers. The 1480-1420 foot interval is a cleaner section made up of alternating fine and coarse beds with some small-scale crossbedding.

Audrain County. – The lower Lamotte rests on the Precambrian at 2546 feet and extends upward to 2300 feet. The unit is highly variable with 20-40 foot alternating layers of fine to medium and poorly sorted fine to coarse sandstone. Hematitic cement occurs throughout most of the formation. Small scale crossbedding is common.

Clark County. – The lower Mt. Simon in this drill-hole extends from 2391-2547 feet. The overall lithology appears to be similar to the lower Lamotte in the Texas and Audrain County holes. The thicker section indicates a more basinal position.

"Upper" Lamotte

Texas County. – A burrowed and shaly sandstone section (1420-1347) containing black phosphatic brachiopod debris distinguishes the marine Lamotte. Glauconite is conspicuously absent. This unit was referred to as the Bonneterre "transition" beds in Kurtz et.al. (1975).

Audrain County. – the 2300-2190 foot interval is fine grained sandstone, strongly burrowed. Basal beds are glauconitic and hematitic and contain phosphatic brachiopod debris. Dolomite is absent in the basal beds but, according to insoluble residues, makes up a significant component towards the top of the unit.

Clark County. – The upper Mt. Simon begins with a 20 foot hematitic (originally glauconitic) shale with sand filled burrows at 2547 feet followed by burrowed sandstones and shales up to 2479 feet. This marine section was not separated from the lower part of the formation in Howe, Kurtz and Anderson (1972).

Bonneterre Formation

"Lower Bonneterre"

Texas County. – "Lower" Bonneterre sedimentation forms a cycle and begins with a thin (1347-1336) glanconitic upper ramp facies followed by lower ramp "ribbon rock" from 1336-1283 feet and terminates in upper ramp ooid and skeletal wackestone – packstones at 1191 feet. *Llanoaspis* at 1211 feet and *Tricrepicephalus* at 1192 feet are *Crepicephalus* Zone trilobites.

Audrain County. – A cycle similar to that found in Texas County occurs in this drill-hole. Ooid and glauconitic upper ramp rocks extend from 2191-2150 feet, followed by shaly lower ramp ribbon rocks (2150-2123) and upper ramp to shoal section from 2123-2019.

Eau Claire Formation

Clark County. – The ramp to shoal carbonates of the "lower" Bonneterre to the south change facies to a largely siliciclastic section, the Eau Claire Formation. Basal Eau Clair beds (2479-2463) are fine to coarse, highly glauconitic and hematitic burrowed sandstones containing phosphatic shell debris. The section from 2453-2346 is more typical Eau Claire lithology, i.e., fine grained sandstones and shales, laminated where unburrowed, but mostly burrowed. A six foot shaly wackestone packstone (2385-91) interrupts the section. The succeeding 2346-2324 foot interval is mostly a mudstone-wackestone with abundant trilobite debris and represents Bonneterre carbonates intruding into an overall clastic and more basinal section. From 2324-2299 feet is a mostly burrowed shaly and sandy limestone section. Clastics again dominate from 2299-2251 feet with a mostly burrowed glauconitic sandstone and shale section. This interval is believed to correlate with the Sullivan Siltstone in the drill holes to the south. Uppermost Eau claire (2251-2231) is a cycle of laminated sandstone and shale, mostly burrowed with heavy glauconitic at the base. This unit was referred to as "upper Eau Claire" in Howe, Kurtz and Anderson (1972). I have not been able to satisfactorily correlate this 20 foot interval with sections to the south. It may represent the basinal equivalent of the Galesville-Ironton to the north.

The Eau Claire contains a diagnostic trilobite fauna with *Crepicephalus* Zone representatives *Kingatonia* at 2,324 feet and *Tricrepicephalus* at 2,324 and 2,286 followed by the name bearer of the *Aphelaspis* Zone at 2,256.

Sullivan Siltstone

Texas County. - The interval from 1,191-1,131 feet is a limy quartz siltstone showing thin and irregular bedding. Thin layers of skeletal packstone-wackestone and thin shaly layers are present. Glauconite is a minor constituent. Trilobites diagnostic of the *Crepicephalus* Zone are scattered through the 1,186-1,172 foot interval. *Aphelaspis* is found at 1,133 feet and continues up into the Whetstone Creek Member.

Audrain County. - The siltstone interval is a relatively thin 26 foot section (2,019-1,993 feet). *Coosina* occurs at 2,016 and 2,008 feet and *Tricrepicephalus* at 2,010 feet, both *Crepicephalus* Zone fossils. *Aphelaspis* was not found in this core, but the upper part of the siltstone and possibly lower part of the overlaying formation should be of *Aphelaspis* zone age.

Clark County. - The Sullivan Siltstone is not present in this hole but Eau Claire beds from 2,299-2,251 feet may correlate, as mentioned earlier.

Whetstone Creek Member

Texas County. - Glauconitic packstones - wackestones interbedded with shale extend from 1,131-1,094 feet. The Aphelaspis Zone continues upward from the Sullivan Siltstone with Angulotreta missouriensis (phosphatic brachiopod) at 1,126 feet and Aphelaspis at 1,123 feet. The Dunderbergia (Aposotreta expansa) zone is represented by a lower subzone characterized by A. attenuata at 1,115.2 and 1,112.5 feet on an upper subzone distinguished by A. stricta up to 1,096.5 feet. Apsotreta attenuata is an excellent guide fossil, in that it is easily recognized and occurs in no more than five feet of strata where encountered in all subsurface sections. The contact between the *Dunderbergia* Zone and *Elvinia - Linnarssonella* Zone is placed at 1,096 feet in as much as *L. costa* and *L. girtyi* appear at 1,095.5, 1 foot below the top of the Whetstone Creek. Palmer (this volume) places the top of the Whetstone Creek higher in the section at 1,037 feet. This silty and shaley unit is here considered part of the Davis as was done in Kurtz, et. al. (1975).

Audrain County. - The interval from 1993 to 1935 feet consisting of a glauconitic sandstone and shale unit with heavy glauconite at the base and interbedded wackestones above is here placed in the Whetstone Creek although equivalence to the Birkmose in the Clark County hole is obvious. Fossils characteristic of the *Elvnia-Linnarssonella* zone are found throughout the interval.

Franconis Formation

Birkmose Member

Clark County. - Highly glauconitic, laminated, fine grained and burrowed sandstones and shales extend from 2231-2183. As mentioned, in Howe, Kurtz and Anderson (1972), the Birkmose was inferred to rest unconformably on the "Upper Eau Claire" because the Ironton and Galesville Formations are absent at this locality. Considering the basinal nature the sediments in the upper Eau Claire-Birkmose interval an unconformity is most unlikely. Rather, a deep-water episode of slow sedimentation with "starved basin conditions" is more likely and the coarse Ironton and Galesville sandstones are absent by reasons of pinchout into the basin and/or possibly minor facies equivalence to the upper Eau Claire and/or the lower Birkmose.

Davis Formation

Texas County. - The interval from 1,030-1,094 feet was considered lower Davis in Kurtz, et. al. (1975) but Palmer, this volume would include this silty and shaly interval in the Whetstone Creek. This interval is certainly a facies of the lower Davis by whatever name it is called. More typical Davis shales and wackestones occur from 1,039 to 985 feet. Faunal control is good. The highest *Elvinia-Linnarssonella* Zone fossil is *Linnarssonella girtyi* at 1,003 feet with *Eoorthis remnicha* coming in at 1,000 feet and *Parabolinoides contractus* at 999.8 feet, both representing the succeeding faunal zone and marking a biomere boundary in the Upper Cambrian as mentioned earlier. *Taenicephalus* is found at 988 feet.

Audrain County. - The rocks from 1,815-1,935 feet are typical Davis. *Housia*, an *Elvinia - Linnarssonella* Zone trilobite is found at 1,905, and *Eoorthis remnicha* at 1,867. The equivalence of the Davis to the Tomah member of the Franconia Formation is obvious.

Franconia Formation

Tomah Member

The fine grained sandstone and shales with subordinate amounts of carbonate from 2,183-2,055 feet can best be described to the Tomah. *Linnarssonella* at 2,155 feet and *Eoorthis remnicha* at 2,117 feet provide faunal control.

Derby-Doerun and Younger Cambrian Formations

The Davis-Derby-Doerun contact is sharp in the type are (see Leadwood section, this volume) with an abrupt change from basinal shales and platy carbonates to ooid skeletal packstones-grainstones and boundstones of the shoal environment. Out in the basin, increases in clastics in the Derby-Doerun leave multiple options as to placement of the contact. In fact, radical thickness and facies changes in all of the post-Davis Late Cambrian renders placement of many contacts arguable.

Texas County. - The lower part of the Derby-Doerun (985-951 feet) is an ooid skeletal packstone-grainstone with minor amounts of shale and silt. The 951-881 foot interval is a dolomitic siltstone and marks the end of clastic deposition in the core. Uppermost Derby-Doerun (881-840) is a lime mudstone-wackestone. The Potosi Formation is distinguished by quartz druze and chert in the core and insoluble residues. Practically all of the Potosi and all of the Eminence is preserved only as churn drill cuttings so no megascopic information is available. The Eminence is distinguished by insoluble residues of chert exhibiting characteristics form (see Kurtz, et.al. (1975). The Potosi-Eminence contact falls at 485 feet and the Eminence-Gunter contact is placed at 235 feet.

Audrain County. - Most of the interval from 1,815 to 1,690 feet is a ribbon carbonate (Palmer, this volume). The lower 45 feet of the interval is characteristized by silt residue and the upper 80 feet has fine sand residue. This 125 foot interval is placed in the Reno Formation but could just as easily be assigned to the Derby-Doerun. Quartz druze has dropped out of the dolomite section rather than Potosi is now best applied. Palmer logs this interval as ribbon dolostones with crystallized boundstones in the upper 40 feet. Quartz druze characteristics of the Potosi is present in the insoluble residues from 1,490 to 1,445 feet. The Jordan sandstone is represented by a sand rich, pelletal grainstone from 1,445 to 1,426 feet. Crystalline carbonates and whiterock dolomites make up the Eminence Formation up to the base of the Gunter at 1,353.

Clark County. - Typical Reno, fine grained, glauconitic, shaly, laminated and burrowed sandstones characterize the interval from 2,055 to 1896 feet. The succeeding interval (1,896-1,797) feet is more dolomitic and is placed in the St. Lawrence Formation. The interval from 1,797 to the top of the Eminence at 1,640 is represented by cable tool samples. Insoluble residues from this part of the section were considered unreliable, but the Potosi was called from 1,797 to 1,763, and the Eminence from 1,763 to 1,640 feet with a lower, sandy part of the interval correlated with the Jordan sandstone (Howe, Kurtz and Anderson, 1972).

CONCLUSIONS

Typical "Ozarks" Upper Cambrian formations with readily distinguishable internal units and boundaries in change character in all directions. The influx of clastics from the north changes the rocks so completely that "Ozark" names no longer apply except in the uppermost part of the section. To the west, the Bonneterre pinches out and the post-Bonneterre changes to a peritidal platform section (Kurtz, et. al., 1975; Palmer, this volume). To the southeast is an uplifed rift margin of Precambrian igneous rock with the igneous islands being progressively buried by complex of shoal and peritidal sediments (Clendenin, 1989; Palmer, this volume). Missouri sets at one of the geological "cross roads" on the continent and will provide avenues for research for many years to come.

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CAMBRIAN PALYNOMORPHS FROM THE WARM-WATER PROVINCIAL REALM, BONNETERRE AND DAVIS FORMATIONS OF MISSOURI AND ARKANSAS (REELFOOT RIFT AREA): BIOSTRATIGRAPHY, PALEOECOLOGY AND THERMAL MATURITY

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ABSTRACT

Cambrian, warm-water realm, organic-walled palynomorphs are illustrated from the Davis and Bonneterre formations of Missouri and Arkansas. The assemblage from these stratigraphic units contain clusters, filaments and sheets considered to be of algal origin and organic-walled microphytoplankton. The latter include the first record of Granomarginata squamacea *Volkova 1968,* Timofeevia phosphoritica *Vanguestaine 1978 and* Vulcanisphaera turbata *Martin in Martin and Dean 1981 from the United States.* T. phosphoritica *and* V. turbata *have previously been reported from the uppermost Middle Cambrian and Upper Cambrian of the cold-water provincial realm (e.g., Newfoundland).*

All productive samples are dominated by sphaeromorphic acritarchs, algal clusters, -filaments and sheets. However, samples from basinal environments display a slight qualitative and quantitative increase in acanthomorphic acritarchs. Visual color characterization of selected palynomorphs tentatively implies a correlation between paleoenvironmental setting, depth of burial and thermal maturity.

INTRODUCTION

The geological province of southeastern Missouri, in the area of the St. Francois Mountains, has been of economic interest since the discovery of lead ore by the French explorer M. LaMotte in the early 18^{th} century. Subsequent geological research in the area has been directed toward the location and mining of these Pb-Zn ore bodies, including the famous "Old Lead District" and "Viburnum Trend", associated with the Bonneterrre Formation. Recent studies in the area have concentrated on the origin and spatial relationships of these deposits using an integration of geological disciplines (Gerdemann and Gregg, 1986; Gregg, 1985; Kisvarsanyi, 1974; Larson, 1977; Lyle, 1977). This research has shown that during deposition of the Bonneterre and Davis formations (Text-Fig. 1) the St. Francois Mountains were an area of high relief (e.g., islands) associated with an intracratonic basin. On the platform, adjacent to these emergent features, shallow subtidal to intertidal environments dominated. From these Precambrian highlands, the craton slopes to the east-southeast into a shelf-margin and basinal complex (aulacogen).

Outcrop sections of Bonneterre and Davis formations have been dated as Upper Cambrian using trilobites (Kurtz, 1971, 1975; Kurtz, et. al., 1975, Lochman, 1940; Lockman-Balk, 1970, 1974). The study area lies within the Cambrian warm-water province (Sweet, et. al. 1959; Bergstrom and Sweet, 1966; Sweet and Bergstrom, 1974, 1984; Miller, 1981, 1984; Shergold, 1988). The warm-water realm is manifest as shallow seas in low- to mid-paleolatitude areas (e.g., North American Midcontinent) in contrast to a contemporaneous cold-water province present in high-paleolatitude areas (e.g., North Atlantic province). All previous papers concerning Upper Cambrian palynomorphs have dealt with cold-water assemblages. For this reason, it is important to note that the subsequent discussion concerning palynostratigraphy follow Acado-Baltic (cold-water) trilobite zonal terminology (Dean, 1985; Bengston and Fletcher, 1983).

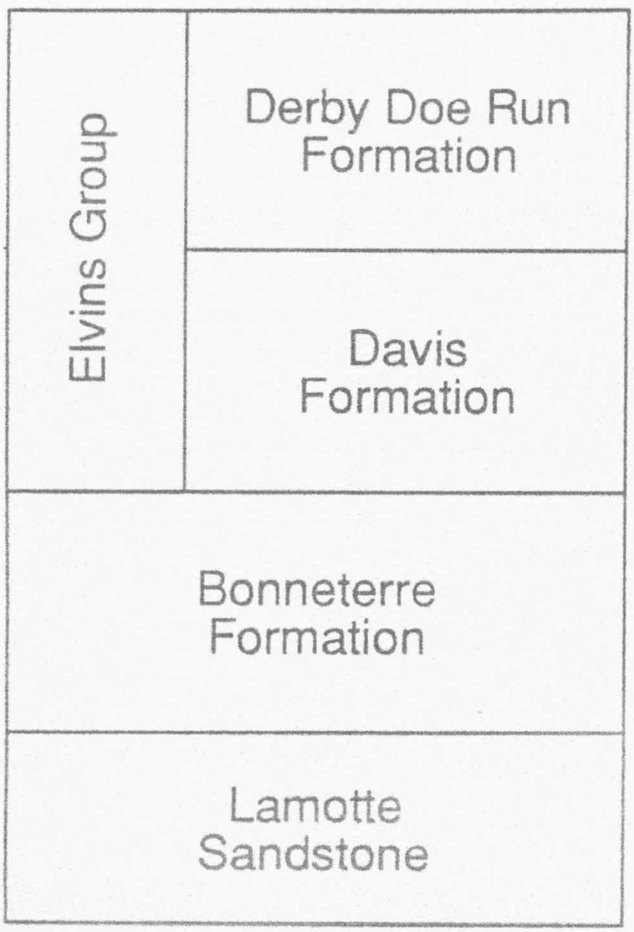

Figure 1. Generalized stratigraphic section in the study area.

Preliminary palynological evidence from outcrop to deep subsurface sections of the Bonneterre and Davis formations is presented here. The inferences gleaned from these data illustrate that only with an integration of disciplines can this geologically complex area be understood.

MATERIALS AND METHODS

Samples from six Upper Cambrian surface exposures in the St. Francois Mountains area of Missouri and eight subsurface localities from southeastern Missouri and northwestern Arkansas were analyzed for microphytoplankton and other organic-walled microfossils. Pertinent geographic information for these localities are given below (see also Text-Fig. 2).

1. Gumbo locality. Roadcut exposures on north and south side of State Highway 8, 5/10 mi. east of Gumbo, St. Francois County (Flat River 7.5' Quad), MO (Lat. 37.8629020 N.; Long. 90.5774232 W.). This section is approximately 5/10 mi. in length, begins at Hulsey Road and ends at near the road entrance to the Rogers Stone Quarry, Inc.

2. Leadwood-north locality. Roadcut exposure on south side of State Highway 8, north of Leadwood, St. Francois County (Flat River 7.5' Quad), MO (Lat. 37.8696937 N.; Long. 90.5892560 W.).

3. Frankclay locality. Roadcut section exposed on State Highway 8, 5/10 mi. east of intersection with Highway M (Marler Road), St. Francois County (Flat River 7.5' Quad), MO (Lat. 37.8680143 N.; Long. 90.6187304 W.).

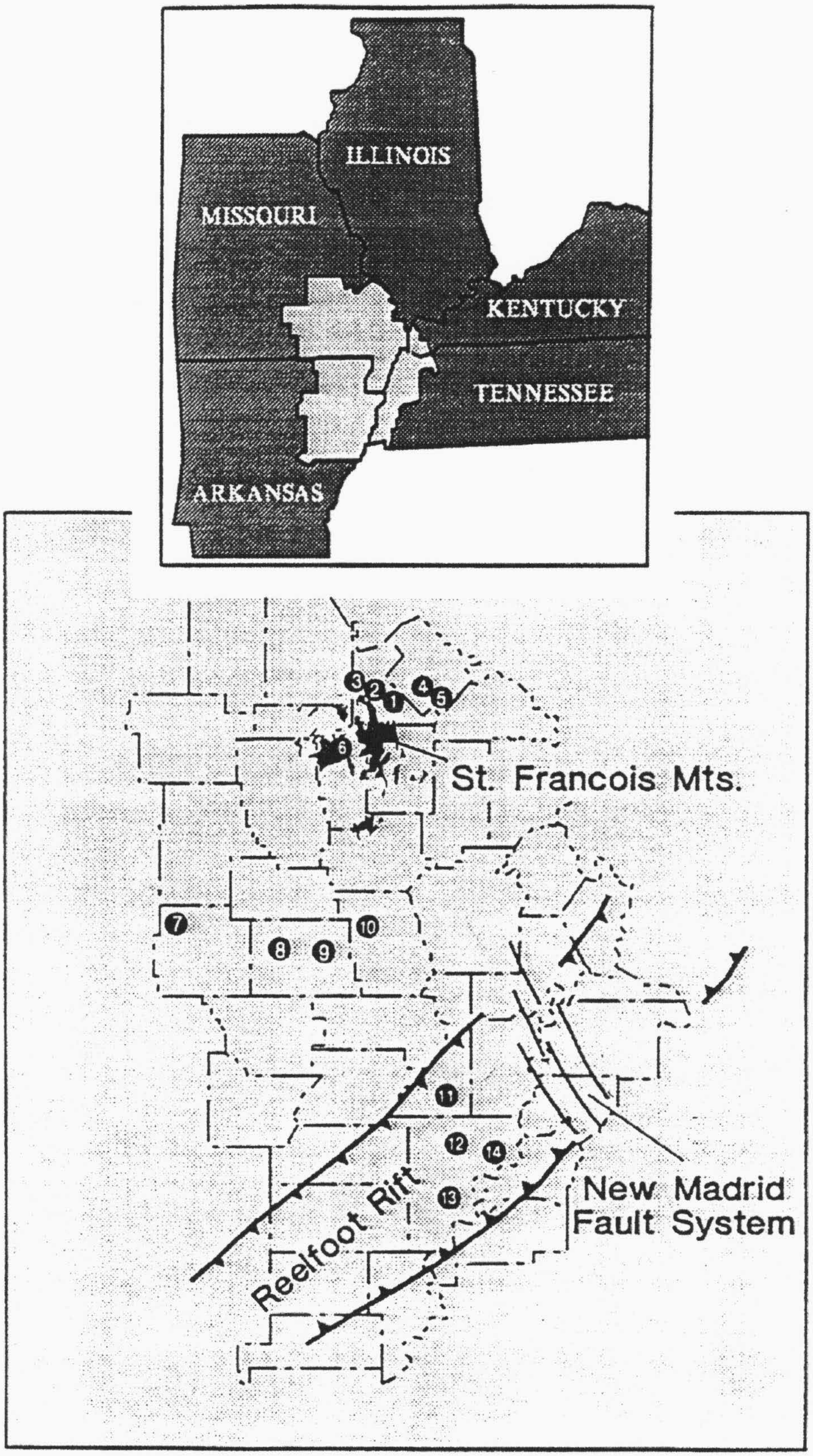

Figure 2. Map showing collecting localities (see text for detailed discussion) and major structural features.

4. Fourche Du Clos Creek "A" locality. Outcrop on north side Fourche Du Clos Creek behind Werner Carron farm (on Highway Y), 6/10 mi. Southwest of Lawrenceton), St. Genevieve County (Lawrenceton 7.5'Quad), MO (Lat. 37.9580533 N.; Long. 90.3164354 W.).

5. Fourche Du Clos Creek "B" locality. Essentially same locality as #4 (above); however, approximately 2/10 mi. downstream (Lat. 37.9560040 N.; Long. 90.3194852 W.).

6. Taum Sauk Mountain locality. South-face exposure of Bonneterre Formation unconformably overlying Precambrian knob of Taum Sauk Rhyolite, exposed at the Union Electric Company's Taum Sauk hydroelectric power plant, 10.8 mi. west of the village of Hogan (see Kisvarsanyi, et. al., 1981; Kisvarsanyi and Hebrank, 1987) Reynolds County (Johnson Shut-ins 7½' Quad), MO (Lat. 37.5492987 N.; Long. 90.8258342 W.).

7. American Zinc, mineral core #L4, Oregon Co., MO (Lat. 36.8509649 N.; Long. 91.6473985 W.).

8. Cominco American, mineral core #SF-32, Ripley County, MO (Lat. 36.5466272 N.; Long. 90.9632562 W.).

9. Houston Oil and Minerals, mineral core #319-11A, Ripley Co., MO (Lat. 36.6734678 N.; Long. 90.8071370 W.).

10. Gulf Mineral Resources, mineral core #PBW-4, Butler Co., MO (Lat. 36.7583672 N.; Long. 90.5258649 W.).

11. Amoco Production Company, #1 Spence Trust, Dunklin Co., MO (Lat. 36.1210500 N.; Long. 90.1937000 W.). API No. 24-069-20001-00.

12. Dow Chemical, #1 B.L. Garrigan, Mississippi Co., AR (Lat. 5.90027 N.; Long. 90.03331 W.). API No. 03-093-10002-00.

13. Dow Chemical, #1 Lee Wilson & Co., Mississippi Co., AR (Lat. 35.66191 N.; Long. 90.09637 W.). API No. 03-093-10001-00.

14. Amoco Production Company, #1 Burmah P. Haynes, Mississippi Co., AR (Lat. 35.8571200 N.; Long. 89.8554000 W.). API No. 03-093-10004-00.

Rock samples were macerated and treated with hydrochloric and hydrofluoric acid to dissolve carbonates and silicates, respectively. Organic residue from selected samples was treated with nitric acid to remove opaque sulphide minerals or to slightly darken light colored specimens for photography. Nitric acid had little or no effect on dark brown-black specimens other than to remove opaque sulphide framboids adhering to organic particles. All slides and extra raw samples are housed at the Amoco Production Co., Houston.

RESULTS

Only three organic-walled microphytoplankton can be assigned to a published species. These are *Timofeevia phosphoritica* Vanguestaine 1978 (Plate 1, Figs. 1-6), *Vulcanisphaera turbata* Martin in Martin and Dean 1981 (Plate 1, Figs. 7-9), and *Granomarginata squamacea* Volkova 1968 (Plate 1, Figs. 22-23). Additional types of organic-walled microphytoplankton, although undescribed, are illustrated for the record. These include several acanthomorphs (possessing spines or processes) and sphaeromorphs (simple circular forms). Algal clusters (Plate 2, Figs. 5-17) and filaments (Plate 3, Figs. 3-6) are abundant in most samples. Several specimens of algal clusters possess a diaphanous membrane (Plate 2, Figs. 15-17) – a character not often preserved after palynological maceration. It is uncertain if algal clusters represent planktonic forms.

Outcrop samples (Localities 1-6) of the Davis Formation yield an assemblage dominated by algal clusters, filaments and organic detritus that may be of algal origin. It is not known whether these represent benthic or planktic algae. Sphaermorphs and acanthomorphs are present but never dominate a sample. Palynomorphs range in color from light yellow to orange-brown. Outcrop samples from the Bonneterre Formation did not yield palynomorphs.

Palynomorphs recovered from the Davis Formation and Bonneterre Formation from the mineral cores (Localities 7-10) were dominated by algal remains (e.g. clusters, filaments, etc.). However, there was a slight increase in acritarch diversity (particularly acanthomorphs) and abundance. Palynomorphs and organic debris ranged in color from yellow to orange-brown.

The down-dip (=basinal) sections of the Davis and Bonneterre formations, and equivalents (Localities 11-14), possessed the most diverse and abundant acritarch assemblage. In sediments presently considered to be the Bonneterre Formation an assemblage not yet observed in updip strata was recovered that includes vulcanisphaera turbata Martin in Martin and Dean 1981 (Plate 1, Figs. 7-9). Palynomorphs in downdip sections were dark brown to black in color (see representatives on Plate 1, Figs. 4-9, 13-15, 17-18, 29; Plate 2, Figs. 1-2, 6, 11-14).

DISCUSSION OF THE PALYNOMORPH ASSEMBLAGE

Palynostratigraphy

Timofeevia phosphoritica Vanguestaine 1978 (Plate 1, Figs. 1-6) has been recovered in the upper part of the Middle Cambrian Manuels River Formation through the lower half of the Upper Cambrian Elliott Cove Formation on Random Island, eastern Newfoundland (Martin, 1982; Martin and Dean, 1981, 1988; see Text-Fig. 3). In this area *T. phosphoritica* has a base in the *Paradoxides paradoxissimus (Ptychagnostus punctuosus)* trilobite zone (=lowermost lower part of their acritarch zone A2), and a top in the *Acerocare* (in part) trilobite zone (=top of their acritarch zone A5b). Welsh (1983; 1986 a,b) found this species in the Middle Cambrian *Paradoxides paradoxissmus* through Upper Cambrian *Acerocare* trilobite zones (=his acritarch zones A II through A IV) of the Kistedal Formation of eastern Finnmark, northern Norway. Bagnoli, et al., (1988) recovered T. phosphoritica from the Upper Cambrian *Agnostus pistiformis* trilobite zone in Sweden. Additional Middle Cambrian occurrences of this acritarch have been reported from Belgium (Vanguestaine, 1968; 1978), France (Fournier-Vinas, 1978), and Turkey (Erkmen and Bozdogan, 1981). *T. phosphoritica* has also been found in Upper Cambrian sediments from Sardinia (Albani, et al., 1985) and Algeria (Baudelot and Gery, 1979).

Vulcanisphaera turbata Martin in Martin and Dean 1981 (Plate 1, Figs. 7-9) is a common species in the uppermost Manuels River Formation and the lower part of the Elliott Cove Formation of eastern Newfoundland (Martin and Dean, 1981, 1988; Text-Fig. 3). In Newfoundland, this species ranges from the *Paradoxides forchhammeri* (*?Leiopyge laevigata*) to the *Leptoplastus trilobite* zones (= their uppermost lower A2 through lowermost A4 acritarch zones). In Finnmark, Norway, Welsch (1986 a,b) recovered *V. turbata* from the Upper Cambrian *Agnostus pisiformis* through *Acerocare* trilobite zones (= his acritarch zones A III and A IV) of the Kistedal Formation. This acritarch has also been illustrated (with *T. phosphoritica*) from the possible "Middle" Cambrian of Sardinia (albani, et al., 1985).

Granomarginata squamacea Volkova 1968 (Plate 1, Figs. 22-23), reported from several Lower and Middle Cambrian sections (e.g., Downie, 1982; Fombella-Blanco, 1986; Hagenfeldt, 1988; Lendzion, Moczydlowska and Zakowa, 1983; Moczydlowska 1981; Moczydlowska and Vidal, 1986, 1988; Vidal, 1981; Volkova, 1968, 1969, 1973) is present in most samples. *?Fimbriaglomerella membranacea* (Kirjanov) Moczydlowska and Vidal 1988 (Plate 1, Figs. 16-18) and *?Micrhystridium* cf. *M. tornatum* Volkova 1968 (Plate 1, Figs. 10-15) have also been recovered.

Palynofacies and Thermal Maturity

Examination of discrete organic particles in a palynomorph preparation has several advantages over standard geochemical assays that evaluate an aggregate "kerogen soup". In addition to grossly characterizing the kerogen (e.g., as amorphous or structured), individual types can be discerned (e.g., cuticle, tracheids, spores, prasinophytes, acritarchs, algal clusters,

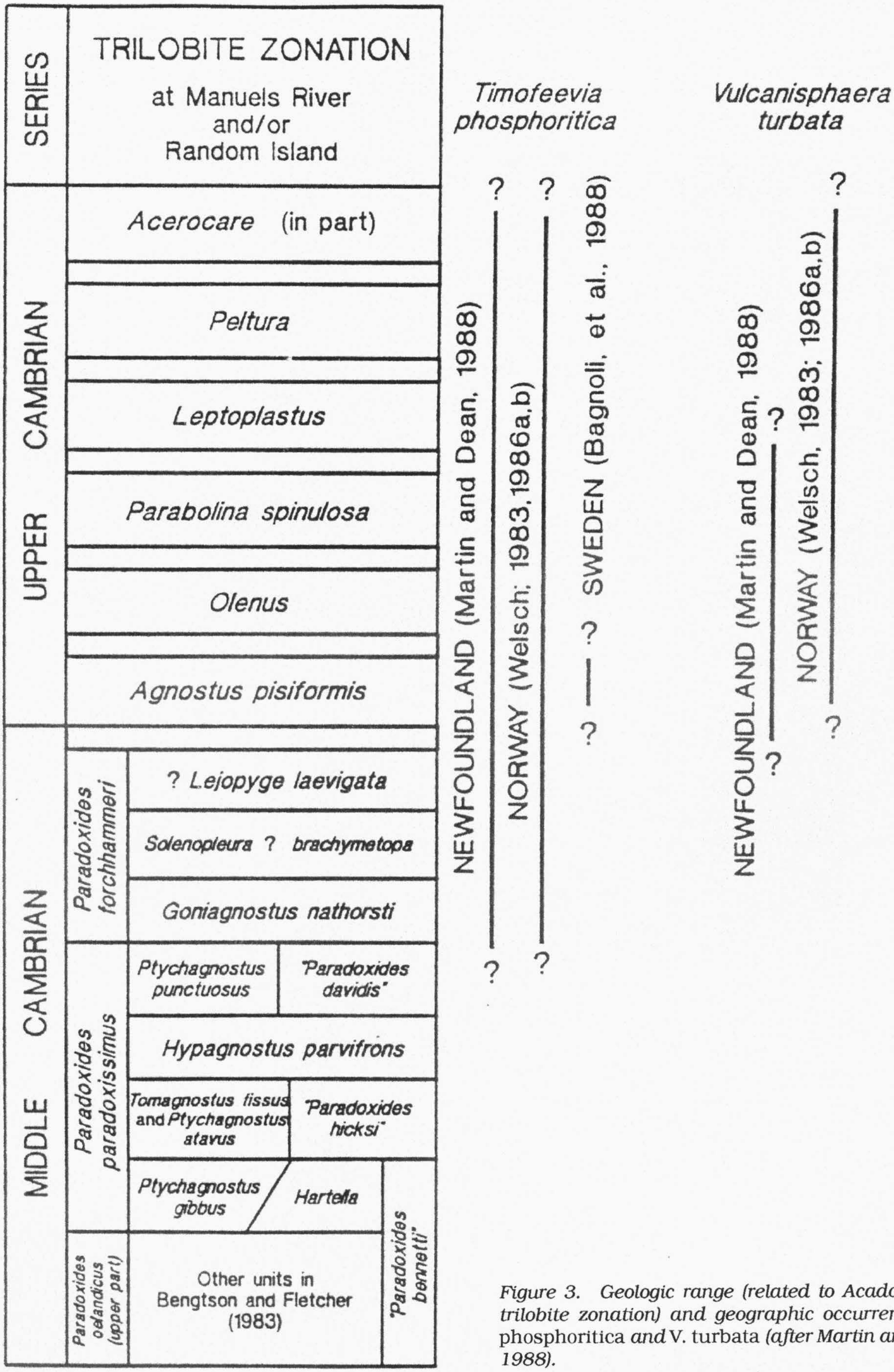

Figure 3. Geologic range (related to Acado - Baltic trilobite zonation) and geographic occurrence of T. phosphoritica *and* V. turbata *(after Martin and Dean, 1988).*

algal filaments, etc.), abundances within and between groups can be determined (e.g., between palynomorphs and types of palynodebris), and thermal maturation can be visually assessed. Using these data, in combination with geological and geophysical information, a palynofacies framework can be established to aid in identification of paleoenvironments and on the evaluation of the hydrocarbon potential of a sedimentary basin. Although few palynofacies studies have been applied to Upper Cambrian strata this technique has proven successful in younger sections (where there is terrestrial organic input) from several areas (Batten, 1982; Fisher, 1980; Habib, 1979, 1982; Manum, 1976; Parry, et. al., 1981). A general paleoenvironmental assessment of the Davis and Bonneterre formations assemblage was generated using qualitative and quantitative techniques.

There is a slight increase in the abundance and diversity of organic-walled microphytoplankton from the nearshore to basinal-rift environments. Analogous nearshore-offshore trends have been reported in studies of younger assemblages (e.g., see Dorning, 1981; Jacobson, 1981). Nonetheless, almost all samples are dominated by clusters, filaments and sheets of probable algal origin.

Thermal history is also recorded in the organic population from the Bonneterre and Davis formations. *Timofeevia phosphoritica* Vanguestaine 1978, exhibits an apparent relationship between color, the occurrence of this species in an outcrop to a deep subsurface transect and burial depth. Compare, for example, the specimen of *T. phosphoritica* recovered from an outcrop sample (Plate 1, Fig. 1), to those from the mineral cores (Plate 1, Figs. 2-3) and petroleum exploration wells (Plate 1, Figs. 4-6). Similar associations are evident in ?*Micrhystridium* cf. *M. tornatum* (Plate 1, Figs. 11-15), *Granomarginata squamosa* Volkova 1968 (Plate 1, Figs. 22-23), ?*Fimbriaglomeralla membranacea* (Kirjanov) Moczydlowska & Vidal 1988 (Plate 1, Figs. 16-18), algal clusters (Plate 2, Figs. 7-17) and algal filaments (Plate 3, Figs. 3-6).

Palynological evidence from overlying rocks also provide insights to thermal history. The conspicuous color difference between Paleocene-Cretaceous palynomorphs (Plate 4, Figs. 6-12) isolated from sediments that unconformably overlie the Cambrian section in a petroleum exploration well (Plate 1, Figs. 13-15, 26; Plate 2, Figs. 2, 12) illustrates this point.

Palynomorphs and Mineralization

The possible connection between ore deposits and organic microfossils has been demonstrated by several workers (Germanov, 1965; Horowitz, 1987; Jelen and Jankokusej, 1982; Marikos, et. al., 1986; Montacer, et. al., 1988; Muir, 1981; Oehler, 1977; Oehler, 1978; Powell and MacQueen, 1984; Robbins, 1985; Robbins, et. al., 1987). Initial recognition of this association was manifest by the geographic coincidence between oil and gas and ore deposits (see Anderson and Macqueen, 1982; Pering, et. al., 1973; Powell and Macqueen, 1984). Organic matter possibly linked with a thermal event (e.g., heat generation related to increasing depth of burial) could have produced hydrocarbon and metal bearing fluids in basinal settings that migrated updip through porous horizons (Connan and Orgeval, 1973, 1977; Orgeval, et. al., 1986). Or, sulphide precipitation via reduction of sulphate sulphur may be associated with the presence of organic matter (Disnar, et. al., 1986; Jelen and Jankokusej, 1982; Montacer, et. al., 1988; Nooner, et. al., 1973). Further research concerning the connection of organic matter and mineral deposits is needed to disclose if a similar association exists in the Pb-Zn districts of Missouri.

CONCLUSIONS

The paucity of published organic-walled microphytoplankton studies from independently dated Middle and Upper Cambrian sections and the presence of several new species whose total stratigraphic range in the warm-water provincial realm is not presently known, precludes definitive biostratigraphic conclusions at this time. However, the palynological information generated, although preliminary, support the following conclusions:

1. This is the first published record of the acritarchs *Timofeevia phosphoritica* Vanguestaine 1978 and *Vulcanisphaera* turbata Martin in Martin and Dean 1981 from the warm-water provincial realm. These species range from the upper Middle Cambrian into the Upper Cambrian in independently dated sections from Newfoundland (cold-water provincial realm).

2. *Timofeevia phosphoritica* Vanguestaine 1978 has been recovered in samples from all dip positions studied. *Vulcanisphaera turbata* Martin in Martin and Dean 1981 was recovered only from samples representing basinal sections. ?*Micrhystridium* cf. *M. tornatum* Volkova 1968 has been recovered from "shelf" and basinal localities.

3. Productive samples are usually dominated by clusters, filaments and sheets believed to be of algal origin. In general, the diversity and abundance of organic-walled microphytoplankton increases in a down-dip direction.

4. The color of organic-walled fossils reflects the thermal history at the specific localities studied.

5. An association between ore precipitation and organic matter, documented in other geographic areas, may exist in the Pb-Zn deposits of Missouri.

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OVERLEAF

Plates 1 - 4

PLATE 1

(All Photos X650 unless otherwise indicated. Coordinates from a Leitz Orthoplan microscope No. 986086).

Figure(s)

1-6 *Timofeevia phosphoritica* Vanguestaine 1978
- 1, slide 29414-A-2 (locality 3), 54.0/112.9.
- 2, slide 28948-A-4 (locality 6), 37.9/100.6.
- 3, slide 28948-A-4 (locality 6), 38.0/99.1.
- 4, slide 28101-A-2 (locality 13), 32.5/107.0.
- 5, slide 28101-A-2 (locality 13), 33.1/105.9.
- 6, slide 28099-A-3 (locality 13), 37.9/104.9.

7-9 *Vulcanisphaera turbata* Martin *in* Martin and Dean 1981
- 7, slide 28105-A-2 (locality 13), 29.0/112.0.
- 8, slide 28106-A-2 (locality 13), 33.2/112.0.
- 9, slide 28109-A-2 (locality 13), 34.8/95.6.

10-15 *Micrhystridium* cf. *M. tornatum* Volkova 1968
- 10, slide 29931-A-2 (locality 7), 25.7/107.0.
- 11, slide 28929-A-3 (locality 8), 36.2/94.0.
- 12, slide 28929-A-3 (locality 8), 42.1/95.3.
- 13, slide 26702-A-2 (locality 11), 30.2/94.0.
- 14, slide 26699-A-5 (locality 11), 54.9/103.0.
- 15, slide 26697-A-5 (locality 11), 34.7/96.2.

16-18 ?*Fimgriaglomerella membrancea* (Kirjanov) Moczydlowska & Vidal 1988
- 16, slide 29841-A-2 (locality 6), 33.8/109.8.
- 17, slide 28101-A-3 (locality 13), 49.1/109.8.
- 18, slide 27265-A-3 (locality 12), 35.3/110.0.

19-21 ?*Fimbriaglomerella* sp.
- 19, slide 28942-A-2 (locality 6), 14.1/106.0.
- 20, slide 29841-A-2 (locality 6), 40.5/108.1.
- 21, slide 27265-A-3 (locality 12), 38.0/97.0.

22-23 *Granomarginata squamacea* Volkova 1968
- 22, slide 29413-A-3 (locality 3), 44.0/112.2.
- 23, slide 29277-A-3 (locality 10), 39.5/108.5

24-27 ?*Granomarginata* sp.
- 24, slide 28929-A-3 (locality 8), 40.1/95.0.
- 25, slide 28929-A-3 (locality 8), 40.9/110.0.
- 26, slide 26677-A-3 (locality 11), 48.6/106.1.
- 27, slide 28101-A-3 (locality 13), 54.0/110.1.

28-29 Acanthomorph sp. A.
- 28, slide 29363-A-3 (locality 3), 51.9/104.0.
- 29, slide 28097-A-3 (locality 13), 50.3/106.9.

30-31 Acanthomorph sp. B
- 30, slide 28929-A-2 (locality 8), 40.0/103.2.
- 31, slide 28952-A-3 (locality 6), 34.2/100.2.

32-33 Acanthomorph sp. C
- 32, slide 31315-A-3 (locality 7), 42.1/106.8.
- 33, slide 31315-A-3 (locality 7), 19.8/109.1.

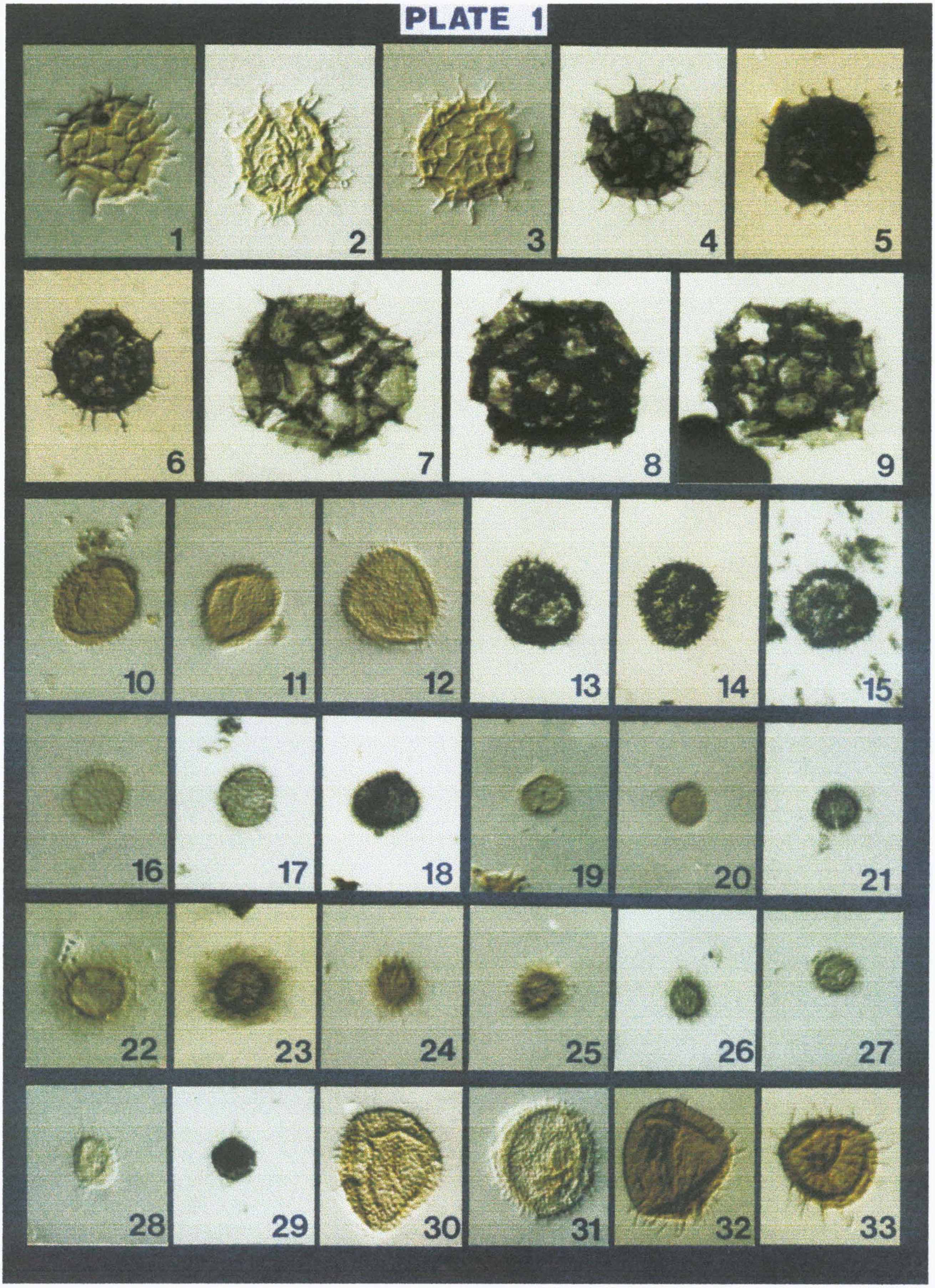
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PLATE 2

(All photos X650 unless otherwise indicated. Coordinates from a Leitz Orthoplan microscope No. 986086.)

Figure(s)		
1-2	?*Pterospermella* sp.	
	1,	slide 28099-A-3 (locality 13), 24.8/99.9.
	2,	slide 26678-A-4 (locality 11), 16.9/97.0.
3	Acanthomorph sp. D	
		slide 29841-A-3 (locality 6), 30.1/105.8.
4	Acanthomorph sp. E	
		slide 29841-A-2 (locality 6), 31.9/107.1.
5-6	Algal cluster A	
	5,	slide 28942-A-2 (locality 6), 43.9/102.0.
	6,	slide 29306-A-4 (locality 10), 35.9/111.9.
7-14	Algal cluster B	
	7,	slide 28923-A-3 (locality 8), 44.1/102.0.
	8,	slide 28923-A-3 (locality 8), 43.4/104.0.
	9,	slide 12948-A-2 (locality 6), 41.9/107.0.
	10,	slide 28948-A-2 (locality 6), 9.7/113.0.
	11,	slide 28113-A-2 (locality 13), 26.2/106.9.
	12,	slide 26689-A-2 (locality 11), 29.7/95.1.
	13,	slide 29306-A-4 (locality 10), 37.0/107.1.
	14,	slide 29307-A-2 (locality 10), 37.7/109.0.
15-17	Algal cluster C (enclosed in diaphanous membrane)	
	15,	slide 28934-A-2 (locality 8), 30.2/111.0.
	16,	slide 28934-A-2 (locality 8), 27.0/107.2.
	17,	slide 28934-A-2 (locality 8), 29.8/113.0.

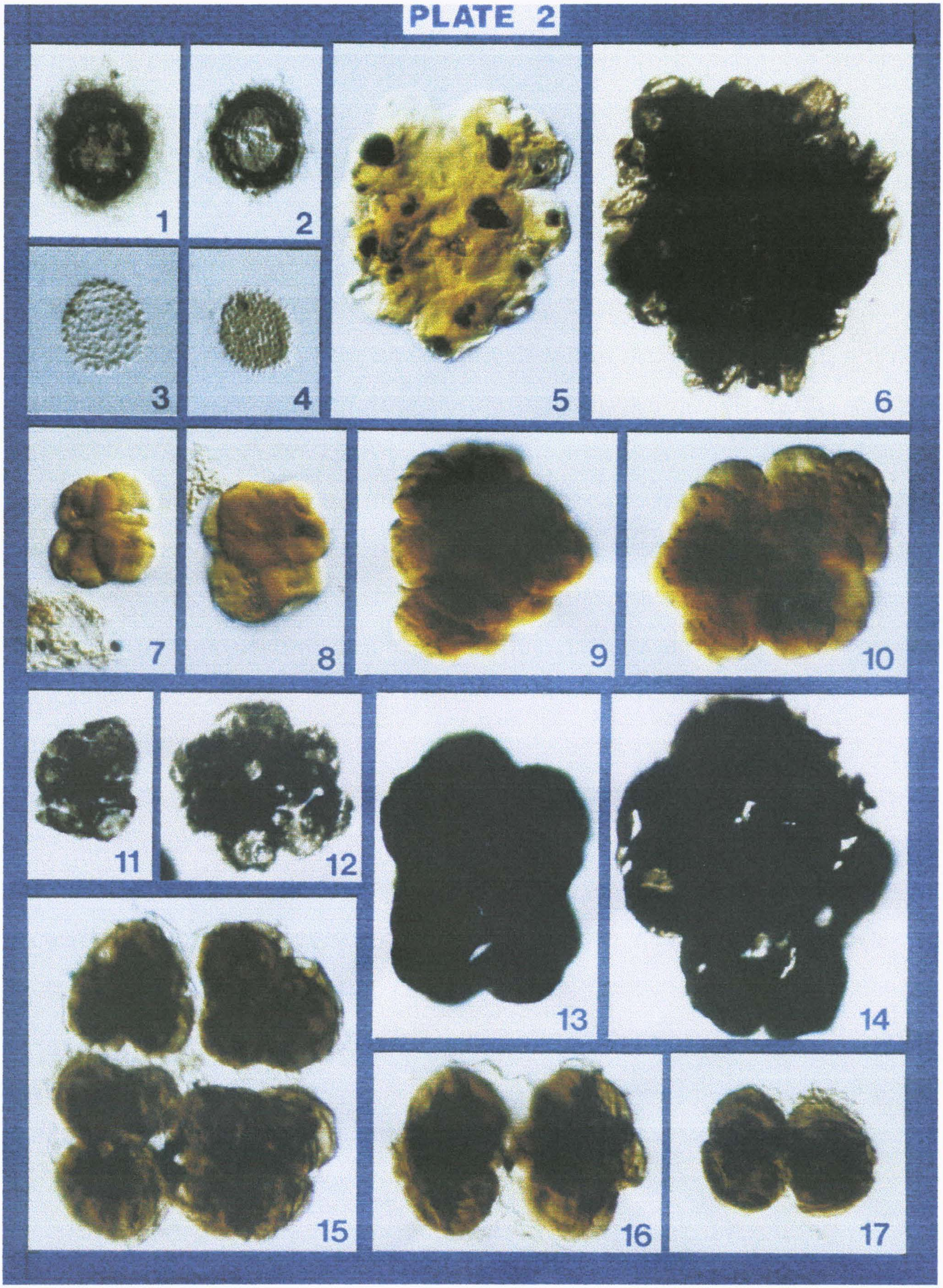
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PLATE 3

(All photos X650 unless otherwise indicated. Coordinates from a Leitz Orthoplan microscope No. 986086.)

Figure(s)

1 Sphaeromorph A (ornamented)
slide 31297-A-3 (locality 7), 33.9/106.7.

2 Sphaeromorph B
slide 29414-A-4 (locality 3), 26.3/110.7.

3-6 Non-septate tubular algal filament
3, slide 28948-A-2 (locality 6), 40.8/102.0,X.
4, slide 28948-A-2 (locality 6), 40.0/99.1,X355.
5, slide 29306-A-4 (locality 10), 36.0/107.8,X355.
6, slide 29306-A-4 (locality 10), 28.9/105.2,X355

7-8 Entangled mass of tubular algal filaments
7, slide 28927-A-2 (locality 8), 29.1/109.0,X180.
8, same as 7, X355.

9 Acanthomorph sp. F
slide 28119-A-2 (locality 13), 34.2/112.1.

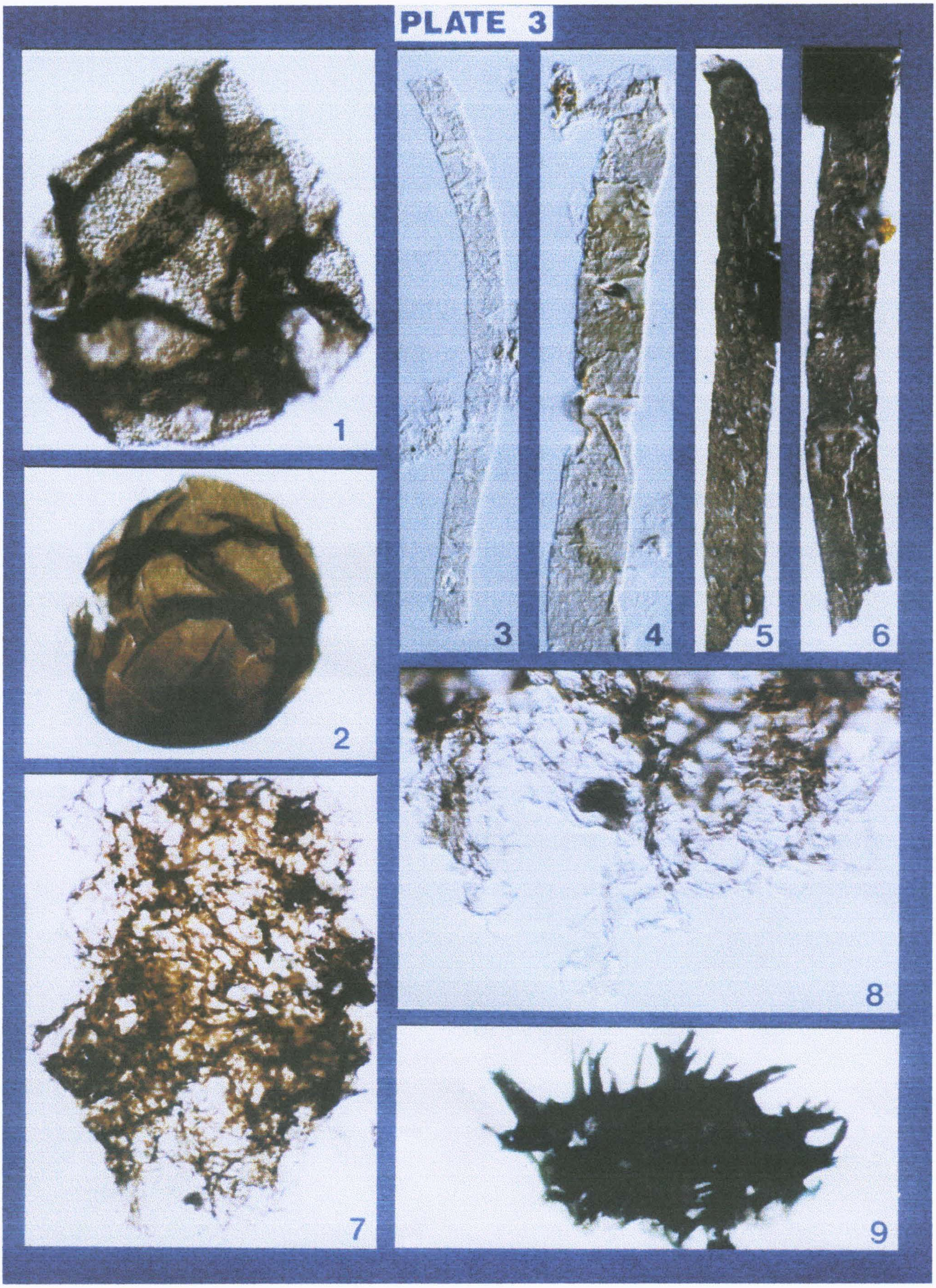
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PLATE 4

(All photos X650 unless otherwise indicated. Coordinates from a Leitz Orthoplan microscope No. 386086.)

Figure(s)

1-2 ?*Comasphaeridium* sp.
1, slide 29415-A-3 (locality 3), 43.2/113.9.
2, slide 29416-A-3 (locality 3), 48.0/102.0.

3-4 Sphaeromorph sp. C
3, slide 28941-A-3 (locality 6), 37.0/106.2.
4, slide 28941-A-3 (locality 6), 35.9/106.1.

5 Sphaeromorph sp. D
5, slide 28940-A-2 (locality 6), 26.1/94.8.

6 *Cordosphaeridium* sp.
Slide 26672-A-3 (locality 11), 50.0/98.0.

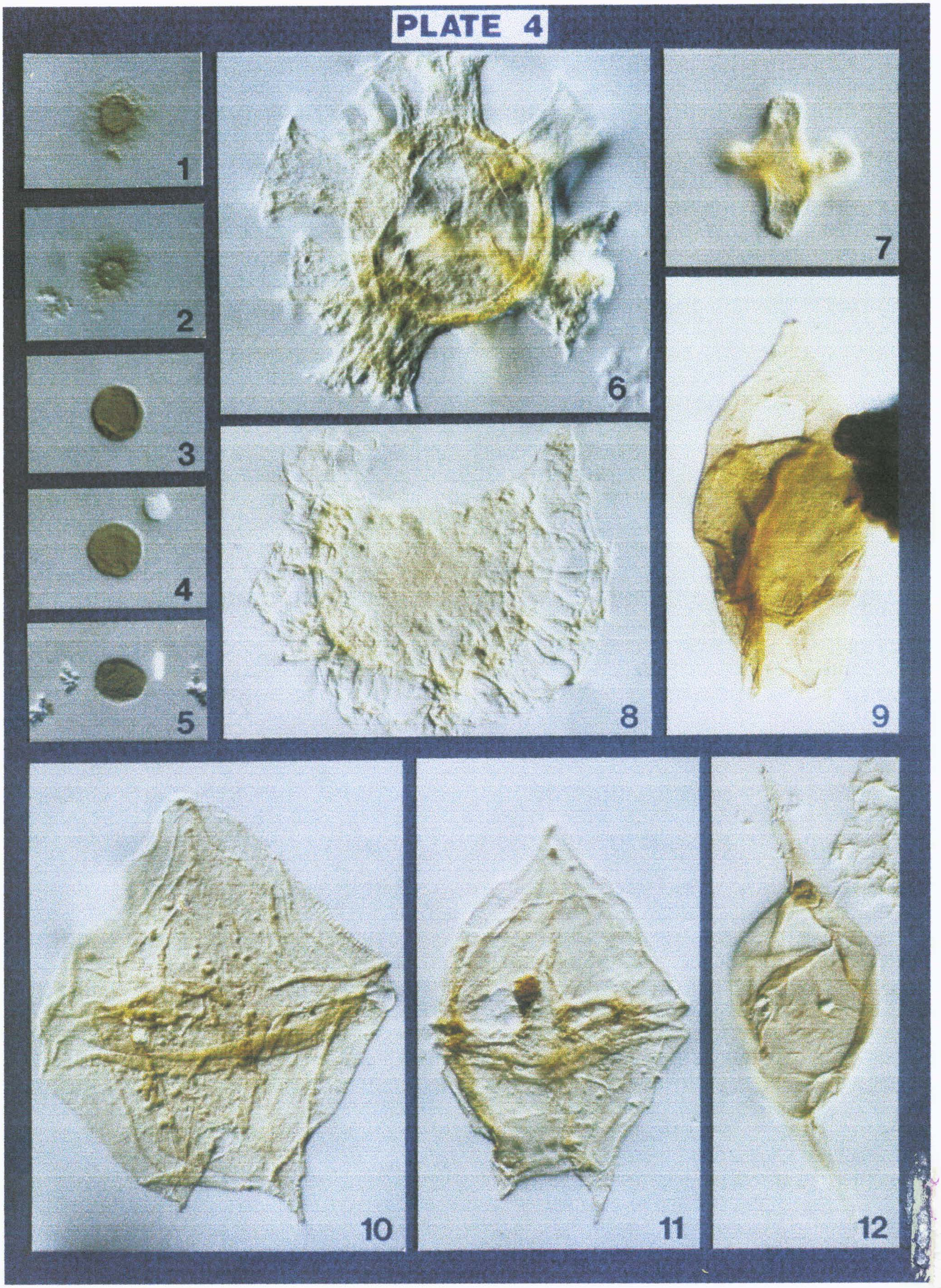
7 *Aquilapollenites* sp.
Slide 26667-A-3 (locality 11), 33.5/96.0.

8 *Glaphrocysta* sp.
Slide 26671-A-3 (locality 11), 45.0/108.0.

9 *Isabelidinium cooksoniae* (Alberti) Lentin & Williams 1977
slide 26670-A-3 (locality 11), 41.2/110.1.

10-11 *Palaeoperidinium pyrophorum* (Ehrenberg) Sarjeant 1967
10, slide 26671-A-3 (locality 11), 45.3/108.1.
11, slide 26668-A-3 (locality 11), 50.2/98.2.

12 *Palaeocystodinium golzowense* Alberti 1961
slide 26670-A-3 (locality 11), 49.9/110.8.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THE MINERALOGY AND PARAGENESIS OF THE VIBURNUM TREND ORES

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ABSTRACT

The ore deposits of the Viburnum Trend, Southeast Missouri Lead District, have been the subject of numerous mineralogical studies. These investigations have shown that the principal minerals are simple in composition, small in number, and deposited in a general paragenetic sequence. The sequence is chalcopyrite, siegenite, sphalerite, dolomite, pyrite and marcasite, octahedral galena, dolomite, cubic galena, quartz and calcite. Minor minerals locally present in the Viburnum ores include: siegenite, bravoite, vaesite, fletcherite, nickelean carrollite, bornite, gersdorffite, tennantite, enargite, luzonite, millerite, polydymite, chalcocite, digenite, anilite, djurleite, covellite, blaubleibender covellite, pyrrhotite, magnetite, anhydrite, and dickite.

Thorough investigations of the paragenetic sequence of Viburnum Trend ores reveal a complex history of ore deposition. Almost all of the ore and gangue minerals have been repetitively deposited, indicating that the introduced ore fluids varied significantly in their chemical compositions and physical conditions through time. A remarkable extent of penetration of the ore fluids throughout most of the district is indicated by the fact that the general paragenetic sequence is similar from one mine to another and by the fact that four periods of gangue dolomite deposition can be traced throughout the Viburnum Trend and even throughout much of Missouri and parts of Arkansas, Oklahoma, and Kansas.

INTRODUCTION

The ore deposits of the Viburnum Trend in the Southeast Missouri Lead District rank first in world lead production, 3rd in zinc, 6th in copper, and 7th in silver production in the United States (Esparza, 1989). The mineralogy and paragenetic sequence of the ores of the Viburnum Trend have formed the subjects for many investigations. An early study of Viburnum ores by Hagni and Trancynger (1977) provided detailed mineralogy and a paragenetic diagram for the ores at the Magmont mine. Subsequent studies on mineralogy and paragenetic sequence were conducted on the ores from the Buick (Jessey, 1981, 1983; Sverjensky, 1981; Mugel and Hagni, 1985), Sweetwater (Clendenin, 1977, Richman, 1981), and Viburnum 28 mines (Horrall, 1983). Recent studies of the ore minerals and paragenetic sequence at the Madison mine in the Fredericktown district have provided numerous electron microprobe analyses of the ore minerals (Pignolet and Hagni, 1983; Pignolet, Brandom and Hagni, 1985; Pignolet-Brandom, 1988) and information on the bornite-rich ores (Hagni, 1988).

Hagni (1986) has summarized the mineralogical studies of the ores of the Southeast Missouri Lead District and provided a comprehensive diagram for the paragenetic sequence of those ores. Heyl (1983) devised a paragenetic sequence that is similar to that of Hagni and earlier workers, but that differs with regard to the placement of calcite and some other minerals.

The trace element content of galena, sphalerite, chalcopyrite, marcasite, and pyrite, and the occurrence of cobalt and nickel in the district were discussed by Hagni (1983a). Mineral zoning, possible directions of ore fluid movement, and aspects of the paragenetic sequence, such as the character of minerals deposited during the hiatus in lead deposition between the octahedral and cubic galena stages were discussed by Hagni (1983b). Dissolution of previously deposited minerals has been discussed by Clendenin (1977), and Gregg and Hagni (1986; 1987). A paragenetic diagram recently was determined for the early, massive chalcopyrite-bornite lenses by Hagni (1988). Small, early, MVT-stage anhydrite crystals were found by Marikos (1989) to occur in rare sphalerite and octahedral galena crystals that are marked by saw kergs or grooves. A recent study of the ores from the West Fork mine has outlined a well-developed ore mineral zoning pattern, correlated it with mineral paragenesis, and noted the presence of sphalerite that has retained its original wurtzite morphology (Mavrogenes et. al., 1989; Mavrogenes, 1989).

Recent studies have focused upon the paragenesis of the dolomite crystals associated with the ore minerals. Voss and Hagni (1985) recognized four periods of dolomite deposition by the application of cathodoluminescence microscopy, and found that the four periods could be recognized throughout the Viburnum Trend. Voss et. al. (1989) have determined when the four periods of dolomite were deposited with respect to the sequence of deposition of the sulfide minerals. The purpose of this paper is to briefly review the salient features of the mineralogy of the ores and their paragenetic sequence, important features of which are: 1) the regional distribution of four generations of cathodoluminescence iron-zoned dolomite, and 2) the interlayered relationships of those dolomite generations with the ore-stage sulfides.

ORE TEXTURES

The ores of the Viburnum Trend have formed by both replacement and open space filling. Replacement ores vary from sulfide disseminations in dolomite to massive sulfide replacements. Open space fillings range from massive sulfide fillings around dolomite breccia fragments to sulfide crystal linings of small vugs and local fracture fillings. The complex combinations of replacement and open space filling textures makes the interpretation of the time relationships for the Viburnum Trend ores more challenging than for some Mississippi Valley-type ores where the ores were formed dominantly by open space filling.

MINERALOGY

The principal ore minerals in the Viburnum Trend ores are galena, sphalerite, and chalcopyrite. The iron sulfides, marcasite, and pyrite, are abundant in most ores. Smaller amounts of other sulfide minerals are present in most ores and locally may be abundant.

Galena

Galena is the most abundant ore mineral. It occurs in two morphological forms: early deposited octahedral galena with cubic modifications, and late deposited cubic galena that may have minor octahedral modifications. Octahedral galena typically occurs as disseminated crystals in dolomite and shaly dolomite and as massive ores, but locally may form euhedral crystals in vugs. Cubic galena is less abundant than octahedral galena, commonly forms as euhedral crystals deposited in vugs, but also may replace host rock dolomite and earlier deposited sulfides. The more thorough mineralogical investigations (Rickman, 1981; Horral, 1983; Hagni, 1986; Pignolet-Brandom, 1988) have distinguished four periods of octahedral galena deposition and as many as three periods of cubic galena deposition.

Sphalerite

Sphalerite is second in abundance among the ore minerals of economic value. Sphalerite occurs dominantly as fine-grained replacements of the host rock dolomite. Many disseminated sphalerite crystals can be easily overlooked by the naked eye, and they are best studied under the microscope. Late, less abundant sphalerite crystals have been deposited in vugs in the host rock dolomite and earlier deposited sulfide minerals. A total of at least five generations of sphalerite have been distinguished in studies of paragenetic sequence, and crystals deposited during each stage typically are characterized by colors that result from trace quantities of iron, germanium, organic matter and zinc:sulfur ratio.

Chalcopyrite

Chalcopyrite is less abundant than galena and sphalerite in most ore from the Southeast Missouri Lead District. Although other copper minerals are present, they occur only locally and in minor amounts. Unusually large amounts of chalcopyrite occur in the ores at some mines, such as Doe Run's Castel or 35 mine. Chalcopyrite occurs as disseminated crystals, massive ores, and as minor late euhedral crystals deposited in vugs.

Marcasite and Pyrite

The iron sulfides, marcasite and pyrite, commonly are associated with the economically valuable ore minerals, and locally they are very abundant. They occur as early, fine-grained disseminated sulfides that may form throughout and at the margins of the ore deposits. Iron sulfides are more abundant in massive ores, where they form colloform bodies in which the two minerals were deposited in alternating bands with pyrite generally early and marcasite more common in the late bands. Late euhedral marcasite and pyrite crystals were deposited locally in vugs.

Cobalt and Nickel Minerals

Small amounts of cobalt and nickel are persistently present in the ores of the Southeast Missouri Lead District, although they are not recovered. The two metals occur principally in the thiospinel, siegeneite. Siegenite usually is deposited immediately after and forms octahedral coatings on chalcopyrite. Seven generations of siegenite deposition have been recognized.

The nickel-iron sulfide, bravoite, also is relatively abundant in the ores. Electron microprobe analyses indicate that bravoite also can contain as much as 9.2% cobalt (Pignolet, 1988). Bravoite most commonly occurs as pyritohedral crystals disseminated in host rock dolomite and other sulfide minerals, but subsequently deposited bravoite may form layers within colloform pyrite-marcasite bodies.

Minor cobalt-nickel minerals include fletcherite, nickelean carrollite, gersdorffite, vaesite, millerite, and polydymite. The latter four minerals are abundant in some ores from the Magmont West ore deposit (Hagni, 1989).

Chalcopyrite-Bornite Lenses

Small lenticular bodies and pods of massive chalcopyrite and bornite replacements of host rock dolomite, which have been deposited early in the paragenetic sequence, are present very locally in the lead district. They also contain small, variable amounts of pyrite, nickelean pyrite, bravoite, fletcherite, nickelean carrollite, sphalerite, gersdorffite, tennantite, enargite, vaesite, digenite, anilite, chalcocite, djurleite, covellite, and blaubleibender covellite (Hagni, 1986).

Dolomite

Four generations of dolomite cements have been recognized by Voss and Hagni (1985) to occur in the Viburnum ores. They have been distinguished by their differing cathodoluminescence character. They also postulated that the extent of dissolution developed on dolomite crystal faces between the deposition of generation 3a and that of 3b may be related to the proximity of sulfide ores.

Millerite

Millerite is a widely distributed minor sulfide in the Viburnum Trend and elsewhere in Missouri. It occurs as acicular crystals that may be preserved within galena and other sulfide crystals, but commonly is largely altered to polydymite and vaesite where the millerite crystals were exposed in vugs to reaction with later more oxidizing fluids (Hagni, 1986). Millerite occurs as abundant colloform masses as well as acicular crystals in ores in the Magmont West ore deposit.

Late Gangue Minerals

Several non-sulfide gangue minerals were deposited at or toward the end of sulfide mineral deposition. Quartz began deposition before cubic galena but was deposited mainly after lead deposition. Calcite was deposited as scalenohedral and prismatic crystals formed in vugs. Dickite formed during and after calcite deposition.

Four types of bitumen were found to occur at the Sweetwater mine by Rickman (1981) and Niewendorp (1987). They vary from yellow-brown resinous material to shiny, black, coal-like blebs, pods, and veinlets. Shiny, black bitumen present in shaly dolomite horizons at the Magmont mine has been interpreted by Marikos et. al. (1986) to have been derived from the host rock at the time that the ore-bearing hydrothermal fluids were introduced. Henry et. al. (1988) found that reflectance measurements and analyses for C, H, O, N in kerogen concentrates from the Bonneterre Dolomite indicate that the threshold of intense hydrocarbon generation was reached only within about 10 kilometers of the Viburnum Trend.

PARAGENESIS

The paragenetic sequence for the ores of the Southeast Missouri Lead District is given in Figure 1. The diagram is based upon the megascopic and microscopic examinations of ore samples collected from throughout the Southeast Missouri Lead District, especially from the Viburnum Trend. The deduction of the complete paragenetic sequence requires the study of a large number of specimens from a given mine; the complete sequence is not evident in a single ore specimen nor even at a given locality within a single mine. Although there are minor differences in paragenetic sequence from one locality to another within the mines and all of the major minerals are deposited repetitively, the general paragenetic sequence is remarkably similar from mine to mine.

The earliest sulfide minerals deposited were disseminated pyrite, bravoite, and marcasite. The massive chalcopyrite-bornite lenses were deposited at an early time from fluids that were different in chemical composition, probably more oxidizing, and possibly slightly hotter than the later lead-zinc depositing fluids. The principal ore minerals were subsequently deposited in the general sequence, chalcopyrite, siegenite, sphalerite, dolomite-2, pyrite and marcasite (commonly in colloform masses), octahedral galena, dolomite-3 and 4, cubic galena, quartz, and calcite.

CONCLUSIONS

The principal ore minerals in the deposits of the Viburnum Trend of the Southeast Missouri Lead District are small in number, simple in composition, and were deposited in a general paragenetic sequence as follows: chalcopyrite, siegenite, sphalerite, dolomite-2, pyrite and marcasite, octahedral galena, dolomite-3 and 4, cubic galena, quartz, and calcite.

The Viburnum Trend also contains a rather large number of minor minerals that are absent or rare in other Mississippi Valley-type ore deposits. These include siegenite, bravoite, vaesite, fletcherite, nickelean carrollite, bornite, gersdorffite, tennantite, enargite, luzonite, millerite, polydymite, chalcocite, digenite, anilite, djurleite, covellite, blaubleibender covellite, pyrrhotite, magnetite, anhydrite, and dickite. It has been suggested that the copper, cobalt, and nickel, required for many of these minerals, has been derived by leaching of mafic and ultramafic #igneous bodies in the Reelfoot Rift (Horrall et. al., 1983).

The paragenetic diagram reveals that the complete history of ore deposition in the Viburnum Trend is complex. The fact that almost all of the ore and gangue minerals have been repetitively deposited indicates that the introduced ore fluids varied significantly in chemical composition and physical condition over time. The fact that many of the minor minerals were deposited only locally further attests to variations in the character of the ore fluids.

The general paragenetic sequence is essentially the same from mine to mine and suggests that the ore fluids were migrating throughout major portions of the district throughout most of the epoch of ore deposition. Further support for this interpretation comes from the fact that four periods of gangue dolomite deposition can be traced throughout the Viburnum Trend. In contrast, the spatial limitation of the early deposited chalcopyrite-bornite lenses and pods indicates that the ore fluids did not migrate freely throughout the district at that time.

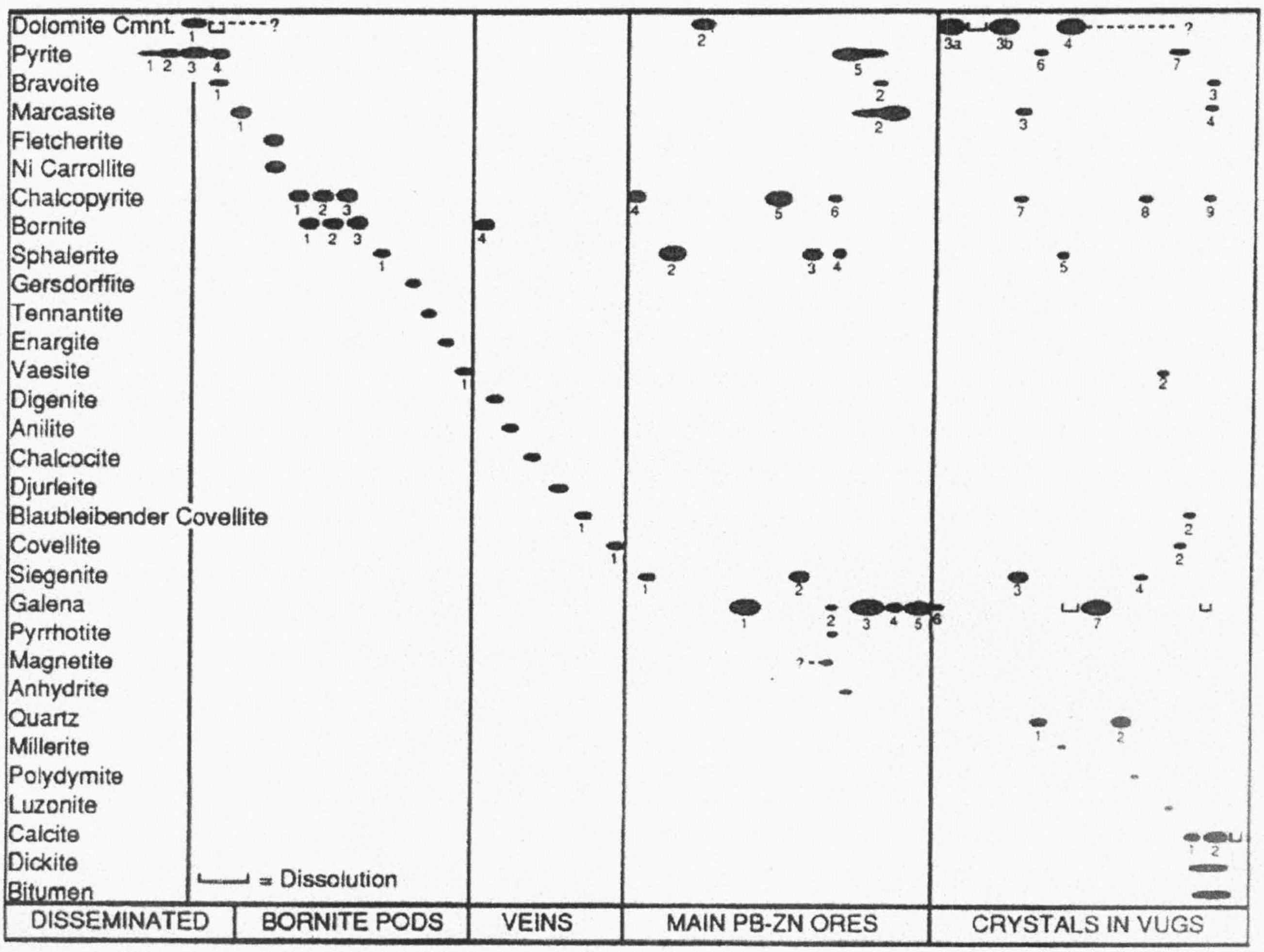

Figure 1. Paragenetic sequence of ore and gangue minerals in the southeast Missouri Lead District (from Voss et al., 1989).

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RECENT EXPLORATION HISTORY IN SOUTHEAST MISSOURI

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Since the first recorded discovery of lead in Southeast Missouri near Fredericktown about 1720, knowledge of the deposits has advanced in spurts as a result of outlying discoveries:

1864 Bonne Terre
1890 Flat River, Desloge, Leadwood
1948 Indian Creek
1955 Viburnum

The original discoveries at Bonne Terre consisted of residual galena in clay, similar to that in the previous finds at Fredericktown. Occurrences in solid dolomite were not noted until mining of the clay pits exposed the walls of the weathered depressions. The St. Joseph Lead Co. had been established to conduct the operations and it was J. Wyman Jones, first President of St. Joe, who at that time brought about the first of the technological advances that were to occur in the district. He proposed use of the newly-invented diamond drill to explore the bedrock showings, after observing the machines in the Vermont Marble Belt.

The first holes were drilled immediately behind the pit walls and were sufficiently successful that a shaft was sunk in 1859. Thus began the underground history of lead mining in southeast Missouri. The Bonne Terre area was the only producer from underground, hard-rock mining for the next 30 years; minor production came from shallow, surface "diggings" and veins near what is now Flat River but was insignificant and spotty. This shallow mineralization was not contiguous with the deep deposits found later.

Major discoveries of deep ore near Flat River were delayed by a negative theory of ore genesis. Although there were some advocates at that time of ore deposition from rising solutions, the most widely held theory called on downward-descending groundwater. This resulted in a negative appraisal of areas where the Bonneterre Formation (the ore host) was overlain by the impervious Davis shale. It was felt that descending groundwater would not be able to penetrate the 150 feet of shale. This ruled out most of the area to the south and southwest of Bonne Terre. Thus it was not until an unknown, venturesome individual drilled holes there anyway that what proved to be the largest orebodies in the "Old Lead Belt" were discovered. Great finds were made in an area nearly twelve miles long in a northwest-southeast direction. They totaled nearly 400,000,000 tons. The sub-districts of Deslodge, Leadwood, Rivermines, and Flat River eventually were interconnected underground.

The Southeast Missouri District has been the largest lead producer in the United States since 1890. Nearly a dozen companies had operations there at one time or another but, by 1933, the St. Joseph Lead Company had consolidated all the properties except those 30 miles to the southeast near Fredericktown. There, National Lead Company continued production until 1961. By 1940, the long period of high-tonnage production mining had reduced reserves significantly even though the cut-off grade had been reduced to +2% lead. This, along with the great metal demands of World War II, led then-St. Joe President, Clinton Crane, to propose a major exploration program. This involved spreading outside the "Old Lead Belt" and was not optimistically undertaken by many, as reasons for the limitation ore to that specific geologic block was deeply ingrained.

To understand the pessimism, it is necessary to note the uniqueness of Old Lead Belt geology. It is the only area around the periphery of the St. Francois Mts. (a domal structure) where the formations dip toward the center rather than in the normal direction. This anomalous situation is the result of 600 feet of movement on the Simms Mt. Fault, and the 80 years of concentration in this block of rock had given rise to the idea that the reversed dip was significant in ore localization. Hence the advent of drilling to the northwest where the dip was normal was approached with skepticism, a feeling which grew as literally hundreds of blank holes were drilled and four years passed. The details of the effort are given in the following in-house account by R.E., Wagner, who directed the work after the first year. Figures 1 and 2 show the geographic locations and geologic features discussed below.

Bonne Terre, Missouri
October 2, 1953

MEMORANDUM TO MR. ELMER JONES:
Reference: Indian Creek Ore Body.

After our recent conversation concerning the events leading up to the discovery of the Indian Creek ore body, I thought it might be of interest to write a short history of those developments while fresh in my mind.

In the early part of 1944 Mr. Crane called Mr. Jewell, Mr. Weigel, and myself (the unofficial geological staff) in for a meeting in Mr. Sicka's office with himself and other Company officials. He told us, in brief, that he wanted us to go out and find another Lead Belt anywhere in Southeast Missouri and that the Company was willing to spend a very considerable amount of money to accomplish this. Discussion developed the fact that Mr. Crane thought that any ore bodies found in the Fredericktown, Annapolis, or Irondale areas would be too small to satisfy the requirements of an ore district such as he wanted to find. There was no doubt that Mr. Crane felt that the most attractive possibility was the deep ground of Washington County, where practically no deep drilling had been done.

The three of us were told to study the matter and to submit recommendations. Mr. Weigel was asked to combine our separate ideas into a single report, which he submitted on April 14, 1944. In regard to where to prospect there was no particular disagreement, the area chosen constituting roughly the central and southern part of Washington County lying north of the Big River and Palmer fault systems and including the Palmer area. Naturally, each of us had some favorite spots. Mr. Jewell liked the area bisected by No. 8 Highway between the Big River fault and Potosi, including the new Diggings area where shallow lead and zinc had been mined. Mr. Weigel was particularly interested in the Shirley fault zone west of Potosi and the ground between it and the Floyd Tower porphyry exposure. I liked the Furnace Creek area south of Potosi and the Palmer area.

After considerable discussion of the report by ourselves, Mr. Crane and Mr. Brown, who was then at Balmat, a second report was made by Mr. Weigel on May 5, 1944 compromising the controversial ideas on pattern of holes and optioning necessary to prospect these areas.

Approval to go ahead with the program was given at the spring directors meeting after an explanatory session in Mr. Sicka's office and optioning was begun by the Real Estate Department. In the end, the distribution of the optioned areas had little resemblance to any of the plans presented ex-

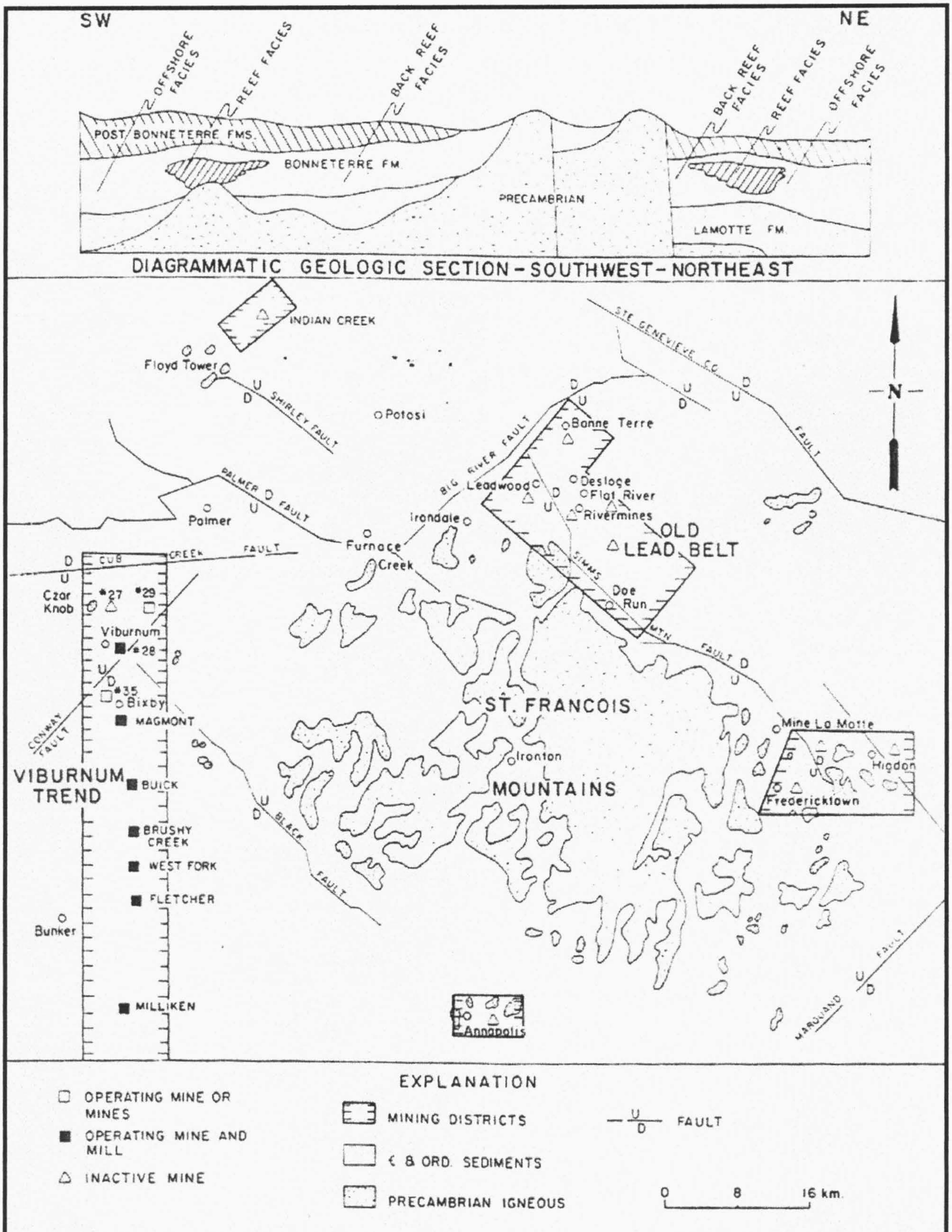

Figure 1. Major geological features and lead districts of southeast Missouri.

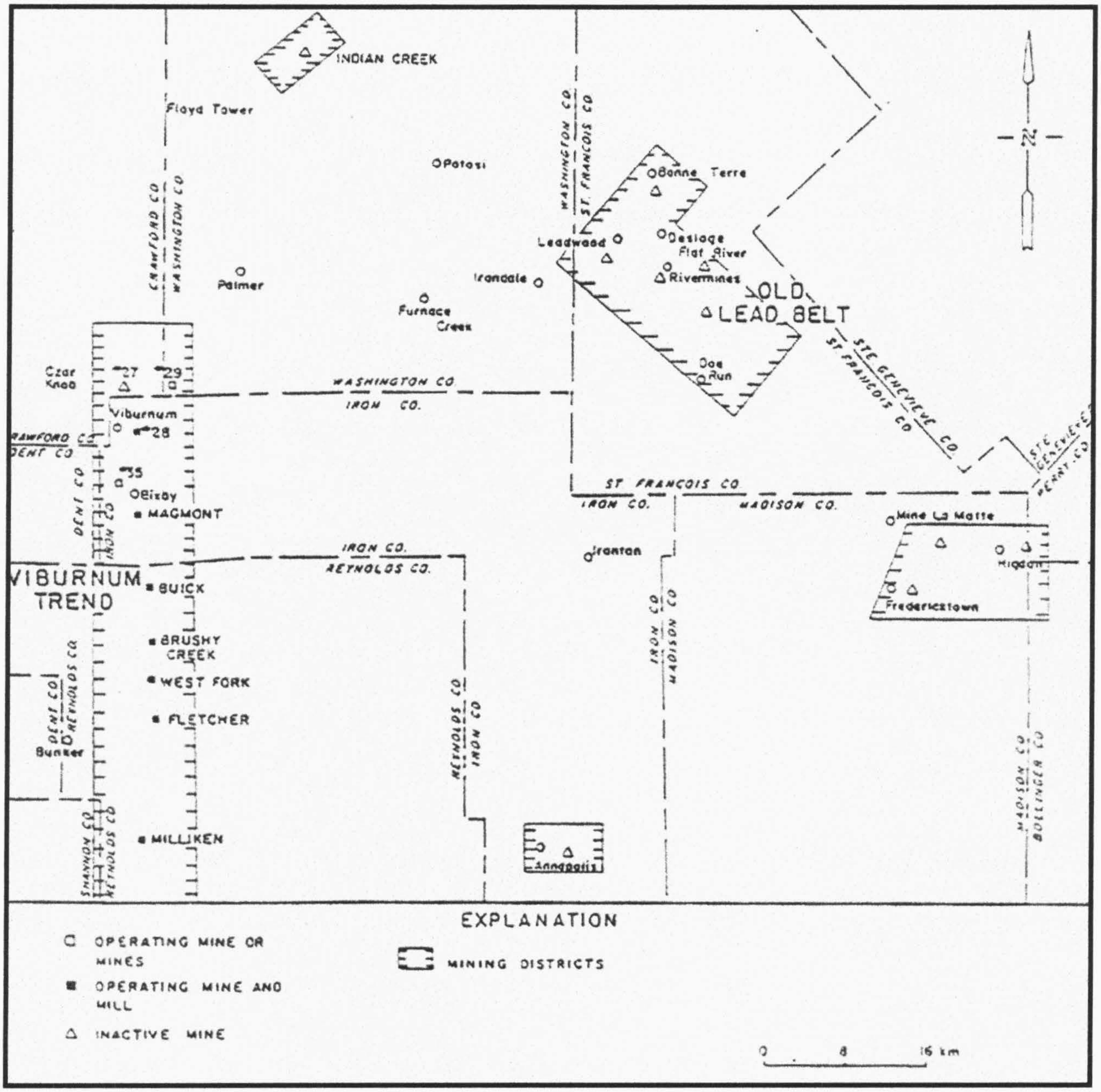

Figure 2. Lead districts of southeast Missouri.

cepting that a rather complete coverage was obtained over the eastern part of the general area recommended for investigation. The Palmer area was not available for reasonable option and much of the western part of the area was found to be in U.S. Forest Land.

In the summer of 1944, the Bonne Terre division started four drills on the Company owned land east of No. 8 Highway, a little later Leadwood division put four drills in the Wallen Creek area and in September Federal division started two drills in the Furnace Creek area. Winter weather stopped the drilling about the first of December. Two holes with fair lead were found in the Furnace Creek area, along with several trace holes, with the other areas were practically negative. We were encouraged to find that the Furnace Creek area rock types were similar to those in the Lead Belt and the point had been proved that mineralization was possible in the deeply covered Bonneterre beds.

No drilling, except churn drilling of sleeve holes, was done in 1945 because of necessity of placing prospecting employees underground to help out in the stepped up war time production effort. In early 1946 the separate exploratory groups were merged into one prospecting organization under Mr. Bain and under my direct supervision. Eighteen drills were put into the field in the early part of March and a great amount of drilling was done in several months time. The encouraging results of the 1944 drilling in the Furnace Creek area did not develop into the expected ore bodies, the New Diggings area was a disappointment and by July the program was greatly curtailed and optimism was conspicuous by its absence.

The first fortunate link in the chain of circumstances leading to the discovery of the Indian Creek ore bodies is found in this first optioning program. Included in the options taken were two large options from the Potosi Tie and Lumber Company containing 3,520 acres and 5,593 acres respectively. The bulk of this land lay in the southern and central part of the county in which we were interested but several isolated tracts as much as 10 miles north of Potosi were included. Also included was a group of holdings comprising 1,302 acres lying roughly 10 miles northwest of Potosi and one to three miles southwest of the present Indian Creek shaft. The fortunate circumstances was that we were forced to include these outlying tracts in order to get the land we wanted in the southern and central part of the county. Had we succeeded in refusing to take these tracts, the Indian Creek ore would not have been found in this campaign.

After the disappointing results in the main area, we decided that, before abandoning the program, we would scatter a few exploratory holes on these isolated tracts to the north. Results were uniformly bad in that the Bonneterre formation was mostly limestone. Because of this, it was not planned to do any drilling on the northwest tract on Indian Creek. While this drilling was being done we got the opportunity to option a 4,016 acre tract most of which lay in the area between the Shirley fault zone and the Floyd Tower porphyry knob. The option was taken about November 1, 1946 and drilling began immediately. Again, results were negative in that, while the Bonneterre formation was dolomitized and favorable appearing, no sign of lead mineralization was found.

Here the second lucky break occurs in the story of Indian Creek. Included in this 4,016 acre option were 800 acres lying about 2 miles north of the main option area and adjoining the aforementioned 1,302 acre tract of the Potosi Tie Company. Together they formed a sizeable and compact block of 2,102 acres lying farther to the northwest than drilling that had been done or was contemplated. This block lay about 3½ miles northeast of Floyd Tower porphyry. It was decided that while we were in the area we would check this block with a few holes to see whether the limestone conditions continued in this direction as indicated by the drilling north and northwest of Potosi. Three holes were spaced over the area.

The first hole contained limestone, bottomed in Lamotte sand and was blank. Of interest only was the fact that a thin bed of porphyry cobbles was encountered above the sand suggesting the proximity of a buried porphyry high. The second hole was all dolomite, bottomed in Lamotte, and showed no mineralization. The third hole, located on Indian Creek, was drilled into the top of the Bonneterre when the bit was stuck.

At this point probably the most crucial decision leading to the discovery of the Indian Creek ore was made. The time was January 1947 and we were anxious to finish the campaign and move in to the Irondale area because of the difficult winter drilling conditions in this roadless isolated area. No one thought that the drilling in the area showed any promise of ore and it did not seem too important whether this third hole was completed. Mr. Sears, who was field engineer on the job, was accordingly told to attempt to get the bit out and complete the hole, if possible, but if it was found necessary to ream the bit out just to abandon the location and move out. He and Mr. Radford, field foreman, supervised the attempt and got everything out of the hole except the core barrel and bit and found that they would have to ream to get them. Instead of abandoning the location, they decided to attempt to wedge off the hole above the barrel and bit. I suspect they were motivated somewhat by the fact that we hadn't tried this before and they wanted to see if they could do it. With somewhat crude and improvised methods they were successful and proceeded to drill by the bit and to bottom the hole.

The hole bottomed in porphyry with no Lamotte present and the Bonneterre formation showed a section of fingered and altered rock very similar to that in the southern part of the Lead Belt. A few speck traces of lead were present in the finger rock. This is really the discovery hole for the Indian Creek ore bodies as all succeeding events stemmed from this showing. Had this hole been abandoned Indian Creek shaft would probably not in existence today.

Mr. Murphy (by that time St. Joe General Manager for Southeast Missouri) and myself decided that the nature of the core was such as to warrant further investigation. The option area was expanded somewhat. In the meantime the diamond drills had been moved to Irondale and Doe Run. Churn drills were moved back into the area and diamond drills followed in the later part of 1947. Wide-spaced holes were scattered over the entire option area and some 500-foot spaced drilling was laid out in the vicinity of the speck trace hole. The outlying holes failed to show anything but the close holes found a few weak pay sections and much trace lead and developed the picture of a buried porphyry ridge extending east-northeast with lead mineralization occurring along its northern flank.

Continuation of the drilling into 1948 failed to improve the picture since the mineralization became weaker as we followed the ridge eastward to the edge of our options. Optimism was dampened and it seemed that we had found a small low-grade ore body which would not warrant development.

After discussion with Mr. Murphy, we decided to option land several miles farther to the east and northeast in the direction of the trend and go follow the trace mineralization until it either got better or disappeared entirely. A high magnetometer reading taken in the road near the present shaft site indicated the probability of the ridge extending at least that far. Mr. Shannon, who was assisting me as field geologist, chose two points for north-south sections, one 4,000 feet northeast of the last drilling and one two miles northeast. Holes were spaced 1,500 feet apart on the first section which passes through the present shaft site. The hole located 1,000 feet south of the shaft was blank and bottomed in high porphyry checking the continued presence of the buried ridge. The hole 500 feet north of the shaft showed weak trace lead and zinc mineralization and was not bottomed on account of caving ground. The presence of both lead and zinc in this hole suggested the possibility of proximity to a mineralization center and two additional holes were located on the section along with two holes offset 800 feet to the east on diagonal lines intended to split the gaps between section holes in the estimated direction of the trend of the ridge. It was the southernmost of these last two holes which came in with 36 feet of 3.6% Pb and became the first pay hole in the main Indian Creek ore area. This was 4 ½ years after Mr. Crane's initiation of the program, 4 years after the first drilling in the southern part of the county and 1 year, 7 months after the discovery of the first speck trace hole on the banks of Indian Creek 13,000 feet to the southwest.

This hole was bottomed in August 1948 during the strike. The contact drills continued working and my office and maps were located in my car. I took Mr. Weigel and Mr. Grayson with me and we spotted 4 locations on 500-foot centers in the vicinity of the pay hole with Brunton compass. Three of these holes came in pay and the remainder of the Indian Creek story consists of following up and expanding the ore area.

In summary the story can be divided into 2 phases. The first, a sequence of fortuitous circumstances which led to the discovery of the first speck trace hole, and the second, the use of geological analysis of drilling results and the persistence of local management in following the trace of the mineralization a distance of2 ½ miles to the main ore area.

The key points in the first phase were:

1. The decision of Mr. Crane to initiate an exploration program in search of a new ore area.

2. The fortunate accident that two separate options included tracts of land outside of the area in which we were interested that we were forced to include in order to get the options and that these outlying tracts combined to form a large enough area to invite a few exploratory holes.

3. The decision by Mr. Sears and Mr. Radford to attempt to wedge by the stuck bit in what became the first trace hole. Had this hole been abandoned no more drilling would have been done in this area.

In the second phase the most important decisions seem to me to be:

1. Mr. Murphy's agreement that the speck trace hole appeared interesting enough to warrant additional optioning and drilling.

2. Mr. Murphy's decision that optioning and drilling should be extended eastward even though the mineralization seemed to be dying out in that direction.

3. The decision that the presence of zinc mixed with lead in the hole north of the shaft might be significant and warranted some closer drilling in the immediate vicinity, although the mineralization was otherwise insignificant.

Of prime importance is the fact that the New York management, patiently authorized the expenditure of considerable money for a period of 4½ years.

There is possibly a lesson to be learned from this story. At the time this campaign was started no surface geology mapping had been done in the Indian Creek area. This was undoubtedly a very important factor in confining our original interest to the Potosi quadrangle, which had been mapped. The reflection of the Indian Creek buried porphyry ridge in the outcropping formations is easily discernable on the areal geology map prepared by Mr. Shannon during the latter part of the campaign. Aerial magnetometer mapping done later also shows a strong anomaly over the buried ridge. Had such maps been available in the beginning this area would probably have become of interest immediately. I dare say that, except for a few fortunate breaks that we were favored with, the Indian Creek ore would possibly have remained undiscovered until such a time as the surface geology in the area was mapped. I consider that there is nothing so important in the planning of exploratory drilling in Southeast Missouri as the development of good surface geology maps over the entire area.

Richard E. Wagner
Geologist

The discovery of the Indian Creek orebody in the late Spring of 1948 was a most significant event. In a sense it opened up the entire southeast quarter of the State of Missouri to exploration because it indicated that ore-forming conditions were not limited to the Old Lead Belt Block. Other companies were quick to sense the situation and an exploration boom began which still continues.

Since the Indian Creek orebody, like the one at Bonne Terre and some others in the Old Lead Belt, was related to a Precambrian knob structure, attention was directed to the many other similar knobs around the periphery of the St. Francois. One of these was a structure in southeastern Crawford county called Czar Knob and, on September 2, 1955. St. Joe drilled the first pay hole there. This was the start of the great effort which defined the Viburnum Trend although, strictly speaking, the initial find (which came to be Viburnum #27 Mine) was not part of the Trend. It was nearby, however, and the first pay hole in the Trend bottomed on May 3, 1956, near the present Viburnum #28 plant site. The hole was spotted at this location because surface geologic mapping indicated the likelihood of a buried Precambrian knob nearby.

Again, exploration by other companies exploded, and by 1964 a near-continuous orebody 40 miles long and with approximately a half-billion tons of +5% ore had been outlined. Most of the mines were found simply by extending St. Joe's effort but the discovery by Kennecott 40 miles to the south of the original discovery was a legitimate, independent success.

In 1947, the St. Joe Geological Department had been established under John S. Brown and, over a period of several years prior to the discovery of Czar Knob orebody, a considerable understanding of the district's ore controls had developed. Of particular note was the pronounced influence of sedimentary depositional structures, particularly algal reefs within the Bonneterre. A facies relationship of carbonate types, limestone, dolomite and distinctive types of dolomite, was revealed by the extensive regional drilling. The digitate algal reefs, usually brown in color, formed a ring surrounding the main St. Francois Mt. "high" and this came to be known as the "brown rock ring". Much Old Lead Belt and Indian Creek ore is in reef rock; at Viburnum, the best ore is in thick-bedded oolite just above the long, narrow reef and often it is marked by trends of collapse breccia. Knowledge of these relationships contributed to the exploration and development of the Trend.

NOTE: This paper was simultaneously published in: Hagni, R.D., and Coveney, R.M., Jr., eds., 1989, Mississippi Valley-type Mineralization of the Viburnum Trend, Missouri: Society of Economic Geologists, Guidebook series, 199 p.

FIELD TRIP STOP DESCRIPTIONS

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INTRODUCTION

What follows are descriptions of the field trip stops used for the 1989 SEPM Midcontinent Section and the GSA field trips to the St. Francois Mts. region. Each description contains detailed directions to the location by road as well as township and range locations to at least the quarter section. A road map is provided (Fig. 1) showing the locations of the numbered stops to allow for visits to the locations by alternate field trip routes.

STOP DESCRIPTIONS

Stop 1. Hwy. 49, 1.7 mile south of J intersection (SW 26, T33N, R.1E, Edgehill Quad.) Exposure of Black fault in road cut. Precambrian felsic volcanics on the north (upthrown) side, Bonneterre back reef facies on south (downthrown) side. Most major faults cutting Cambrian rocks in the St. Francois Mts. region trend in a northwesterly direction. The Black Fault has been the epicenter of recent seismicity in southeast Missouri.

Stop 2. At Hwy. 21 – Hwy. M intersection turn north on Hwy. M and go 3 mi road cuts mostly on southeast side of the road (NE 30, T33N, R2E, Johnson Shut-Ins Quad.) Dolomitized platform carbonates on the Elvins Group (Palmer, this volume). Section contains 110 ft. of crystalline carbonates containing herring-bone cross bedding and igneous rock fragments. Upper part of the section has *Eorthis remnicha*.

Stop 3. From Hwy U Hwy 49 intersection go east 0.5 mi to outcrop on the north side of the road (across from the Lesterville Jeep Clubhouse) (NE 15, T32N, R2E, Lesterville Quad.) Lower Davis Formation "white rock" facies. Note cryptalgalaminates, rip-up clasts and other shallow subtidal and intertidal features, which are similar to those in the underlying Bonneterre

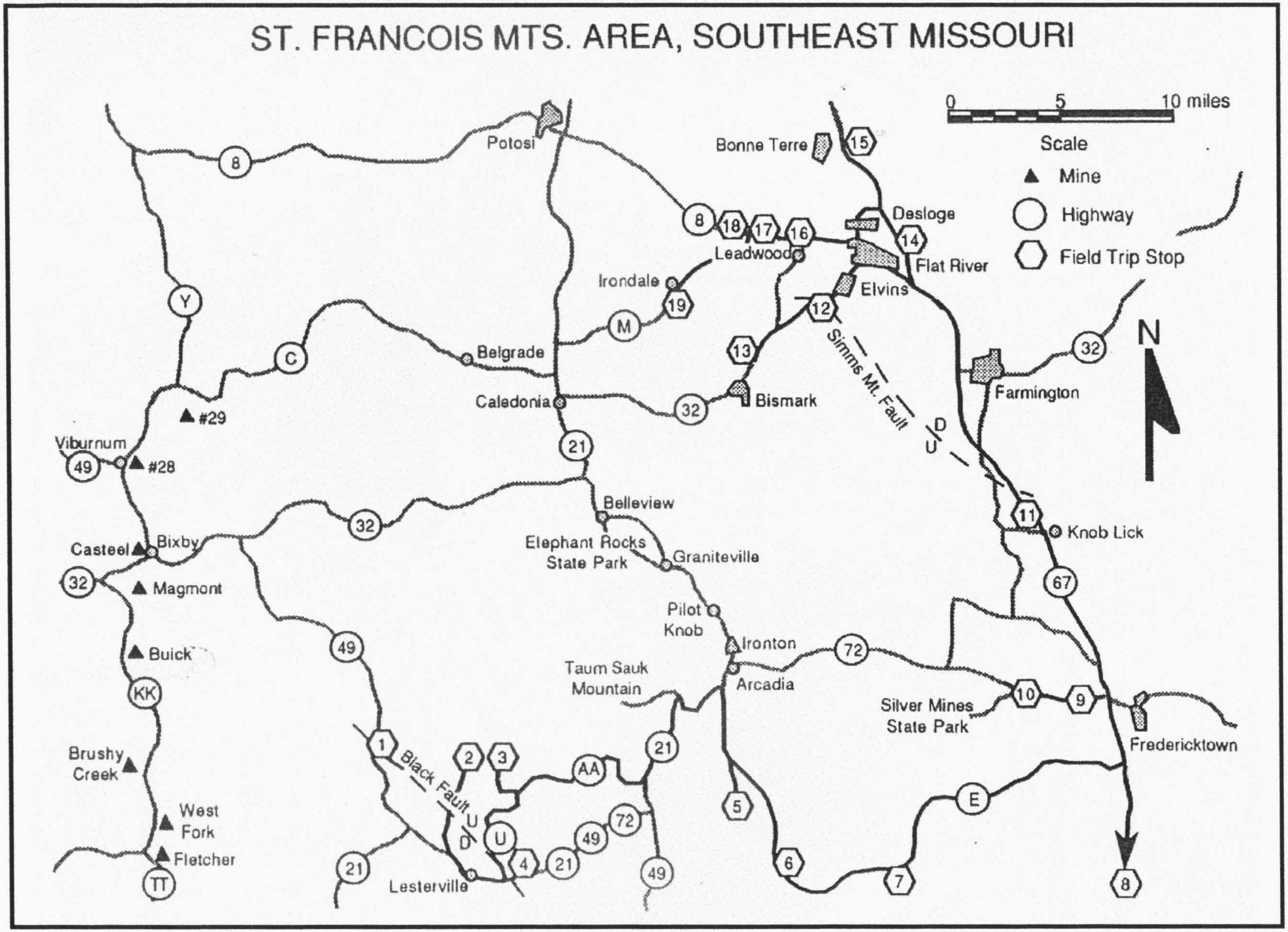

Figure 1. Road map of the field trip area, St. Francois Mts. region, southeastern Missouri.

"white rock" and which contrast with the deeper water, Davis shale facies at Stops 16 and 18. On the south side of the road, at top of the hill on the flanks of a Precambrian knob, are coarse crystalline dolomite "net fabric" (Zenger, 1983) replacing lagoonal mudstone (see Stop 5 below). This contrasts with the fine crystalline dolomite replacing the laminites in outcrops along the road.

Stop 4. Turn north on Hwy U at Hwy 49 intersection, go 5.7 mi to Hwy AA, turn left (west) and go 1.8 mi to fork in road. Take left fork to Taum Sauk power plant (S 21, T33N, R2E, Johnson Shut-Ins Quad.) Cambrian carbonate and shale units are draped over a Precambrian igneous knob. Excellent exposure showing the structural relationships between the sediments and the underlying igneous complex. The steep dip of the Cambrian units is the result of original sedimentary dip, combined with differential compaction and pressure solution of the sediments (Bridge and Dake, 1929). Similar relationships between Precambrian igneous highs and the overlying sediments exist in the subsurface, as observed underground in the Viburnum Trend mines. Pinch outs of the Lamotte Sandstone aquifer and the overlying carbonates where they onlap Precambrian highs are believed to have formed "traps" where sulfide ores precipitated (see Grundmann, 1977).

Stop 5. At Hwy 21 – Hwy E intersection turn south on Hwy E and go 3.4 mi to county road on the southwest. Turn southwest and go 1 mi to outcrop on the left (SE 29 & NE 32, T33N, R4E, Ironton Quad.) "Burrowed" mudstone of Howe (1968). This probably represents a "back reef" lagoonal facies. Pelleted micritic limestone and coarse crystalline dolomite form a "netted rock" similar to the "net fabric" dolomite described by Zenger (1983) in the Lost Burro Formation (Cambrian), California. The dolomite at this location is believed to be epigenetic and probably was formed at about the time of lead and zinc mineralization. The outcrop is on private property; therefore, please do not hammer on the rock!

Stop 6. On Hwy E, 8.3 mi east of stop 5) on the north side of the road (NE NE 15, T32N, R4E, Des Arc NE Quad.) Bonneterre Dolomite back reef "white rock" facies. Dolomite with cryptalgalaminates, stacked hemispheroids, fenestral porosity, etc. These features are consistent with the view that the back reef was a setting for evaporite deposition (Gregg and Gerdemann, this volume). Evaporites are considered as a possible source of the sulfur in MVT ore bodies (Jackson and Beales, 1967). However, no direct evidence of evaporites, such as gypsum casts, tepee structures, or chicken-wire structures, have been reported in the Bonneterre "back reef". This view, therefore, remains controversial. Note the sandstone channels that cut the dolomite beds. These sandstones contain volcanic rock fragments and quartz eroded from nearby Precambrian highs.

Stop 7. Along Little Rock Creek bed about 50 yards south of Hwy E, 8 mi east of stop 6 (NE SE 16, T.32N, R5E, Rock Pile Quad.) Arkose sandstone onlapping Precambrian along Little Rock Creek. Good cross bedding and well developed basal conglomerate is exposed. This arkose is laterally equivalent to probable Bonneterre back reef facies that outcrops along nearby Marble Creek.

Stop 8. From Hwy 67 at intersection of N go west 5.3 mi to intersection of Hwy C. Turn northwest on Hwy C and go 3 mi to the bridge over the St. Francois River (NE 10, T31N, R5E, Rock Pile Mt. Quad.) The bluffs on the north side of the river have more than 60 ft of dolomites equivalent to the upper Bonneterre and lower Davis Formations. At road level, the basal portion of a platform cycle of transgressive, thin bedded brown dolomite "ribbon rocks" overlie "white rock" dolomite which contains patches of red clay and saddle dolomite cement in small vugs. The ribbon rocks grade upward into thicker beds of coarser-grained, light gray dolomites. Depositional cycles such as these are present in the Upper Cambrian throughout the southeast portion of the St. Francois Mts. (Palmer this volume).

Stop 9. On Hwy 72, 1.7 mi west of intersection with Hwy 67 (N 11, T34N, R6E, Fredericktown Quad.) Precambrian rhyolite pyroclastic volcanics intruded by a basaltic dike nonconformably overlain by bolder conglomerates in the basal Lamotte. The conglomerate is overlain by dolomite cemented quartz sandstones.

Stop 10. West on Hwy 72, 3.4 mi from the junction with Hwy 67 (SE 4, T33N, R6E, Rhodes Mountain Quad.) This Lamotte, matrix-supported conglomerate contains rhyolite boulders up to 9 ft in length, in beds more than 6 ft thick. Parallel laminated shaley sandstone forms very irregular contacts with this conglomerate. This sequence has been interpreted as conglomerate dominated alluvial fan deposits (Houseknecht and Ethridge, 1978; Yesberger, 1982; Houseknecht, this volume)

West of the above road cut, 0.4 mi on Hwy 72 (SW 4) are exposures of interbedded laminated lithic sandstones and burrowed dolomites of the Lamotte-Bonneterre contact. Many of the burrows are filled with sand from overlying beds. These rocks are interpreted as marginal marine deposits of the upper Lamotte (Houseknecht and Ethridge, 1978).

West of the preceding road cut, 0.8 mi on Hwy 72 (SE 5), are exposures of sand dominated fan deposits of the Lamotte Sandstone (Houseknecht and Ethridge, 1978). These are thin, massive bedded, trough cross-bedded, and planar cross-bedded lithic arkosic sandstones with locally abundant hematite cement.

These exposures of the Lamotte and Basal Bonneterre are probably temporally equivalent facies, in part. They represent the development of fan deltas during marine transgression into the St. Francois Mountains (Houseknecht and Etheridge, 1978; Houseknecht, this volume).

Stop 11. On Hwy. 67, 2.5 mi north of Hwy DD intersection (south of Farmington) (SE 29, T35N, R6E., Wachita Mountain Quad.) Thin-bedded Lamotte Sandstone nonconformably overlays Precambrian Butler Hill Granite. Note the thin paleosol at Lamotte-Granite contact. This sandstone section was interpreted by Yesberger (1982) as a braided fluvial plain.

Stop 12. On both sides of Hwy 32, 2.7 mi west of the city limits of Elvins (S 22, T36N, R4E, Flat River Quad.) Lamotte Sandstone with arkose, quartz arenite, conglomerate, and shale facies. Note the cross bedding and channel cuts in parts of the exposure. The Lamotte Sandstone is regarded as a regional aquifer that transported the warm mineralizing brines from the basin to sites of sulfide ore deposition in southeastern Missouri. The outcrop is cut by several faults (Fig. 2) of the Simms Mountain fault system. The main trace of the fault system is to the immediate northeast of the outcrop along Dry Creek, where is about 800 feet of throw, with the downthrown side to the northeast. The Upper Cambrian Derby-Doerun Formation crops out on the northwest side of the road, just northwest of the Lamotte outcrop. These road cuts have sha-

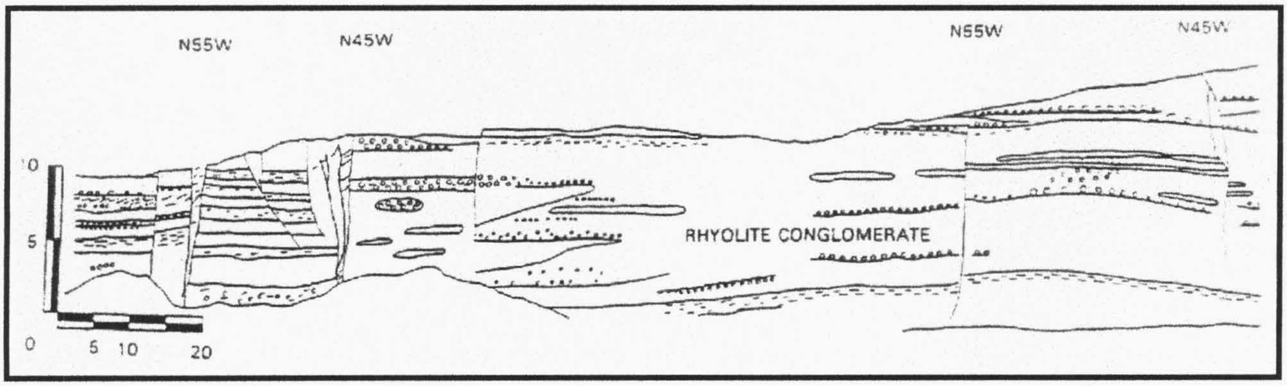

Figure 2. Part of a >300 foot lower Lamotte Sandstone section at Stop 12, south side of the highway. Bases of rhyolite conglomerate beds are shown with associated thin lenses of fine grained sandstone. The shales shown from center to far right are hemititic wackes. Bearings are fault strikes; scale in feet.

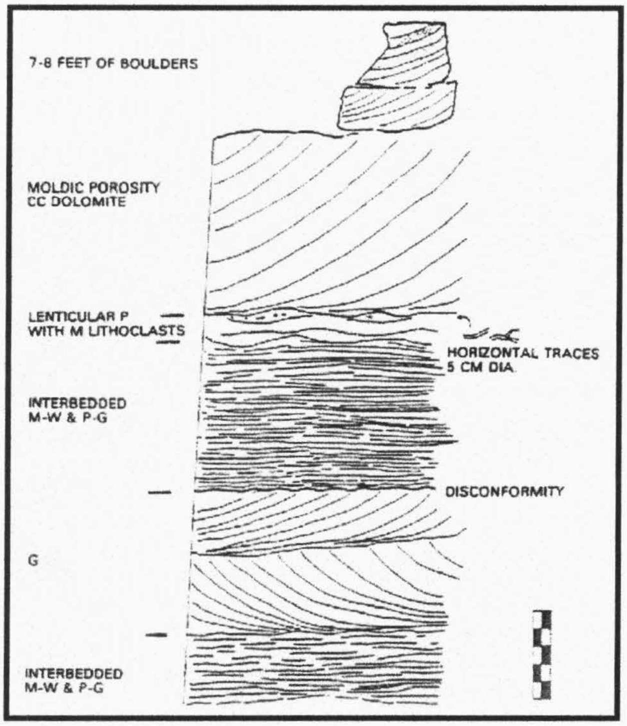

Figure 3. Derby-Doerun Dolomite at Stop 12. Upper large trough cross-bedded set has molds of grains up to 2 cm. CC = crystalline carbonate; M = mudstone; W = wackestone; P = packstone; G = grainstone. Scale in feet.

ley ribbon rock and thinly interbedded to large scale trough cross-bedded dolomites (Fig. 3).

Stop 13. Hwy 32, 0.2 mi west of intersection with Mitchel Rd. at intersection with county Rd. BB (N 28, T36N, R4E, Flat River Quad.) The outcrop is on the right; it shows the conformable contact at the Lamotte-Bonneterre transition. The rocks are dolomitic, arkosic sandstone and sandy dolomite, with cross-bedding, minor faulting, fracturing and vuggy weathering patterns.

Stop 14. Highway 67 at Rosener's Motel and Restaurant (SE SW 4, T36N, R5E, Farmington Quad.) Dolomitized complex breccia body in the Bonneterre (south bound lane road cut). Breccias in these Upper Cambrian rocks are not uncommon. This might be a late collapse breccia, caused by karst associated with a late Cambrian regression superimposed by later hydrothermal brecciation generated during MVT mineralization (see Gregg and Gerdemann, this volume).

Stop 15. East on Hwy K, 1.3 mi from Hwy 67 intersection at bridge over the Big River (SW SW, T37N, R5E, Bonneterre Quad.) Bonneterre Formation in bluff on northwest side of bridge a 20 ft high dolomitized, cryptalgal mound is underlain and overlain by tan oolitic dolomites. Further east 0.6 mi across Terre Bleue Creek (SW 9, T37N,R5E, French Village Quad.) Low road cuts on both sides of the road are Bonneterre Formation limestone. Ooid-skeletal-intraclast and pelletal glauconitic packstones and grainstones in thin lenticular to wave rippled beds. One limestone bed has stacked and laterally linked cryptalgal structures, that are partly thrombolitic (Fig. 4). These are a different sort of feature from the biohermal structure 0.6 mi to the west where individual cryptalgal structures coalesced into larger mounds. The distance between these road cuts is less than 1 mile and illustrates how abrupt the changes between limestone and dolomite in the Bonneterre can be.

Stop 16. Hwy 8, 1.4 mi west of Hwy P intersection (NW 3 & NE 3, T36N, R4E, Flat River Quad.) Outcrops on both sides of the road. Interbedded dolomites and shales of the Davis Formation. Note the large concretion-like "boulders", which are dolomitized algal thrombolite bioherms (Fig. 5). The Davis represents a transgressive offshore or intrashelf basinal facies. The water was probably never deeper than the photosynthetic limit (about 40 m), as is shown by fossil algal and faunal remains. Note the ripple marks at the west

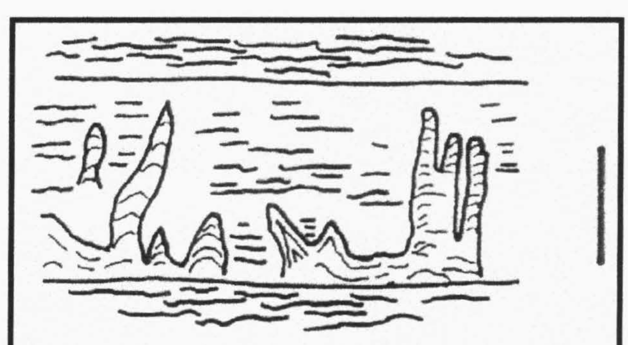

Figure 4. Sketch of a portion of cryptalgal boundstone bed at Stop 15. Vertical bar = 12 inches.

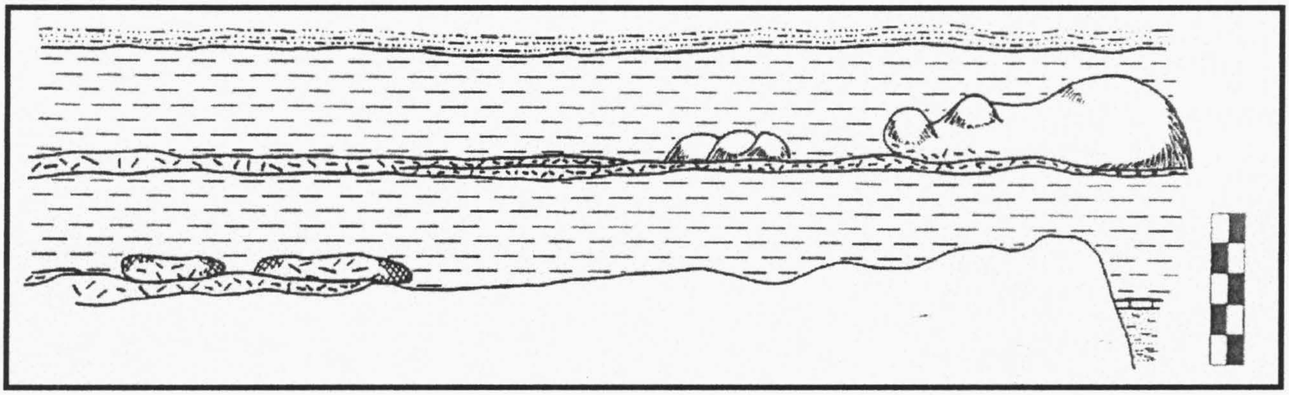

Figure 5. Sketch of a part of the Davis Formation road cut, south side of the road, at Stop 16. Thrombolite bioherms (boulder beds) overlie conglomerate beds (upper right) and encrust conglomerate lenses (cross-hatch lower left). Scale in feet with 2X vertical exaggeration.

end of the outcrop (north side of the road). Saddle dolomite, sphalerite, and galena crystals, which can be found in the road cut, indicate that these rocks were exposed to mineralizing fluids.

Stop 17. At Hwy M-Hwy 8 intersection, 1 mi east of Stop 16. Outcrops on both sides of the road (NE 4 & NW 3, T36N,R4E, Flat River Quad.) Upper part of the Bonneterre Dolomite contains interbedded oolitic grainstones, some with cross-bedding (Fig. 6). An unconformable contact with the overlying Davis Formation is visible near the top of the outcrop, on the south side of the road. A thin interval of the Whetstone Creek Member of the Bonneterre is visible just below this contact. It is the only representative of 120 ft of Sullivan Siltstone and Whetstone Creek in the central Missouri intrashelf basin (Palmer, this volume).

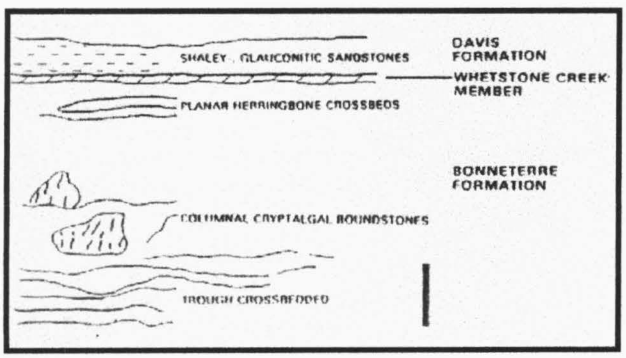

Figure 6. Summary of features at Stop 17 in road cuts on both sides of the road. Vertical bar = 5 feet.

Stop 18. On Hwy 8, 0.6 mi west of intersection with Hwy M at Frankclay (N 5, T36N,R4E., Flat River Quad.) Upper Davis Formation and Lower Derby-Doe Run dolomite represent the transition across the intrashelf basin - deep ramp margin, and shows several periods of transgression-regression. The bioherms in the basal Derby have an apparent width of 24 ft, and contain mottled thrombolite boundstone and distinct columnar thrombolite. The base of the dolomite (Fig. 7) marks a eustatic event that coincides with the *Pterocephalid-Ptychaspid* Biomere boundary, and the introduction of *Eorthis remnicha*.

Stop 19. From Hwy 21-Hwy M intersection go 6.5 mi east on Hwy M. Outcrops on both sides of the road (SW 14, T36N,R3E, Irondale Quad.) Bonneterre Dolomite, digitate algal stromatolite "reef" facies. Mounds are of thrombolitic- and locally stromatolitic-bound wackestones and to a lesser extent mudstones (Fig. 8). These mounds are the "roll structures," described by Ohle and Brown (1954) from exposures in underground mines.

Interpretation of the reef as a control on the distribution of mineralization in the "Old Lead Belt" led to discovery of the Viburnum Trend (Ohle and Gerdemann, this volume) and delineation of the reef trend and associated grainstone facies played an important part in the development of the Viburnum Trend (Gerdemann and Myers, 1972;

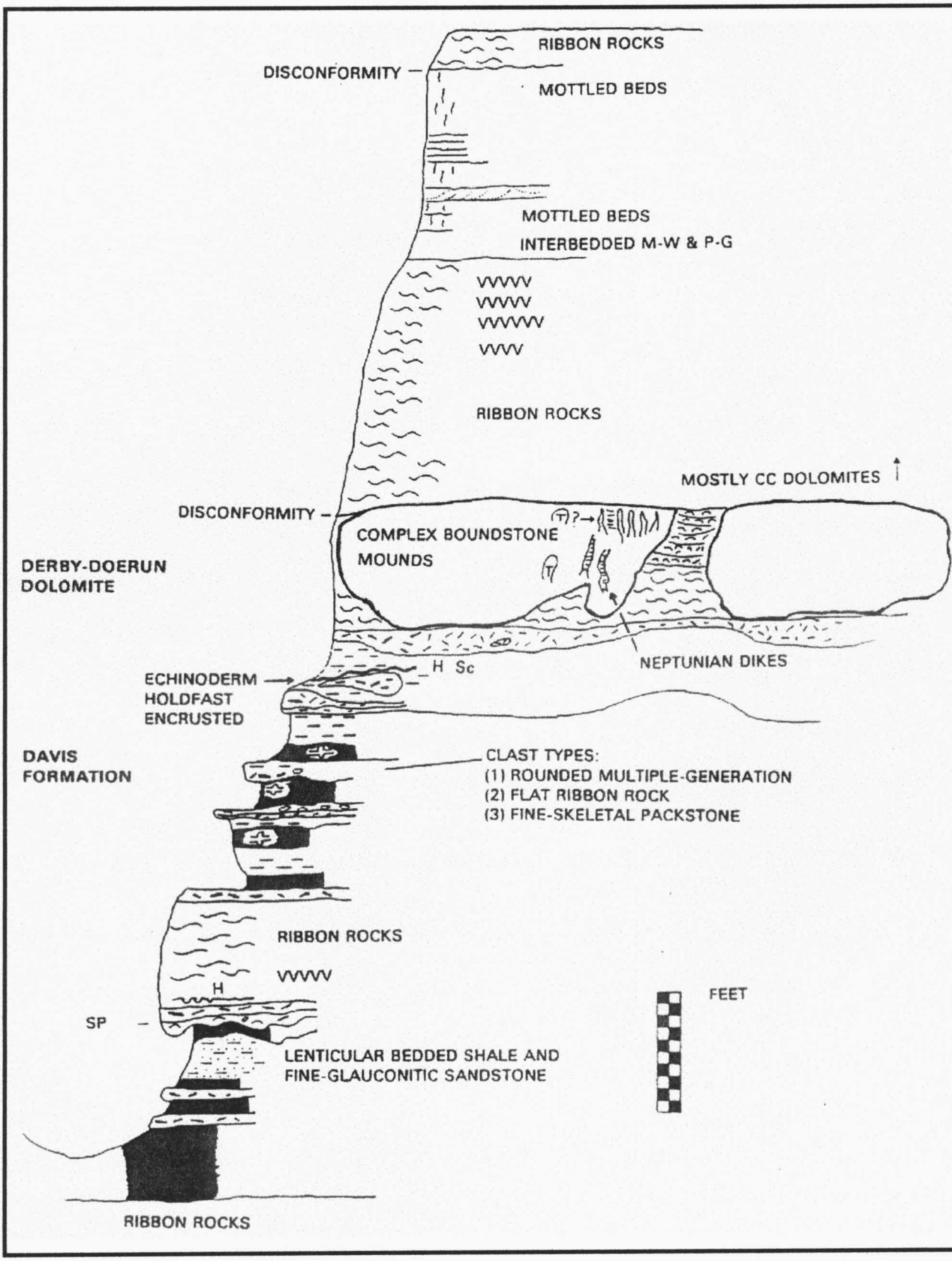

Figure 7. Upper Davis Formation and lower Derby-Doerun Dolomite at Stop 18. SP = sphalerite; H = hardground; Sc = scoured surface; VVVV... = rows of vugs.

Gregg and Gerdemann, this volume). Rock at this outcrop is completely dolomitized. Galena was mined from the Bonneterre Formation about 1 mi northwest of this road cut, in the old Irondale Mine, on the bank of the Big River.

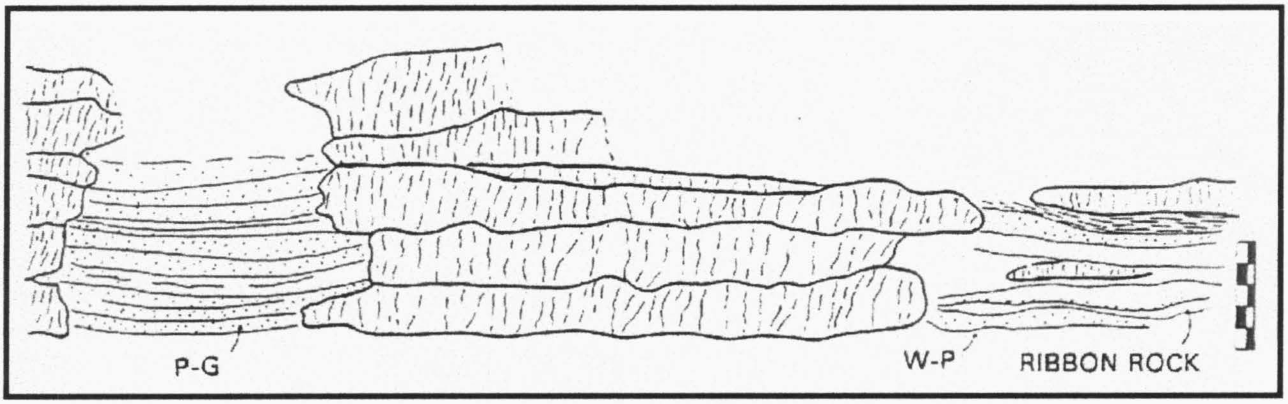

Figure 8. Sketch of cryptalgal mounds in the Bonneterre Formation at Stop 19. P = packstone; G = grainstone; W = wackestone. Scale in feet.

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