PETROLOGY AND DIAGENESIS OF THE SHORT CREEK OOLITE MEMBER OF THE BOONE FORMATION, NORTHEAST OKLAHOMA

By

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CHAPTER I

INTRODUCTION AND PREVIOUS INVESTIGATIONS

Introduction

Northern Ottawa County, Oklahoma, is important as the site of extensive commercial exploitation of zinc and lead ores from the Tri-State District. These ore deposits are largely confined to the Mississippian Boone Formation. As a result, the literature contains many studies on mining geology, local structures, and Boone Formation stratigraphy. Comparatively little has been published, however, concerning the sedimentation, petrography, and diagenesis of the Boone Formation, or its various members. The Short Creek Oolite Member of the Boone Formation was chosen for such a study because of its unique lithologic character, and because it has been mapped on the surface.

The Short Creek Oolite is a thin, but persistent bed of oolitic limestone which outcrops widely along the Neosho and Spring Rivers, and their tributaries, in Ottawa County, Oklahoma. The unit is also exposed to the south in Delaware County, Oklahoma and in southwest Missouri; it is also known in the subsurface of southeast Kansas.

Location of Study Area

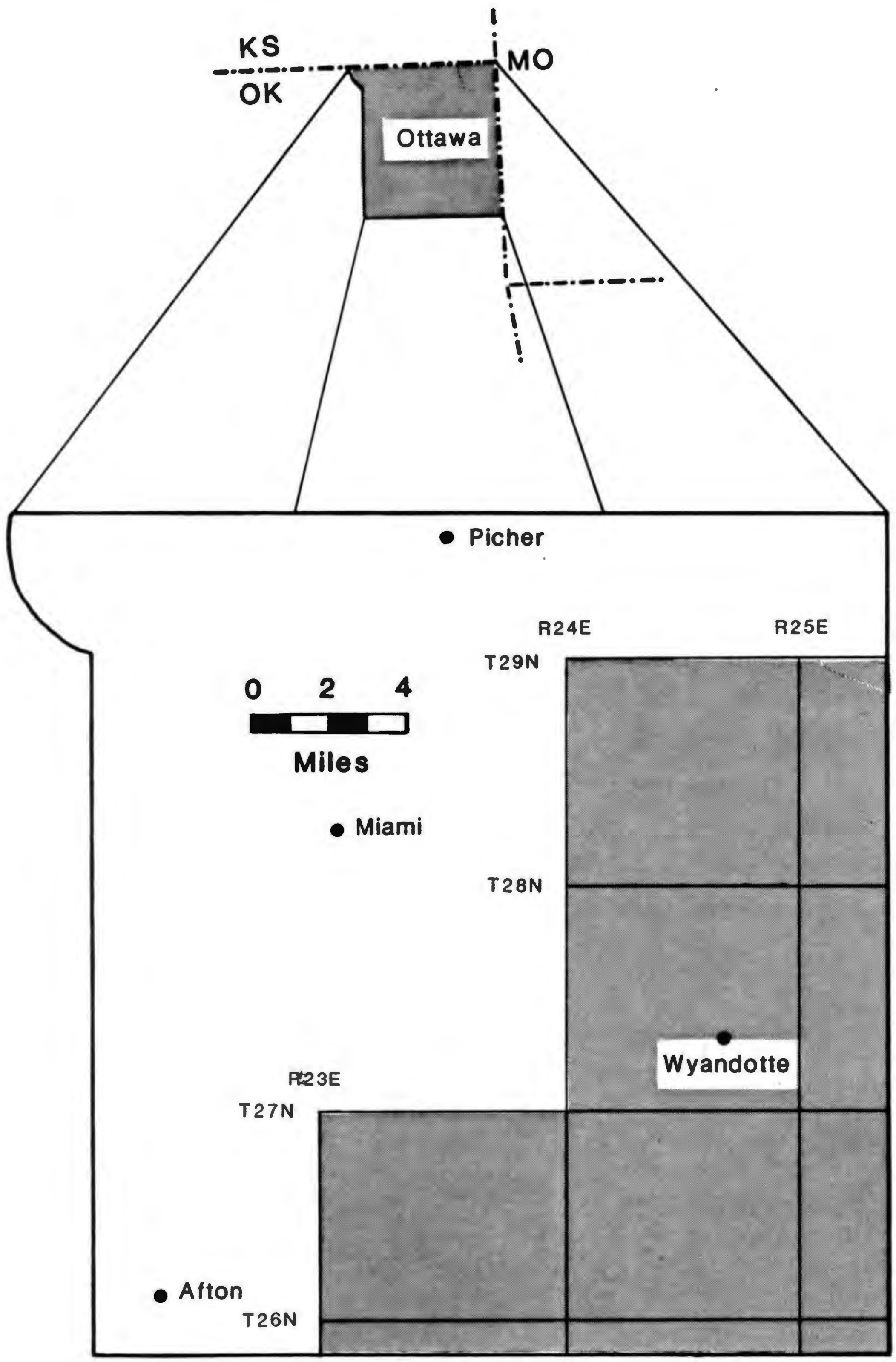
The area under investigation is located in eastern and southeastern Ottawa County, Oklahoma (Figure 1). Adjacent areas in Delaware County, Oklahoma, and in Kansas and Missouri have been visited during the course of this investigation, but exposures of the Short Creek Oolite are mainly limited to the indicated area.

After investigating many different exposures, three outcrops were selected for detailed study. Their locations are presented as follows: Outcrop 1 is located at NE1/4, Sec.29, T27N, R24E, and occurs along the east bank of the Neosho River a few hundred feet upstream of its confluence with the Spring River; Outcrop 2 is located at NE1/4, NW1/4, Sec.13, T26N, R23E, and occurs along a nameless tributary to the head-waters of Grand Lake; Outcrop 3 is located at SW1/4, NW1/4, Sec.35, T27N, R24E, and occurs along State Highway 10 about 2 miles southeast of Wyandotte, Oklahoma.

Physiography

The northeastern Oklahoma study area occurs on the southwestern flank of the Ozark uplift. The Ozark uplift is a broad asymmetric dome occupying an area of approximately 40,000 square miles in Missouri, Arkansas, and Oklahoma (Huffman, 1958, p. 10). The axis of the structure trends northeast, passing through the St. Francis Mountains of eastern Missouri, and plunges southwest into northeastern

Figure 1. Location of northeastern Oklahoma study area


KS
OK
MO
Ottawa
Picher
R24E
R25E
T29N
0 2 4
Miles
Miami
T28N
Wyandotte
R23E
T27N
Afton
T26N

Oklahoma. Mississippian and Pennsylvanian strata dip uniformly to the northwest at 20 to 25 feet per mile (McKnight and Fischer, 1970, p. 72).

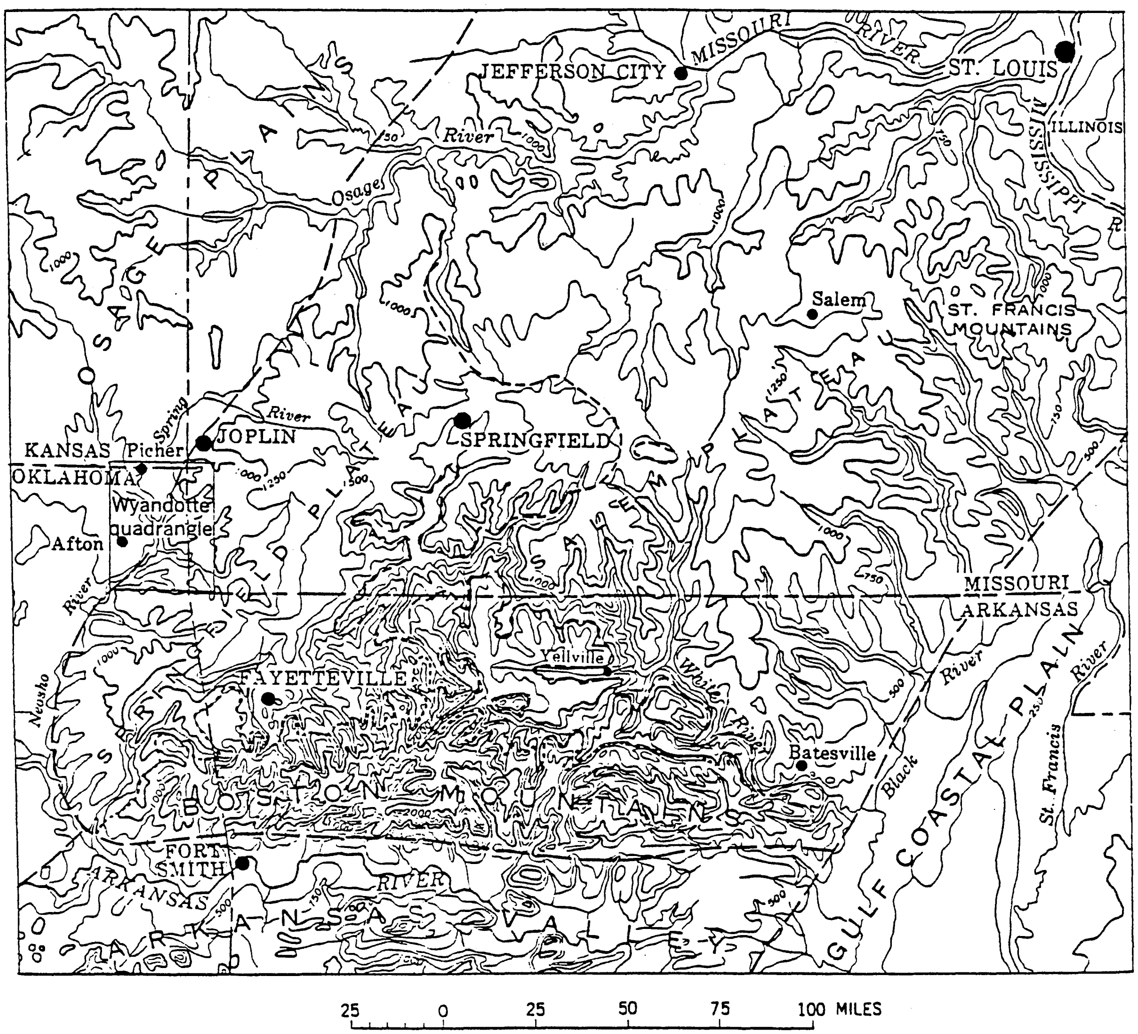
The physiographic divisions of the Ozark region are illustrated in Figure 2. The uplift is divided into the Salem Plateau and the St. Francis Mountains of eastern Missouri, the Springfield Plateau of Missouri, Arkansas, and Oklahoma, and the Boston Mountains of Arkansas and eastern Oklahoma. The Ozark region is bounded on the southeast by the Gulf Coastal Plain, on the south by the Arkansas Valley, and on the west by the Osage Plains.

Methodology

Field work in the study area and adjacent areas began in 1983 with a study of the various Boone Formation members and their lithologic characteristics. Many outcrops of the Boone Formation exposed along the Spring and Neosho Rivers above Grand Lake were visited by canoe. Once the Short Creek Oolite was chosen as a thesis topic, emphasis in the field was shifted to the location and description of Short Creek outcrops.

Three outcrops were chosen for detailed study, based on the quality of the exposure, and their overland accessibility. The outcrops were walked laterally as much as was feasible and were measured and described in detail. Samples were collected from the base, middle, and top of the Short Creek Oolite at each outcrop, as well as from unique or

Figure 2. Physiographic subdivisions of the Ozark region (Source: McKnight and Fischer, 1970)



EXPLANATION

Physiographic division

Eureka Springs Escarpment

Boston Mountains Escarpment

interesting points in the Short Creek section. In addition, samples were collected from adjacent strata, with careful attention paid to collecting representative samples of the overall lithology, and the lithology near contacts with other stratigraphic units. The samples were slabbed and selected thin sections were made.

Representatives of each sample were chosen for analysis by X-ray diffraction. The rock was pulverized in a Spex Mix-Ball Mill, and then ground by mortar and pestle. Samples were prepared for use in random powder analysis. A Phillips Random Powder Diffractometer was used to analyze each sample for 2θ angles ranging from 20 to 35 degrees, in order to characterize the gross carbonate mineralogy. The results were assembled for use during petrographic analysis of selected thin sections.

Selected thin sections were stained with a mixture of Alizaren Red-S and potassium ferricyanide using methods oulined by Dickson (1966). A stock solution of Alizaren Red-S is made by adding 0.2 grams of the reagent to 100 milliliters of 1.5% HCl. A stock solution of potassium ferricyanide is made by adding 2.0 grams of the reagent to 100 milliliters of 1.5% HCl. The two solutions are mixed at the ratio of 3:2, Alizaren Red-S to potassium ferricyanide. Thin sections are emersed in this mixture for 15 to 30 seconds and then rinsed in water.

The stain is effective on calcite, ferroan calcite, and ferroan dolomite. Calcite is stained pink, ferroan calcite is stained purple, and ferroan dolomite is stained blue, while non-ferroan dolomite remains unstained.

Previous Investigations

Reference to the Boone Formation was first published in reports of the Arkansas Geological Survey by Simonds (1891, p.27-37), and Penrose (1891, p.129-138) to designate widely outcropping Mississippian units in northern Arkansas. The Boone Formation was mapped by Siebenthal in the Joplin mining district (Smith and Siebenthal, 1907), who also described the Short Creek Oolite Member and the Grand Falls Chert Member.

The Boone Formation is well-known for its role as host to the extensive zinc and lead sulfide ore deposits of the Tri-State District (McKnight and Fischer, 1970). In the early 1900's, prompted by the need to understand geologic controls on ore distribution, a number of workers began studies of stratigraphy and structure.

Aerial geology of the Wyandotte quadrangle was reported in 1908 by Siebenthal, but the information was brief and general; a final report was planned but never completed. A map of the area prepared by Siebenthal and Messler in 1906-1907 has been included in several later papers, such as Snider (1915), Ireland (1930), and Reed, Schoff, and Branson (1955).

A major contribution to the stratigraphy of the Ozark area was made by Moore (1928) with his report on the Early Mississippian strata of Missouri. His findings and conclusions have influenced the opinions of a number of later workers. Kaiser (1950) has modified some of Moore's conclusions in a similar study of southwestern Missouri.

Other papers relevant to the stratigraphy of the area include Cline (1934), Laudon (1939), Spreng (1961), and Weidman (1932). Lee (1940) published distribution maps of major Mississippian units in the subsurface of Kansas. In addition, he presented a series of cross-sections which provide more detail on the distribution and geometry of subsurface Mississippian units of the area than has been presented by any other worker to date.

The first of an important series of papers by Fowler and Lyden, and by Fowler and others, appeared in 1932. This work provided the first concise subdivisions of the Boone Formation and were widely accepted by geologists and operators in the field. The units of the Boone were designated, from top to bottom, by the capital letters B to R, and their variable susceptibility to mineralization was outlined.

Later papers (Fowler, 1933; Fowler and Lyden, 1934; Fowler, Lyden, Gregory, and Agar, 1935; Fowler, 1938, 1942, 1943; Fowler, Hernon, Conrow, and Stone, 1955) served to elaborate or modify the conclusions of the 1932 paper by Fowler and Lyden.

More recent reports by McKnight and Fischer (1970), and Hagni (1976) have been published since the cessation of commercial mining operations in the Tri-State District. The report by McKnight and Fischer (1970) is a monumental effort and has been of very great value during the preparation of this document. McKnight and Fischer (1970) discuss in considerable detail the geology of the area and the geology of the ore deposits of the Tri-State. The Boone Formation has been subdivided into seven members by them, and stratigraphic correlatives are identified. Unfortunately, mapping is incomplete at this time.

To date, three of the seven members described by McKnight and Fischer (1970) have been mapped in or near the northeastern Oklahoma study area. Included are the St. Joe Limestone (Siebenthal and Messler, 1907), the Grand Falls Chert (Smith and Siebenthal, 1907), and the Short Creek Oolite (Speer, 1951).

Structures of the area have been mapped by a number of previously mentioned early workers. Extensive field work conducted in preparation for the new State geological map (Miser, 1954) was summarized in a report on the geology of the Ozark flanks by Huffman (1958). Deep drilling was utilized by Brockie, Hare, and Dingess (1968) to identify several new structures. McKnight and Fischer (1970) have presented summaries of many of these structures, as they pertain to the Picher mining field. Nodine-Zeller and Thompson (1977), have reported several new structures on the basis of foraminifera and conodont correlations. Denison (1981) has mapped the Precambrian basement surface in northeastern Oklahoma, and discussed Precambrian structural evolution in the area. Patterson (1986) has reported that the Seneca Fault may represent wrench faulting in northeastern Oklahoma.

Very little has been written concerning the environment of sedimentation for the Boone Formation or any of its members. McKnight and Fischer (1970) provided very general conclusions when necessary to their discussion of the stratigraphy of the Boone. One exception is in their discussion of crinoidal-bryozoan mounds which occur in the lower Boone. Harbaugh (1957) was first to report on these bioherms, and provides detailed descriptions of several localities, particularly in areas to the south of the current study area.

More general reports by Lane (1978), and by Gutschick and Sandberg (1983) provide discussions of regional sedimentation in early to middle Osage (Lower to Middle Mississippian) time. The period of time considered is in both cases slightly before Short Creek time, but an understanding of the general setting has proved to be useful to the discussions presented in this report.

Only very general accounts of the petrography of non-mineralized Boone lithologies have been published (McKnight and Fischer, 1970), but outcrops used in stratigraphic correlations have been described in detail (Moore, 1928; Cline, 1934; Laudon, 1939; Kaiser, 1950; Harbaugh, 1957; Huffman, 1958; Spreng, 1961; McKnight and Fischer, 1970). The author is not aware of any published accounts which are concerned with the diagenesis of the Boone Formation, or any of its members.

Purpose of Investigation

The need for a more detailed understanding of the petrologic and depositional aspects of the Boone Formation was recognized, and became the basis for this investigation. Petrology, as defined by the American Geological Institute (1976), refers to a study of the origin, occurrence, structure, and history of rocks. On this basis, a general understanding of Boone stratigraphy was required in order to properly interpret field and laboratory observations.

This report is not intended to provide clear answers to the stratigraphic problems which have concerned numerous workers for over three-quarters of a century. Rather, it is intended to provide the reader with a gross summary of the voluminous literature on the subject, and to set the stage for a discussion of depositional environments; particularly that of the Short Creek Oolite.

It was decided that the study of a single Boone Formation member would provide more detailed results than a general study of the entire formation. The Short Creek Oolite was chosen because of its unique lithology, and because its outcrops have been mapped (Speer, 1951).

This investigation is intended to provide detailed petrographic descriptions of the Short Creek Oolite, along with interpretations concerning its environment of deposition, and diagenetic modifications. A thorough understanding of these aspects is far from complete, so there is considerable potential for future research, particularly in the areas of mapping, facies occurrence and distribution, and diagenesis.

CHAPTER II

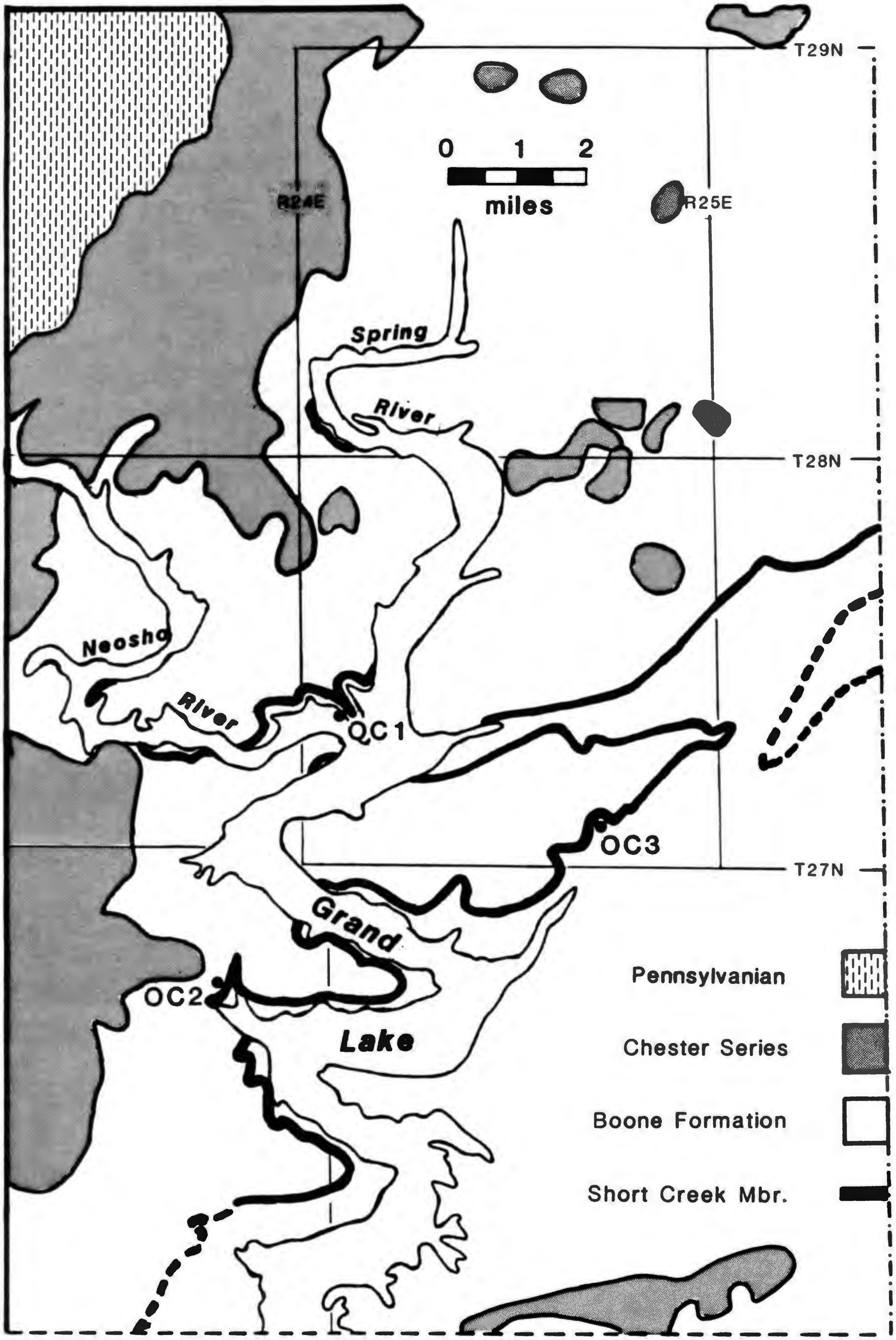
OUTCROP GEOLOGY

Exposures of the Short Creek Oolite

The Short Creek Oolite Member of the Boone Formation crops out widely in the study area (Figure 3). Topographic relief is typically very low in the study area except along major surface drainage systems. The surface is drained by the Neosho and Spring Rivers and their confluence marks the head waters of Grand Lake. Stream cuts commonly produce spectacular exposures of the Boone Formation, and the area is popular among sportsmen. These exposures are typically very steep escarpments and may be accessible only by boat.

Many exposures developed in stream and road cuts have been visited by the author during the course of this investigation and three have been chosen for detailed analysis (Figure 3). Outcrops chosen for detailed study share certain attributes, namely, high quality exposures of the Short Creek Oolite and adjacent strata, and overland accessibility.

Figure 3. Geologic map of exposures in the northeastern Oklahoma study area, including outcrops of the Short Creek Oolite Member


T29N
0 1 2
miles
R24E
R25E
Spring
River
T28N
Neosho
River
OC1
OC3
T27N
Grand
OC2
Lake
Pennsylvanian
Chester Series
Boone Formation
Short Creek Mbr.

Outcrop 1

General

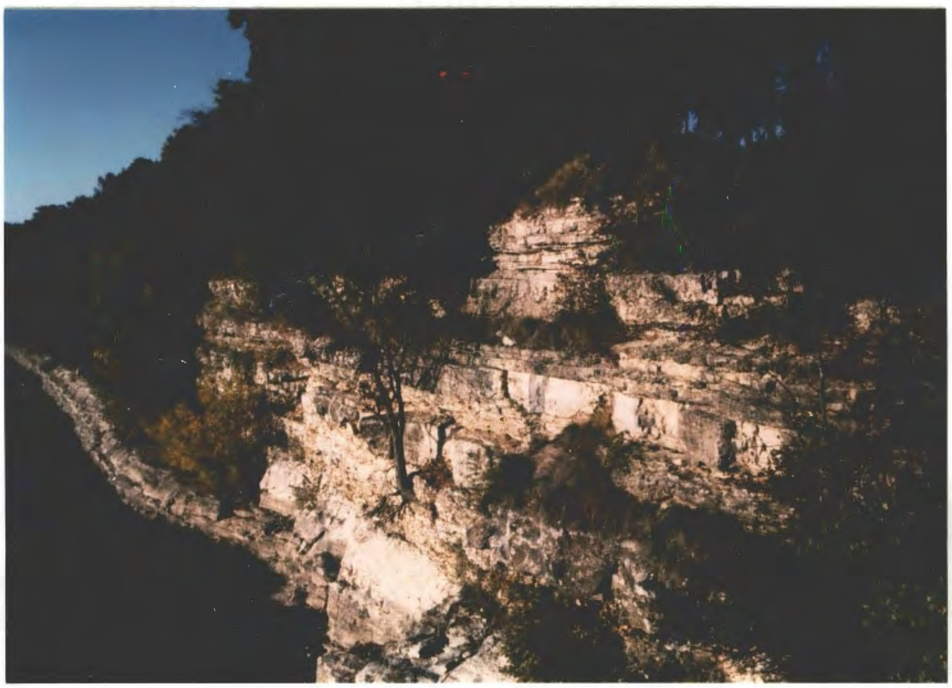
Outcrop 1 (NE1/4, Sec.29, T27N, R24E) was described from exposures along the Neosho River near its confluence with the Spring River, in the Twin Bridges State Recreation Area (Figure 3). The exposure was accessed at the intersection of US Highway 60 and the Neosho River. The section was measured near this point, although the Short Creek and the Baxter Springs Members remain beautifully exposed for some distance upstream (Figure 4).

The upper few feet of the Joplin Member of the Boone Formation are exposed above the waters of the Neosho River at this locality. The Joplin Member is overlain with apparent conformity by the Short Creek Oolite Member. The Short Creek is separted from the overlying Baxter Springs Member by an apparently conformable, but undulatory contact. The lower Baxter Springs Member is overlain unconformably by strata of Meramec age. Meramec strata exposed at this location include the J bed subunit of the Baxter Springs Member and the Moccasin Bend Member of the Boone Formation.

The Joplin Member

The Joplin Member, at this exposure, consists of medium to coarsely crystalline bioclastic limestone and white chert. The Joplin Member is highly fossiliferous, with pelmatozoan, brachiopod, and bryozoan skeletal debris comprising the bulk

Figure 4. Photograph of the exposures at Outcrop 1



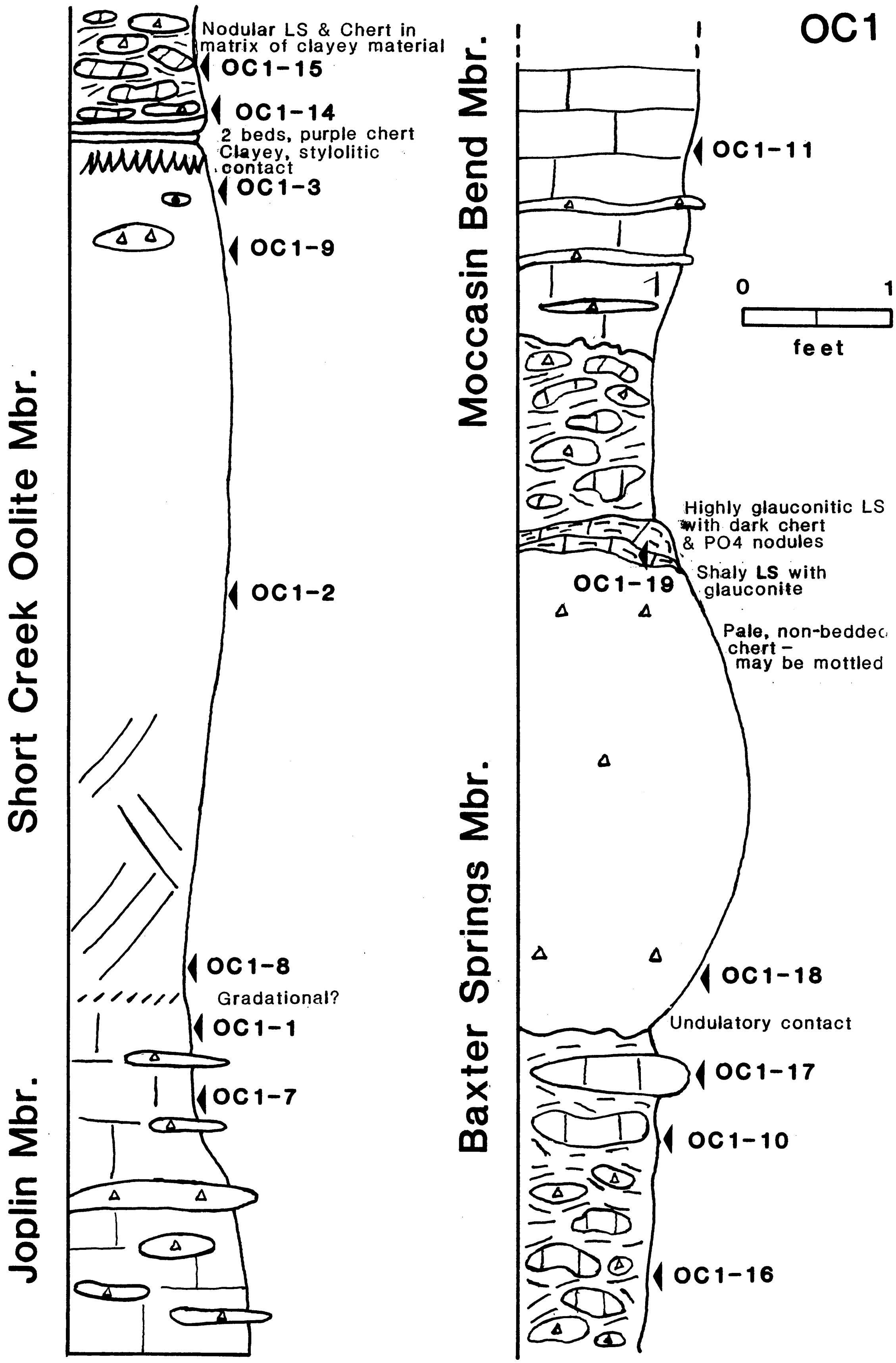
the most commonly identified grains. The chert occurs in nodules ranging in diameter from several centimeters to several tens of centimeters. These nodules commonly coalesce to form a sort of pseudo-bedding. Except for the occurrence of the pseudo-bedding, the Joplin is best described as massive, or indistinctly bedded (Figure 5). The contact between the Joplin and the overlying Short Creek Oolite is conformable if not gradational.

The Short Creek Oolite

The thickness of the Short Creek Oolite Member is about 6.5 feet at this location (Figure 5). The Short Creek is slightly fossiliferous throughout the section, but is more so near its base. Pelmatozoan and brachiopod debris are the most commonly identified skeletal fragments. The oolite is very well sorted and bedding is typically massive; medium-scale planar cross-bedding has been observed in the lower half of the section. The Short Creek weathers to a rounded, blocky profile and its outer surfaces spall creating the impression of vertical exfoliation. Its light gray color helps make it conspicuous in outcrop.

The Short Creek is only slightly siliceous, in contrast with much of the Boone Formation. Occasional chert nodules occur, particularly near the top of the unit. The chert nodules exhibit an originally oolitic texture, and are rounded to ellipsoidal. The nodules may reach 1 foot or more in diameter. The oolite also becomes slightly glauconitic

Figure 5. Idealized measured section from Outcrop 1


OC1
Nodular LS & Chert in matrix of clayey material
OC1-15
OC1-14
2 beds, purple chert
Clayey, stylolitic contact
OC1-3
OC1-9
OC1-2
Short Creek Oolite Mbr.
OC1-8
Gradational?
OC1-1
OC1-7
Joplin Mbr.
Moccasin Bend Mbr.
OC1-11
0
1
feet
Highly glauconitic LS with dark chert & PO4 nodules
Shaly LS with glauconite
OC1-19
Pale, non-bedded chert - may be mottled
Baxter Springs Mbr.
OC1-18
Undulatory contact
OC1-17
OC1-10
OC1-16

toward the top.

The contact between the Short Creek and the overlying Baxter Springs Member is conformable but undulatory, and commonly stylolitic. The two units are separated by a thin clayey layer, which is overlain by 2 to 4 inches of purple, oolitic chert. The undulatory, clayey and stylolitic contact is believed to represent section-thinning as a result of overburden stresses.

The Baxter Springs Member

The Baxter Springs Member consists of three similar but distinct lithologies at Outcrop 1 (Figure 5). The basal 4 feet are extremely cherty, with chert occurring as ellipsoidal to highly irregular nodules. Similar nodules of fine-grained limestone occur with less frequency. The nodules commonly interpenetrate one-another, and are surrounded by a fine-grained siliceous matrix. The siliceous matrix is clayey, and probably represents insoluble residue derived from the dissolution of limestone during compaction. This lithology is believed to represent the L bed subunit of the Baxter Springs Member, as described by McKnight and Fischer (1970), and is overlain by the K bed subunit of the Baxter Springs Member with apparent conformity.

The K bed subunit of the Baxter Springs Member consists of about 4 feet of pale, buff-colored chert at Outcrop 1. The chert is massive and relatively featureless with the exception of mottling and rare fossil debris, both of which occur throughout the section. Thin sections prepared from samples of this chert indicate that the mottled appearance is derived from incompletely silicified fossil debris, most of which is not identifiable.

The massive chert is overlain by 2 to 3 inches of fine-grained to silty limestone, which contains numerous blebs of glauconitic, and fossiliferous material. The glauconitic material is identical in appearance to the overlying sediment of the J bed subunit. The blebs are believed to represent the borings of some organism into a hardground developed in the upper K bed subunit, with subsequent infilling by glauconitic J bed sediments. The K bed subunit of the Baxter Springs Member is overlain unconformably by the J bed subunit of the Baxter Springs.

The J bed subunit of the Baxter Springs Member is a medium to coarse-grained, highly glauconitic, phosphatic, and fossiliferous limestone. Its thickness is only 2 to 4 inches as measured at Outcrop 1 (Figure 5). The subunit displays a distinctive green color, with small grains of dark phosphate and chert, and scattered pelmatozoan debris. As interpreted herein, the J bed subunit represents the base of the Meramec Series in the study area, and is overlain with conformity by the Moccasin Bend Member of the Boone Formation.

The Moccasin Bend Member

The Moccasin Bend Member is the upper-most unit of the Boone Formation in the study area, as interpreted by McKnight and Fischer (1970), and herein. The unit has been divided into various subunits, but lithologic distinctions between the various subunits are often poorly represented (McKnight and Fischer, 1970).

The basal 1.5 to 2 feet of the unit consists of nodular chert and limestone in a clayey matrix, which is very similar in appearance to the basal strata of the Baxter Springs Member (Figure 5). This nodular lithology is overlain by about 2 feet of hard, dense siliceous limestone with thin cherty laminae. The cherty laminae are fairly continuous, giving the impression in outcrop of a horizontally-banded wall.

A hard, dense siliceous limestone similar in appearance to the siliceous limestone below, continues for at least 10 feet above the cherty zone. Most of this upper-most 10 feet is covered with a red, fine-grained residuum derived from the weathering of cherts in the upper Moccasin Bend Member. This red, rubbly sediment is common throughout the study area in areas underlain by the Moccasin Bend Member.

Outcrop 2

General

Outcrop 2 (NE1/4, NW1/4, Sec.13, T26N, R23E) was described from a stream cut about 3.5 miles east of Fairland, Oklahoma (Figure 3). A small outcrop occurs on the east bank of the nameless stream, just south of the section road, and continues along the cut made for the road. The stream flows into Grand Lake a few hundred yards to the south.

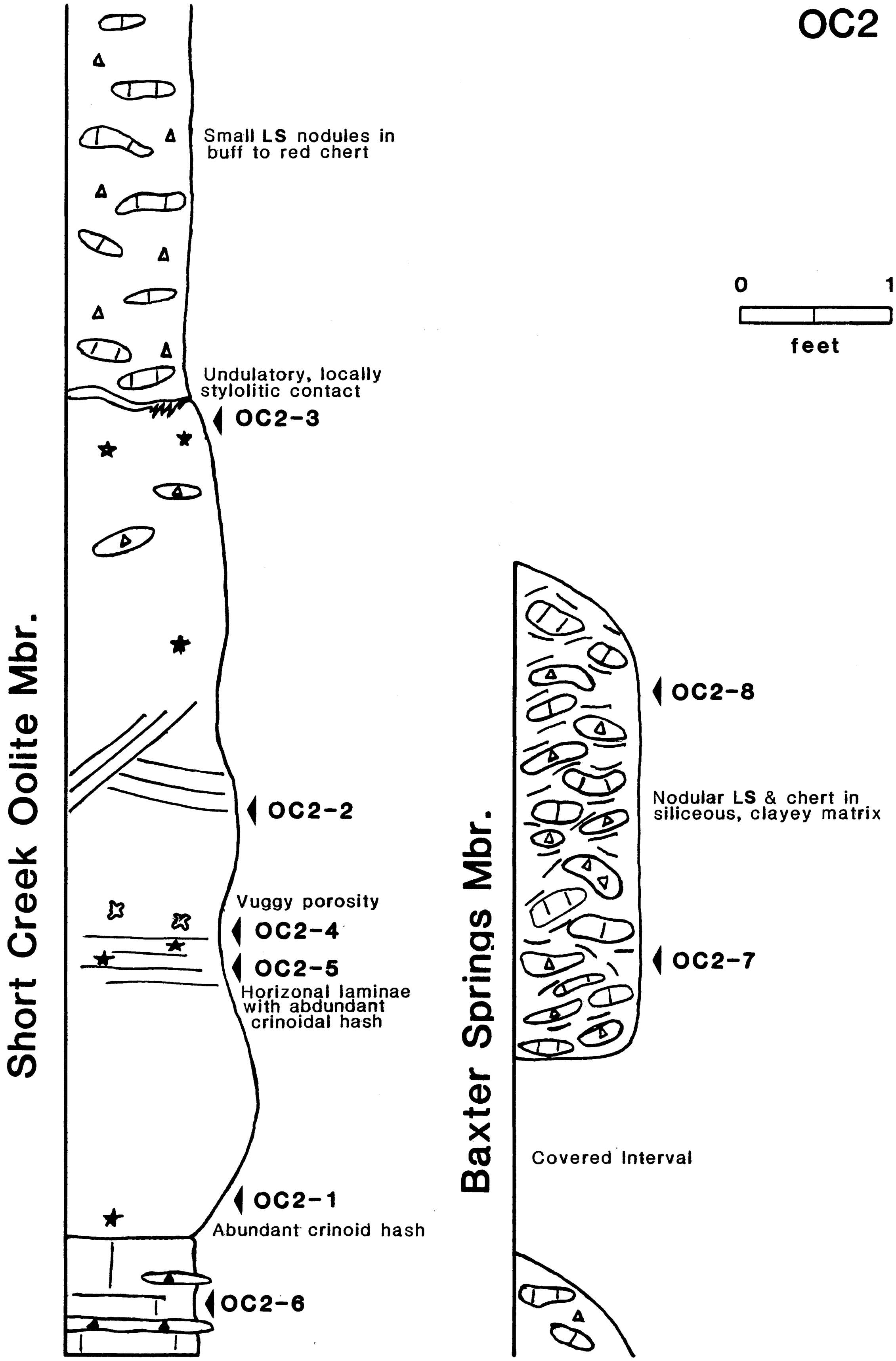
About 1 foot of the upper Joplin Member is exposed above the base of a generally dry channel, and is overlain with apparent conformity by the Short Creek Oolite Member. The Short Creek is separated from the overlying Baxter Springs Member by a conformable but undulatory, and locally stylolitic contact. The Moccasin Bend Member is not present at this locality, having been removed by recent erosional processes (Figure 6).

The Joplin Member

The Joplin Member consists of medium to coarsely crystalline bioclastic limestone and gray to white chert (Figure 7). The unit is highly fossiliferous with pelmatozoans and brachiopods being the most commonly identifiable skeletal debris. The chert occurs in nodules which have coalesced into thin pseudo-beds 1 to 4 inches thick. Aside from the pseudo-bedding of the chert, the

Figure 6. Photograph of the exposures at Outcrop 2

Figure 7. Idealized measured section from Outcrop 2


OC2
0
1
feet
Short Creek Oolite Mbr.
Small LS nodules in buff to red chert
Undulatory, locally stylolitic contact
OC2-3
OC2-2
Vuggy porosity
OC2-4
OC2-5
Horizonal laminae with abdundant crinoidal hash
OC2-1
Abundant crinoid hash
OC2-6
Baxter Springs Mbr.
OC2-8
Nodular LS & chert in siliceous, clayey matrix
OC2-7
Covered Interval

Joplin is best described as being indistinctly bedded at Outcrop 2. The contact between the Joplin and the overlying Short Creek Oolite is apparently conformable.

The Short Creek Oolite Member

The Short Creek Oolite Member is 7 to 7.5 feet in thickness at Outcrop 2 (Figure 7). The Short Creek is on average a well sorted oolitic calcarenite which is sparsely fossiliferous. Within about 3 feet of the base, however, discontinuous lenses of bioclastic debris have been observed. These lenses lack a distinctive geometry but tend to occur as thinnly laminated bioclastic grainstones. Pelmatozoan debris is the most commonly identified skeletal material. Medium-scale planar cross-beds have been observed 1 to 2 feet higher in the section. Elsewhere in this exposure the unit is massive.

A few chert nodules have been observed near the top of the oolite. The chert is light in color and exhibits the originally oolitic texture. Nodules of oolitic chert range in size from a few centimeters to about 20 centimeters, and are commonly ellipsoidal.

The Short Creek weathers to a rounded, blocky profile. A peculiar vuggy porosity is developed locally near the mid-section of the Short Creek exposure as a result of recent karstic dissolution. The vugs range in size from a few millimeters to a few centimeters and are commonly partially filled by a reddish, clayey residue derived from the overlying strata.

The contact between the Short Creek Oolite and the overlying Baxter Springs Member is conformable, but undulatory and locally stylolitic. The two units are separated by a clayey seam about 0.5 centimeters thick.

The Baxter Springs Member

The basal 4 feet of the Baxter Springs Member is a poorly exposed, extremely cherty unit. Rare fine-grained nodular limestones occur in the chert and are often surrounded by a clayey, siliceous matrix (Figure 7). Bedding is best described as massive in this lithology and the rock is stained a reddish color. The Baxter Springs is covered for 6 to 8 feet above the upper-most exposure of the massive chert, but is once again exposed for a few feet along the cut made for the section road.

Along the north side of the road cut, the Baxter Springs Member consists of nodular cherts and fine-grained limestone in a clayey, siliceous matrix, very similar in appearance to the basal Baxter Springs sediments at Outcrop 1. The fine-grained limestones are commonly intraclastic, with micritic intraclasts reaching several millimeters in diameter. The chert and limestone nodules are irregularly ellipsoidal and commonly interpenetrate one another. The fine-grained matrix may be soft and clayey or very hard. About 4 feet of the nodular lithology is exposed in the road cut. This nodular lithology and the more massive one beneath it are both interpreted herein as representing the L bed subunit of the Baxter Springs Member.

Outcrop 3

General

Outcrop 3 (SW1/4, NW1/4, Sec.35, T27N, R24E) was described from exposures along State Highway 10 about 2 miles southeast of Wyandotte, Oklahoma (Figure 3). The Short Creek Oolite, the Baxter Springs Member, and the basal Moccasin Bend Member are exposed for approximately 100 feet along the east side of the highway (Figure 8).

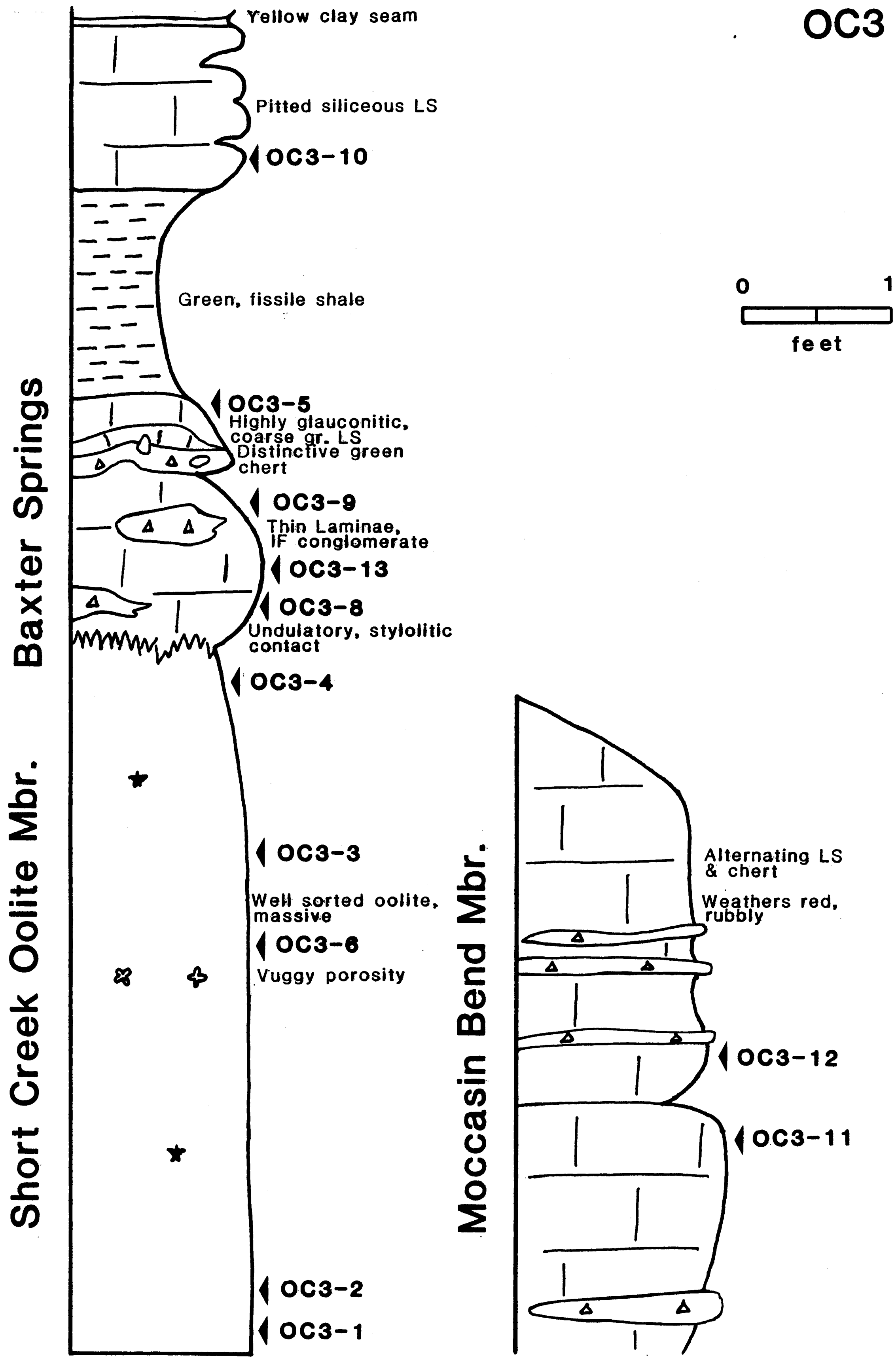
The quality of the exposure is variable along its length. The Short Creek is uniformly well-exposed, while the Baxter Springs and the Moccasin Bend are partially covered by soil and vegetation (Figure 9). The Joplin Member is apparently covered by soil in the drainage ditch on the east side of the highway.

The Short Creek Oolite

The thickness of the Short Creek Oolite measured at Outcrop 3 is 6 feet (Figure 9). Thin sections made from samples of the basal strata from this locality indicate a complex lithology consisting of ooids and bioclastic debris. Petrographically, the sample resembles the upper Joplin Member, except that the upper Joplin is not known to contain ooids. This lithology is interpreted herein as representing

Figure 8. Photograph of the exposures at Outcrop 3

Figure 9. Idealized measured section from Outcrop 3


OC3
Yellow clay seam
Pitted siliceous LS
OC3-10
Green, fissile shale
0
1
feet
OC3-5
Highly glauconitic, coarse gr. LS
Distinctive green chert
OC3-9
Thin Laminae, IF conglomerate
OC3-13
OC3-8
Undulatory, stylolitic contact
OC3-4
Baxter Springs
Short Creek Oolite Mbr.
OC3-3
Well sorted oolite, massive
OC3-6
Vuggy porosity
OC3-2
OC3-1
Moccasin Bend Mbr.
Alternating LS & chert
Weathers red, rubbly
OC3-12
OC3-11

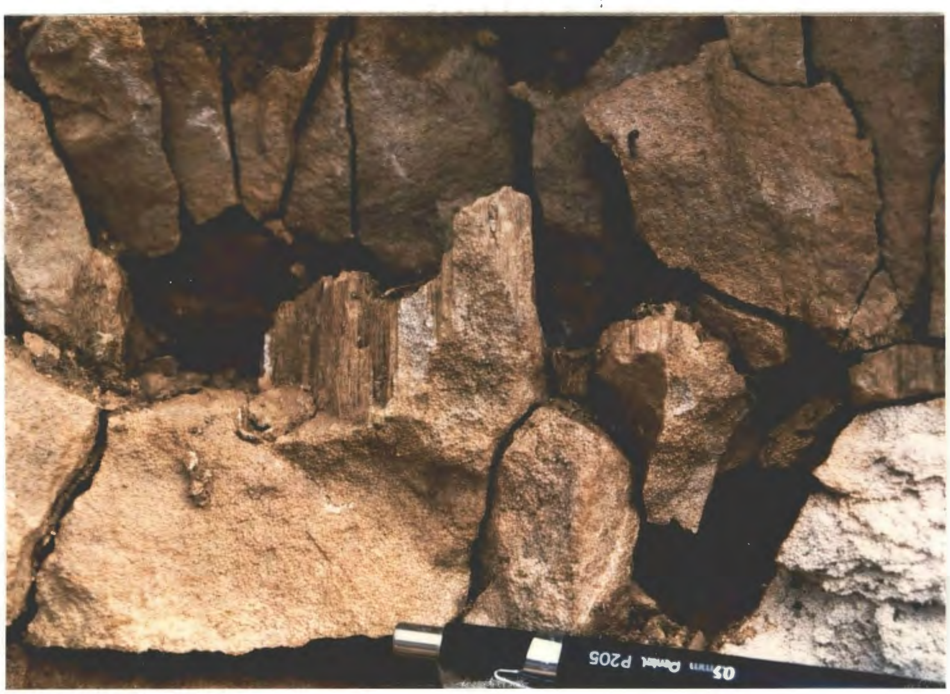
a gradational contact between the Joplin Member and the overlying Short Creek Oolite.

Throughout the rest of the section the Short Creek is a well-sorted oolitic calcarenite with only traces of scattered fossil debris, and is very typical of exposures elsewhere in the study area. The unit appears massive in outcrop, but polished slabs reveal a vague inclined lamination believed to represent cross-bedding.

The Short Creek weathers to a rounded, vertical escarpement displaying the typical white to light gray color. As in Outcrop 2, vuggy porosity occurs near the middle of the unit. Most of the pore volume is filled with a fine-grained, reddish sediment derived from the weathering and erosion of the overlying Moccasin Bend or the Baxter Springs Members.

The contact between the Short Creek and the overlying Baxter Springs is conformable but undulatory, and extremely stylolitic. These stylolites are better displayed at this outcrop than at any other visited by the author during the course of this study. Peak to peak amplitude may exceed 3 centimeters, while the wavelength is only a few millimeters (Figure 10). Stylolitization apparently occurred in the Short Creek, as a distinctive oolitic texture is preserved.

Figure 10. High-amplitude stylolitization occurring at the contact between the Short Creek and the Baxter Springs Members



The Baxter Springs Member

The Baxter Springs Member displays a unique lithology at Outcrop 3 and measures only 1.5 to 2 feet in thickness. The unit consists of siliceous limestones and nodular cherts, and bedding is poorly defined (Figure 9). The limestone is mud-supported and rather poorly sorted, with occasional skeletal debris. Polished slabs of samples taken from this lithology almost always reveal small micritic intraclasts, as well as vague horizontal lamination. These muddy sediments may exhibit a mottled appearance, apparently the result of bioturbation. Limestones of the unit are slightly glauconitic and phosphatic. Chert occurs as irregular lenticular nodules, and is light in color and commonly mottled.

The identity of this subunit of the Baxter Springs is problematic. As the unit directly overlies the Short Creek, it is tentatively identified as the L bed subunit of the Baxter Springs Member. It is conceivable, however, that this rock represents the K bed subunit which is now in contact with the Short Creek as a result of the dissolution of a thin L bed section during compaction.

The siliceous limestone is overlain by a thin, but distinctive, green chert. The chert layer is 2 to 3 inches thick and contains occasional blebs or nodules of glauconitic and fossiliferous limestone. The green chert may be overlain by a thin, discontinuous fine-grained limestone with scattered ooids. The glauconitic blebs occurring in the green chert occur in the fine-grained limestone as well, and individual blebs may cross the contact between the two units to occur in both simultaneously.

The glauconitic blebs are believed to represent boring by some organism into a hard substrate, followed by infilling glauconitic J bed sediments. The hard substrate might have resulted from hardground development, or the winnowing away of unconsolidated sediments during the erosional emplacement of the overlying J bed subunit.

The J bed subunit is highly glauconitic, and contains scattered dark chert pebbles and phosphatic nodules. The unit also contains scattered and, on the whole, rather abundant pelmatozoan debris. The glauconitic limestone is 2 to 5 inches in thickness, varying locally, and is overlain by about 1.5 feet of green, fissile shale. The shale contains scattered siliceous and calcareous nodules 1 to 2 centimeters in diameter. The green shale is interpreted herein as representing an upper phase of the J bed subunit at Outcrop 3, and is overlain with apparent conformity by the siliceous limestones of the Moccasin Bend Member.

The Moccasin Bend Member

The green shale of the upper Baxter Springs Member is overlain with apparent conformity by hard, dense, siliceous limestones and chert of the Moccasin Bend Member. The lower 1.5 feet of the Moccasin Bend is a siliceous limestone which has weathered to a very rough, irregular and massive surface.

The surface of this rock is pitted as a result of the removal of lenticular chert nodules during recent weathering. The lenticular pits may reach 1 foot or more in length, and are commonly 2 or more centimeters in height (Figure 9). The chert removed weathers to a gravelly rubble which litters the outcrop below. The siliceous limestone has a mottled appearance suggesting bioturbation of the fine-grained sediment.

A thin siliceous limestone (1.5 to 2 feet) overlies the pitted limestone. Separating the two units is a thin, yellowish clayey seam. The thin siliceous limestone differs from the one below in that the lenticular cherty layers are still in place. Furthermore, this unit exhibits poorly defined bedding, with beds ranging in thickness from 2 to 6 inches. The sediment is finely crystalline and contains scattered skeletal debris.

The poorly bedded limestone is overlain by at least 10 feet of interbedded siliceous limestone and chert. The basal 2 to 3 feet of this unit consists of a massive limestone with thin, continuous cherty layers, and resembles the horizontally-banded Moccasin Bend described at Outcrop 1 (Figure 9). The horizontally-banded rock is overlain by 7 to 8 feet of siliceous limestone and chert, each occurring in beds 1.5 to 2 feet thick. This upper portion of the outcrop is rather poorly exposed, as the chert layers weather to a reddish rubble which tends to cover the outcrop below.

CHAPTER III

STRATIGRAPHY OF THE BOONE FORMATION

General Stratigraphic Features

Rocks exposed at the surface in the northeastern Oklahoma study area are predominantly Mississippian and Pennsylvanian in age. Lower Paleozoic sediments and the granitic Precambrian basement are known from deep drill holes.

The topography and structure of the Precambrian basement in northeastern Oklahoma has been mapped and discussed by Denison (1981). He reports (p. 25) that because of the rugged topography of the basement surface, the best datum for the study of later structures is the top of the Cambro-Ordovician carbonate strata. He emphasizes (p. 25) his suspicion that earlier maps of Ireland (1955) and Dille (1956) may be controlled by the density of well data. Denison believes that where control is sufficient a rugged topography is indicated, but where control is sparse, a more gentle surface is indicated. He reports (p. 25) that the thickness maps of Arbuckle and younger sediments of Chenowith (1968) show the basement surface to be a significant influence on the thickness of the overlying sediments and their distribution.

Lower Paleozoic formations are important aquifers in the tri-state area and have been described in detail by Reed, Schoff, and Branson (1955) in connection with their study of ground water in Ottawa County, Oklahoma. These Lower Paleozoic strata are dominantly dolomite, with lesser chert, sandstone, and shale, and include rocks of Upper Cambrian and Lower Ordovician age. Locally, the Lower Paleozoic strata truncate into the flanks of Cambrian granite knobs, which may represent islands in the early Paleozoic seas (Reed, et al., 1955, p. 36). The knobs were subsequently overlain by younger sediments (McKnight and Fischer, 1970, p. 14).

In the northeastern Oklahoma study area, the Lower Ordovician Cotter Dolomite is overlain with major unconformity by the Chattanooga Shale of Devonian-Mississippian age (McKnight and Fischer, 1970). The erosional surface on which the Chattanooga was deposited was a level peneplane of very wide extent (McKnight and Fischer, 1970, p. 19).

The Chattanooga Shale is overlain with apparent disconformity by the Boone Formation of Mississippian age (McKnight and Fischer, 1970, p. 19). Stratigraphic relationships and correlations with time-equivalent strata are problematic. It is generally accepted by recent workers in this area that the Boone Formation includes sediments of Osage and Meramec ages. The placement of a boundary between the Osage and Meramec Series remains a disputed topic among workers in the area.

Strata of the upper Boone Formation are overlain locally by the Quapaw Limestone of Warsaw or Salem age, with uncertain relations (McKnight and Fischer, 1970, p. 55). In places where the Quapaw Limestone is not present the Boone Formation is overlain unconformably by the Hindsville Limestone of Chester age, or the Krebs Group of Pennsylvanian age (McKnight and Fischer, 1970, p. 55).

The Boone Formation

Reference to the Boone Formation was first published in reports of the Arkansas Geological Survey by Simonds (1891, p.27-37), and Penrose (1891, p. 129-138) to designate widely outcropping Mississippian units in northern Arkansas. A basal part, the St. Joe Limestone, was differentiated shortly after by Hopkins (1893, p. 253). The Boone Formation was mapped by Siebenthal in the Joplin mining district (Smith and Siebenthal, 1907), and two additional members were described: the Short Creek Oolite Member and the Grand Falls Chert Member.

The part of the Boone occurring between the St. Joe and the Grand Falls Members was named the Reeds Spring Limestone by Moore (1928, p. 144). Cline (1934, p. 1134) proposed that useage of the term "Boone", which he considered to be a synonym of Osage, be suppressed, believing that the term "Osage" had clear priority. He also proposed that the St. Joe and Reeds Spring Members be raised to formational rank, and that the names Burlington Formation, Keokuk Formation, and Warsaw Formation of the standard Mississippian section of southeastern Iowa and Illinois be extended into the southern Ozark region to apply to equivilant strata in the Boone.

Moore, Fowler and Lyden (1939) adopted the idea of extending the standard Mississipian section names into the area, although they believed that the Burlington Formation did not extend into the Tri-State mining district. These authors fitted the informal letter designation of Fowler and Lyden (1932) into their new classification. In the letter designation of Fowler and Lyden, the Boone is divided into 16 horizons, labeled "B" to "R", from the top down, and the variable susceptibility of each to mineralization is outlined.

Although the Boone Formation can be divided into several lithologies and faunal units for mapping, this has not been completed to date. The Grand Falls Chert Member of the Joplin district was mapped by Smith and Siebenthal in 1907, and the Short Creek Oolite Member, mapped by Speer in 1951, was included in the geologic map of Ottawa County published by Reed, Schoff, and Branson in 1955. The St. Joe Limestone Member of the Wyandotte quadrangle was mapped by Siebenthal and Messler in 1907.

McKnight and Fischer (1970, p. 19) have stated that they do not believe that extension of the standard Mississippi valley formation names into the area is practical because of differences of opinion regarding the placement of boundaries. They retained the term "Boone Formation" and divided the section into seven members, three of which are new. They stated further that some or all of these could rank as formations, but are best retained at the lower rank of member until mapping is complete. The classification advanced by McKnight and Fischer (1970) is useful and is largely followed in this study. These authors have also fitted the informal letter designations of Fowler and Lyden (1932) into their classification (Figure 11).

The Osage Series

A number of important papers have been published concerning the stratigraphy of Osage sediments in the northeastern Oklahoma study area and adjacent regions. Differences of opinion concerning the placement of stratigraphic boundaries and age relationships are common in the literature. Figure 12 is presented to help the reader assimilate the stratigraphic interpretations of several important authors. Many of these interpretations are presented in greater detail in the following discussions.

The St. Joe Limestone Member

The St. Joe Limestone was named by Hopkins (1898, p. 150, 253) for a reddish-colored limestone occurring at the base of the Boone Formation in northern Arkansas. This limestone is widespread, and typically chert-free (McKnight

Figure 11. Comparison of currently recognized Boone Formation members with the informal letter designations of Fowler and Lyden, 1932 (Source: McKnight and Fischer, 1970)

Series	Members of Boone Formation	Informal letter classification (Fowler and Lyden, 1932; Fowler, 1942)
Meramec (Upper Mississippian)	Moccasin Bend Member	*Bed* B C D E F G H
	Baxter Springs Member	J K L
	Short Creek Oolite Member	M
Osage (Lower Mississippian)	Joplin Member	M
	Grand Falls Chert Member	N O P Q
	Reeds Spring Member	R
	St. Joe Limestone Member	

Figure 12. Comparison of Boone Formation stratigraphy and correlation of a number of important authors along with the conclusions generated from this study; figure 12 is continued on page 55

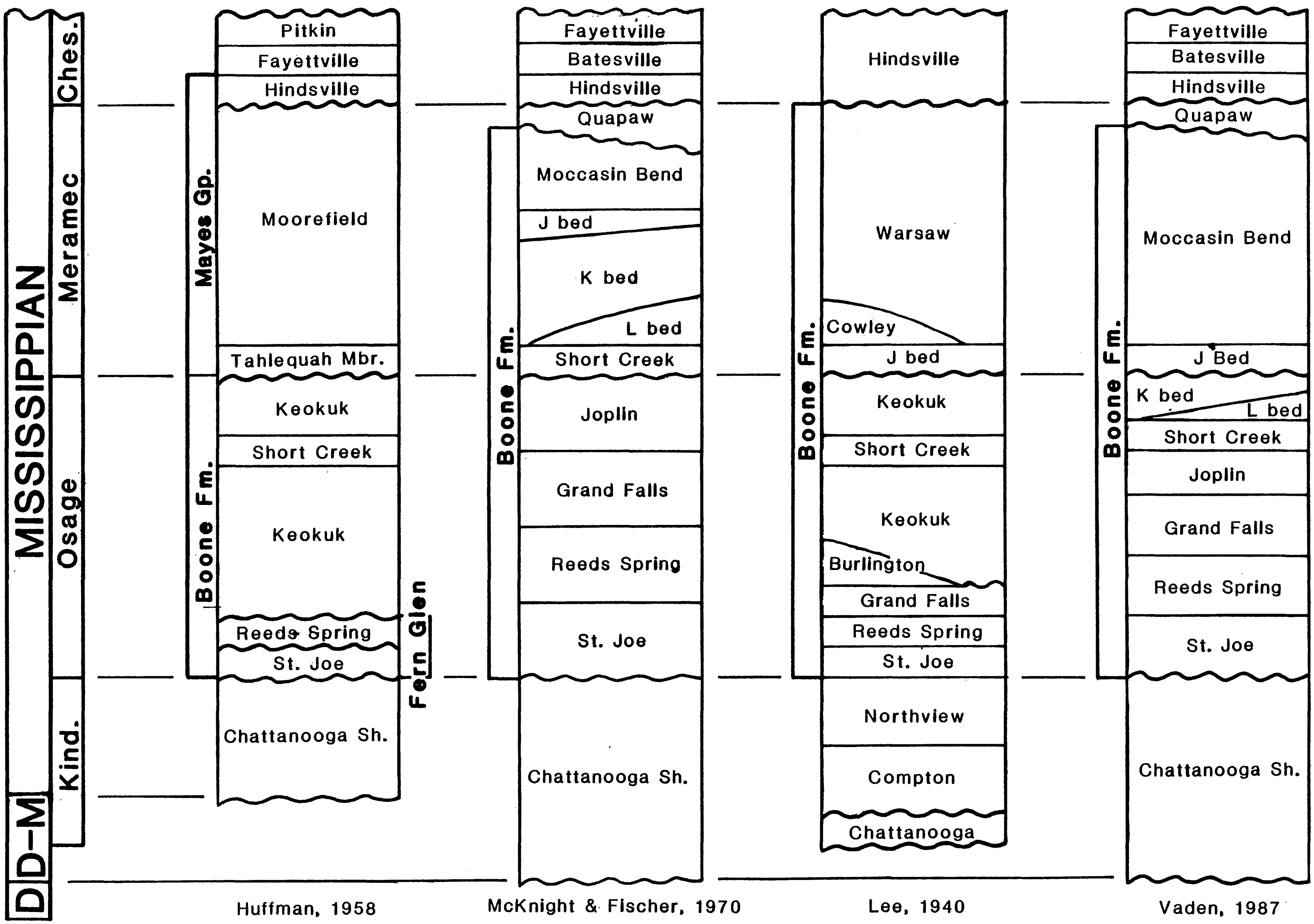
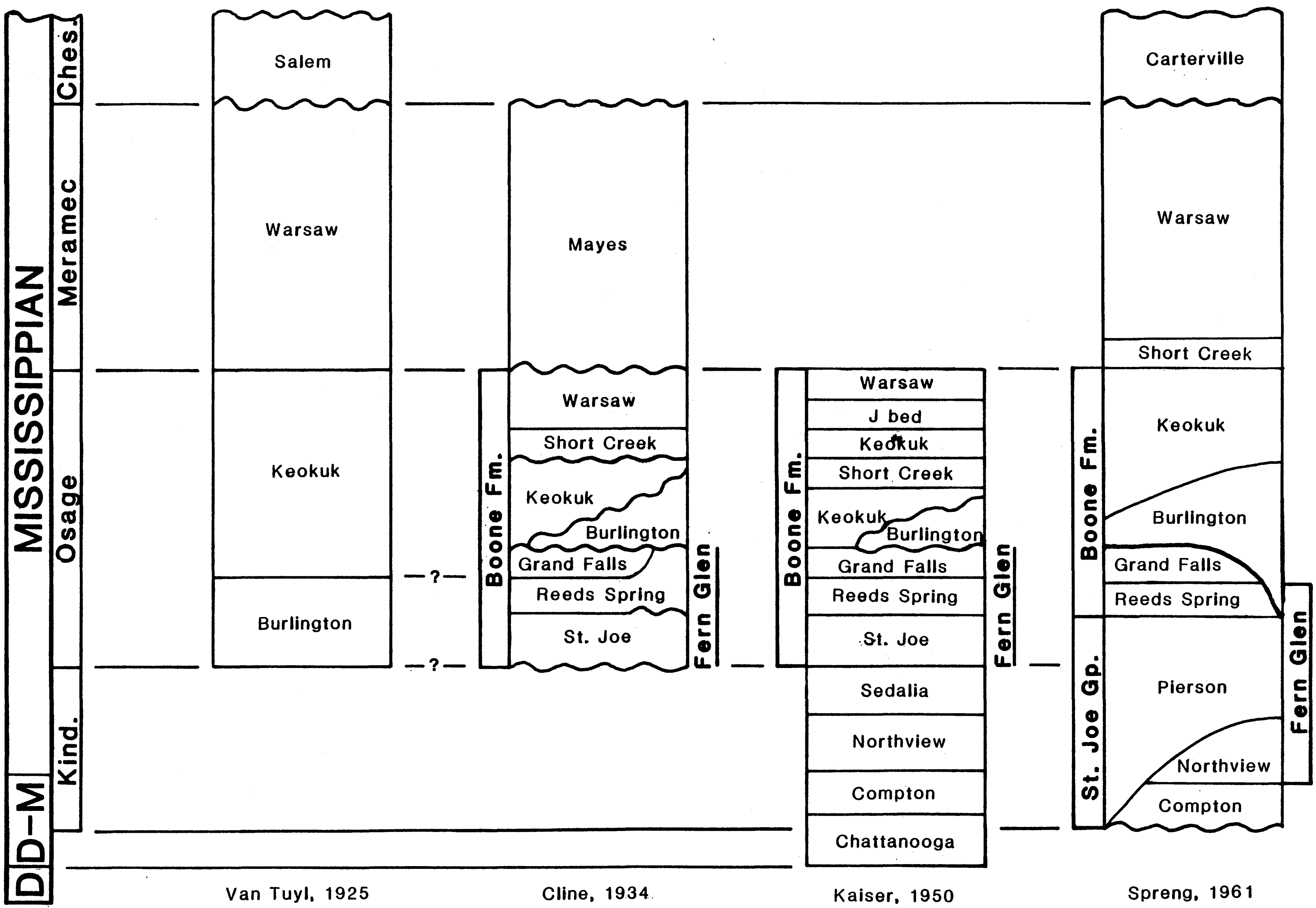

MISSISSIPPIAN
D
D-M
Ches.
Meramec
Osage
Kind.
Pitkin
Fayettville
Hindsville
Mayes Gp.
Moorefield
Tahlequah Mbr.
Keokuk
Short Creek
Keokuk
Boone Fm.
Reeds Spring
St. Joe
Fern Glen
Chattanooga Sh.
Huffman, 1958
Fayettville
Batesville
Hindsville
Quapaw
Moccasin Bend
J bed
K bed
L bed
Short Creek
Boone Fm.
Joplin
Grand Falls
Reeds Spring
St. Joe
Chattanooga Sh.
McKnight & Fischer, 1970
Hindsville
Warsaw
Cowley
J bed
Boone Fm.
Keokuk
Short Creek
Keokuk
Burlington
Grand Falls
Reeds Spring
St. Joe
Northview
Compton
Chattanooga
Lee, 1940
Fayettville
Batesville
Hindsville
Quapaw
Moccasin Bend
J Bed
K bed
L bed
Boone Fm.
Short Creek
Joplin
Grand Falls
Reeds Spring
St. Joe
Chattanooga Sh.
Vaden, 1987

Figure 12, continued



MISSISSIPPIAN
D
D-M
Ches.
Meramec
Osage
Kind.
Salem
Warsaw
Keokuk
Burlington
Mayes
Warsaw
Short Creek
Keokuk
Burlington
Grand Falls
Reeds Spring
St. Joe
Boone Fm.
Fern Glen
Warsaw
J bed
Keokuk
Short Creek
Keokuk
Burlington
Grand Falls
Reeds Spring
St. Joe
Sedalia
Northview
Compton
Chattanooga
Boone Fm.
Fern Glen
Carterville
Warsaw
Short Creek
Keokuk
Burlington
Grand Falls
Reeds Spring
Pierson
Northview
Compton
Boone Fm.
St. Joe Gp.
Fern Glen
Van Tuyl, 1925
Cline, 1934
Kaiser, 1950
Spreng, 1961

and Fischer, 1970, p. 20). The St. Joe forms the base of the Osage series in northeastern Oklahoma, northwestern Arkansas, southwestern Missouri, and southeastern Kansas.

Moore (1928, p. 165, 166) reports that the St. Joe resembles the Fern Glen Limestone of southeastern Missouri both lithologically and faunally. The St. Joe was believed by Moore, Fowler, and Lyden (1939, p. 7) to be equivalent to the Pierson and Sedalia Limestones of southwest and central Missouri. Kaiser (1950, p. 2151) has demonstrated, however, that the St. Joe is younger than the Pierson. Furthermore, Kaiser (1950, p. 2160) states that the term "Pierson" should be dropped as a synonym of St. Joe because both occupy the same stratigraphic position in the Osage series, and because they are both practically identical faunally and lithologically. Spreng (1961, p. 60) still favors the use of "Pierson", in Missouri, believing that the St. Joe is a partial equivalent. In 1934, Cline (p. 1137) proposed that the St. Joe be raised to formational rank.

Moore, Fowler, and Lyden (1939, p. 5), and McKnight and Fischer (1970, p. 19) believe that the contact between the St. Joe and and the underlying Chattanooga Shale is disconformable. Huffman (1958, p. 42) reports the contact to be unconformable, as indicated by a weathered zone separating the two units, and the local absence of the Chattanooga Shale beneath the St. Joe. Cline (1934, p. 1139) states that in places where the Chattanooga is missing, the St. Joe rests unconformably on Ordovician or Silurian strata. This relationship is also reported by McKnight and Fischer (1970, p. 21), who state that drilling records show the St. Joe to rest with profound unconformity on the Ordovician-age Cotter Dolomite in parts of the mining district. A thin sand occurring at the base of the St. Joe where it overlies the Cotter Dolomite is referred to as the Sylamore Sandstone by Moore (1928, p. 110), and McKnight (1935, p.67).

Most workers agree that the contact between the St. Joe and the overlying Reeds Spring Member is conformable, if not gradational. Cline (1934, p. 1141) and Huffman (1958, p. 42) report, however, that locally the Reeds Spring overlies the Chattanooga, and older strata, with unconformity.

The Reeds Spring Member

The Reeds Spring Member was named by Moore (1928, p. 190) for exposures that occur in southwestern Missouri. The Reeds Spring is reported by Laudon (1939, p. 328) to be exceptionally fossiliferous at its type location, but only sparsely so in northeastern Oklahoma. The unit in northeastern Oklahoma consists of dark, bluish-colored, thinnly bedded, extremely cherty limestones, and forms the R bed subunit of Fowler and Lyden (Fowler, 1942). The regularity of the thin beds creates the impression of a horizonally banded wall in outcrop, as expressed by Moore (Cline, 1934, p. 1143).

McKnight and Fischer (1970, p. 23-26) discuss the occurrence of crinoidal bioherms in the Reeds Spring Member of northeastern Oklahoma. The bioherms consist of a muddy core flanked by coarse-grained skeletal debris, composed largely of crinoids and bryozoans. These authors state that, in lithology, the bioherms resemble the underlying St. Joe much more closely than the Reeds Spring. In fact, they have been classified as St. Joe by Laudon (1939) and Harbaugh (1957). They are believed to be Reeds Spring in age by McKnight and Fischer because they occur above a thin limestone ledge regarded by them as the top of the St. Joe (p. 25). Harbaugh (1957, p. 2542, 2543) believes that the bioherms formed wave-resistant organic structures and displayed significant topographic relief which continued for some time after the cessation of their growth. He cites the sloping of later beds over the massive core as evidence.

Moore (1928, p. 191) stated that the Reeds Spring was the time-equivalent of at least part of the lower Burlington strata. He announced, however, in 1933 (p. 203, 204) that a study of the type section of the Fern Glen Formation near St. Louis showed the presence of stratigraphic units corresponding to the Sedalia and Reeds Spring limestones. He stated further that a disconformity and a marked difference in faunal character served to distinguish the beds of Fern Glen age from the succeeding Burlington units.

Cline (1934, p. 1146) agrees with Moore that the Reeds Spring seemed to be of pre-Burlington age. In addition he reports (p. 2162) that where the Reeds Spring is not overlain unconformably by the Burlington, as in extreme southwestern

Missouri, it is overlain unconformably by the Keokuk Limestone. Cline states that (p. 2164-2165) the Burlington has been removed by erosion in eastern portions of southwest Missouri and was "seemingly never deposited in the Tri-State mining district." According to Kaiser (1957, p. 2165) the Reeds Spring is overlain unconformably by the Burlington. He reports that the Reeds Spring and the St. Joe pinch-out a short distance north of Springfield, Missouri, and here the Burlington rests on the Northview or Sedalia Formations.

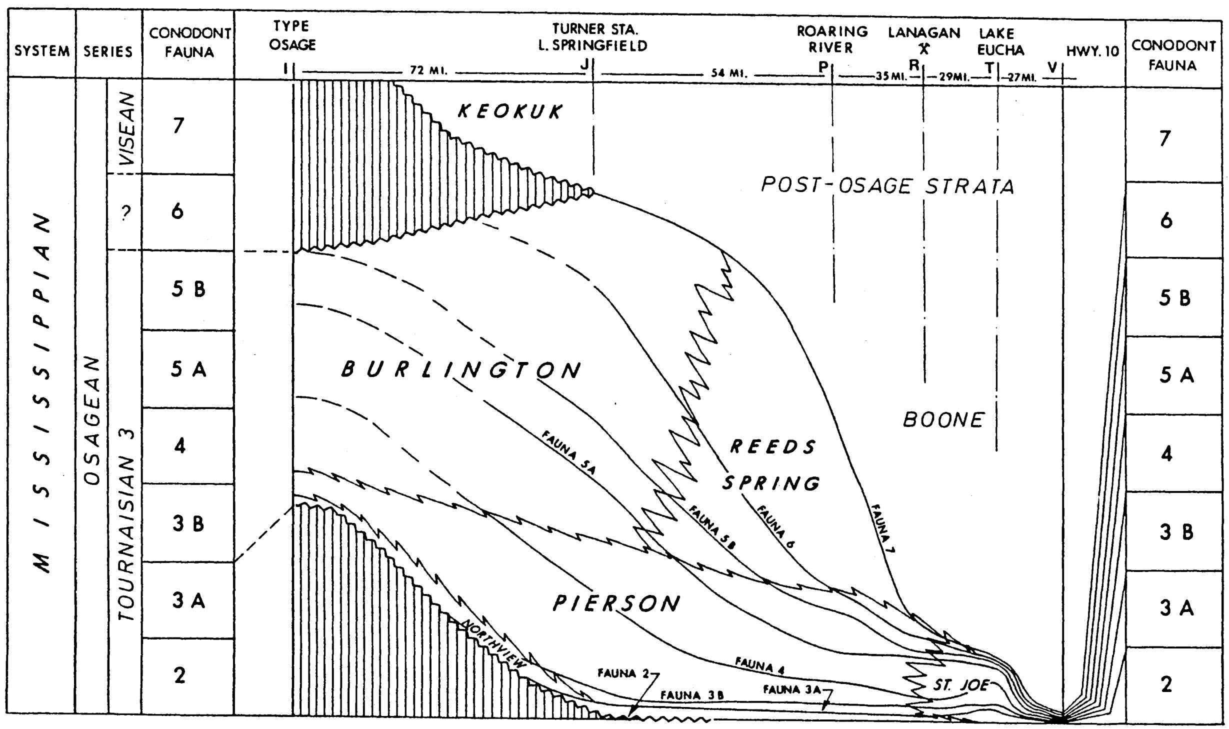
McKnight and Fischer (1970, p. 26, 27) disagree with this interpretation. They cite a written communication from Gordon (1965) who reports that fossils from the Reeds Spring were pronounced to be clearly of Burlington age. Lane (1978, pp. 169-170) believes that the cherty muds and wackes of the Reeds Spring represents sedimentation on the margin of the Burlington shelf, and that the underlying St. Joe represents a basinal facies (Figure 13).

McKnight and Fischer (1970, p. 27) believe that the contact between the Reeds Spring and the underlying St. Joe Members is conformable, if not gradational. Spreng (1961, p. 63) is in partial concurrence stating that the lateral equivilants of the Reeds Spring are the Fern Glen, the Grand Falls Member and "possibly the lower Burlington."

The Grand Falls Member

The relationship of the Grand Falls Chert Member of the Boone Formation to the underlying Reeds Spring is the subject

Figure 13. Cross-sectional representation of regional facies development (Source: Lane, 1978)


SYSTEM
SERIES
CONODONT FAUNA
TYPE OSAGE
TURNER STA. L. SPRINGFIELD
ROARING RIVER
LANAGAN "X"
LAKE EUCHA
HWY. 10
CONODONT FAUNA
I
72 MI.
J
54 MI.
P
35 MI.
R
29 MI.
T
27 MI.
V
MISSISSIPPIAN
OSAGEAN
VISEAN
?
TOURNAISIAN 3
7
6
5 B
5 A
4
3 B
3 A
2
KEOKUK
POST-OSAGE STRATA
BURLINGTON
BOONE
REEDS SPRING
PIERSON
NORTHVIEW
ST. JOE
FAUNA 5A
FAUNA 5B
FAUNA 6
FAUNA 7
FAUNA 4
FAUNA 2
FAUNA 3B
FAUNA 3A

of considerable debate. The name was proposed by Siebenthal (1907, p. 4) for a prominent cherty bed particularly well developed at Grand Falls on Shoal Creek about 10 miles east of Baxter Springs, Kansas. The unit includes the N, O, P, and Q beds of Fowler and Lyden (Fowler, 1942) however, no distinctive lithologic features can be distinguished. As its name implies, the unit is composed predominately of chert.

The Grand Falls at its type location is considered by Cline (1934, p. 1142) to be "only a local variant of the upper Reeds Spring," though he also believes that it is best to regard the two as separate formations. This is in agreement with Moore (1933, p. 203, 204). Kaiser (1950, p. 2161, 2162) concurs, stating that the Grand Falls at the type locality represents a zone of the upper Reeds Spring formed during mineralization of the Tri-State mining district and is not a widespread stratigraphic marker.

In a written communication to McKnight and Fischer (1970, p. 30) dated 1965, Gordon reports that the fauna of the Grand Falls is characterized by the earliest appearance of several brachiopod species generally regarded as Keokuk forms, the most characteristic being *Rotaia subtrigona*. He also reports that the unit contains several Burlington species not found in the overlying Joplin Member, and that the Grand Falls is an approximate equivalent of the lower Keokuk of Van Tuyl (1925, p. 47, 146).

McKnight and Fischer (1970, p. 31) report the contact between the Grand Falls and the underlying Reeds Spring to be one of gradational conformity, or with interfingering between the two. They also state (p. 32) that the Grand Falls is overlain with apparent conformity by the Joplin Member of the Boone Formation.

The Joplin Member

The Joplin Member of the Boone Formation is a cherty limestone which crops out widely in the Wyandotte quadrangle of Oklahoma. The term was coined by Hinchey (1946, p.38) for exposures at the Joplin Marble Quarries Company, three miles southwest of Joplin, Missouri. The Joplin Member has been the major ore-producing stratum in the Picher mining field. It corresponds to the M bed of Fowler and Lyden (Fowler, 1942). McKnight and Fischer (1970, p. 32) report that the M bed of Fowler and Lyden also includes the overlying Short Creek Oolite Member, but that the oolite is so universally leached, squeezed, and replaced in the mineralization process that it becomes indistinguishable at the top of the M bed.

Fossils are abundant in the Joplin Member. In a written communication to McKnight and Fischer (1970, p. 37), Gordon reports that the entire fauna consists of species which range upward from the Grand Falls Member. Several species do not occur above the top of the Joplin Member. Gordon states further that as none of the species is restricted to the Joplin, it is the "strong Keokuk flavor of the fauna and the absence of any characteristic Burlington or Warsaw elements that typify the Joplin fauna." He correlates the Joplin with the type Keokuk section of Van Tuyl (1925, p. 142-154) at Keokuk, Iowa.

McKnight and Fischer (1970, p. 37) report that the Joplin Member overlies the Grand Falls Chert Member with apparent conformity, although the "marked change in lithology must record an abrupt change in the conditions of deposition." They view the contact with the overlying Short Creek Oolite Member as one of disconformity.

Two opinions are reflected in the literature concerning the nature of the contact between the Joplin Member and the overlying Short Creek Oolite Member. One opinion is that the contact is one of disconformity, representing the boundary between Osage and Meramec sedimentation. The other opinion is that the contact is conformable, and that the boundary between Osage and Meramec sedimentation should be placed higher in the section. The author is in agreement with the latter opinion for reasons which are discussed below.

The Short Creek Oolite Member

The Short Creek Oolite is a thin but persistent bed of oolitic limestone that crops out widely along the Neosho and Spring Rivers and their tributaries in Ottawa County, Oklahoma. Much of the outcrop belt in southeastern Ottawa County as mapped by Speer (1951) is presented as Plate 1 of the Oklahoma Geological Survey Bulletin 72 (Reed, Schoff, and Branson, 1955). Several exposures have been omitted from this map, however, particulary along the Spring River and its tributaries (McKnight and Fischer, 1970, p. 37), and along the Neosho River upstream from Mudeater Bend.

The type location as described by Siebenthal (Smith and Siebenthal, 1907) occurs along Short Creek near Galena, Kansas. The unit is lithologically unique and aerially persistant, and is commonly used as a stratigraphic marker to which other parts of the Boone are tied. Mcknight and Fischer (1970, p. 32) report that the Short Creek marks, in effect, the top of the M bed subunit of Fowler and Lyden.

Considerable difference of opinion exists regarding the age and stratigraphic correlation of the Short Creek. In 1928, Moore (p. 232) placed the Short Creek at the base of the Warsaw Limestone (Meramec) and reported the existence of a disconformity separating the unit from the underlying Keokuk Limestone. Spreng (1961, p. 65) agrees, in part, with this interpretation though he believes that the boundary between the Keokuk (Osage) and the Warsaw (Meramec) must be placed arbitrarily. He reports the difficulty in establishing the boundary between the Keokuk and the Warsaw in the subsurface and, on this basis, places the Short Creek at the base of the Warsaw. Moore (1932) originally regarding the Short Creek as the basal member of the Warsaw, now includes it in the Keokuk.

The alteration of Moore's original opinion has served to shape the interpretations of many geologists working in the area. Authors which have placed the Short Creek in the Keokuk include Laudon (1939, p. 331), Moore, Fowler and Lyden

(1939, p. 9), Lee (1940, p. 62), Kaiser (1950, p. 2169), and Huffman (1958, p. 45).

Cline (1934, p. 1155, 1156) places the Short Creek at the base of the Warsaw, but believes that the Warsaw is of Osage age, not Meramec. Kaiser (1950, p. 2157) also believes that the Warsaw is an Osage unit. Kaiser (p. 2171) reports that beds of Meramec age are absent in the Tri-State mining district, the Warsaw being overlain unconformably by the Carterville Formation (Chester). Kaiser is the only worker known by this author to conclude that beds of Meramec age are absent in the Tri-State mining district. South and southeast of the study area Huffman (1958, p. 45, 48-49) reports that the Keokuk is overlain with unconformity by strata of the Mayes Group (Meramec and early Chester).

Two schools of thought exist concerning the placement of the boundary between the Osage and the Meramec in this area. McKnight and Fischer (1970) are proponents of the idea that a disconformity, which they believe separates the Short Creek from the underlying Joplin Member, marks the base of the Meramec series in the Tri-State region. The other idea is that the boundary occurs well above the Short Creek in the section. Many workers place this boundary at the base of the J bed subunit of Fowler and Lyden (Fowler, 1942, p. 207). The J bed subunit marks the upper-most strata of the Baxter Springs Member of the Boone Formation (McKnight and Fischer, 1970).

In a written communication to McKnight and Fischer

(1970, p. 39), Gordon recounts the faunal evidence which suggested to him that the placement of the Osage-Meramec boundary should be made at the base of the Short Creek Oolite Member. Gordon reports that brachiopod species of the Short Creek include a number of late Osage species that range up from the beds below, as well as associated early Meramec species. *Tetracamera arcitirostrata*, described originally from the oolitic Salem Limestone (Meramec) appears to be restricted, in the Wyandotte quadrangle, to the Short Creek Oolite Member where it is common (McKnight and Fischer, 1970). *Marginirugus magnus*, also originally described in the Salem Limestone, is reported by Gordon to occur locally at the base of the Short Creek Oolite.

In a study of the subsurface Mississippian rocks of Kansas, Lee (1940) presents convincing evidence of a regional transgression whose base is marked by the J bed subunit of Fowler and Lyden. Lee's report (1940) describes the erosional truncation of the Keokuk, Burlington, and Reeds Spring Limestones (Osage) beneath the J bed subunit in southeastern Kansas and northeastern Oklahoma. The map presented as Figure 14 depicts the line of section (E-F') of the cross section in Figure 15. Notice in Figure 15 that the oolitic limestone is correlated as the Short Creek by Lee (1940, p. 61), who reports its occasional occurrence in wells from Cherokee County to Rice County, Kansas.

Lee has concluded that the Short Creek Oolite is an Osage unit occurring in the upper Keokuk (1940, p. 61). He

Figure 14. Map of well locations and lines of cross-section utilized during the preparation of the cross-section presented as Figure 15 (Source: Lee, 1940)

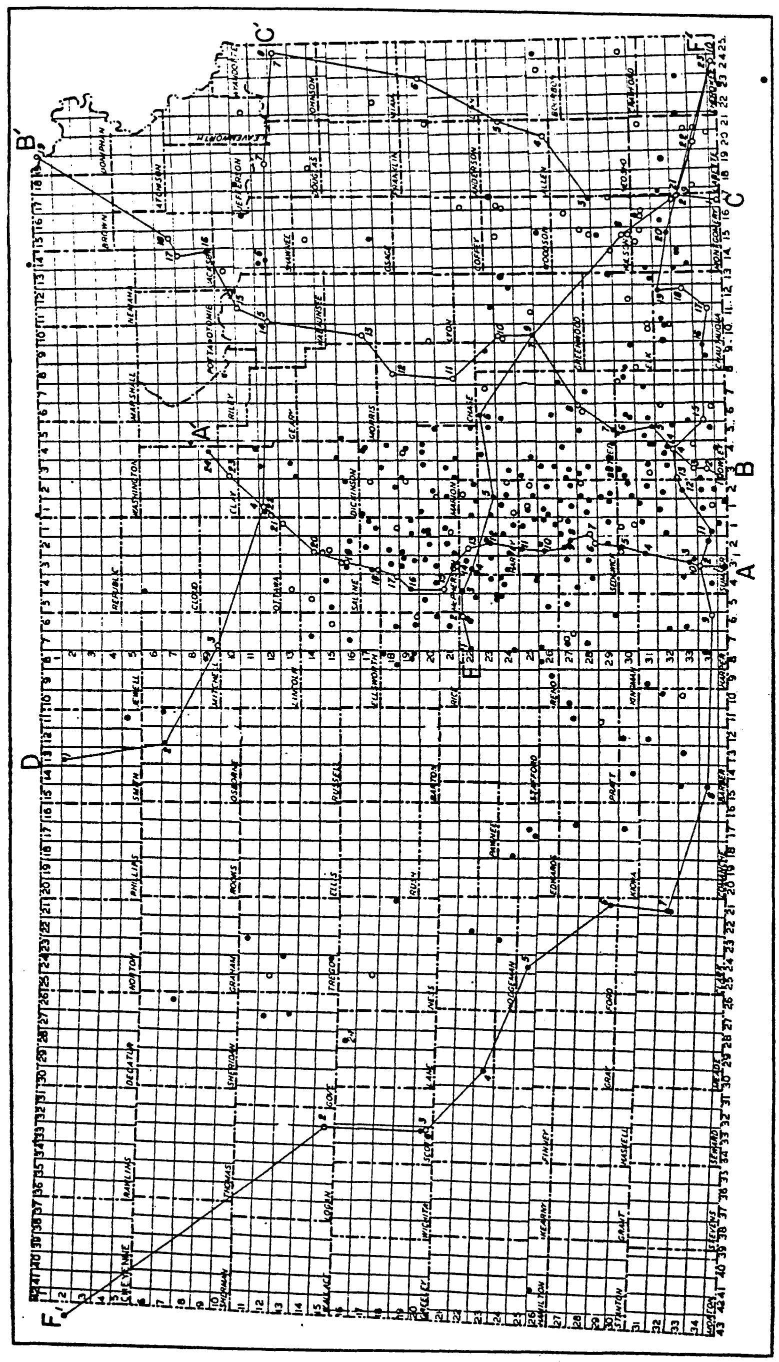
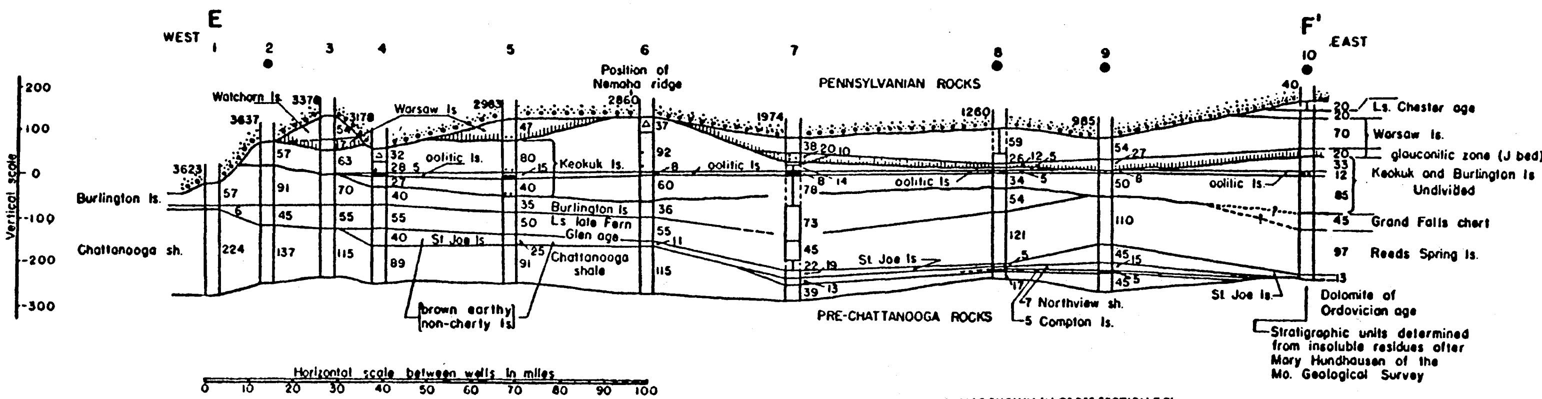


Figure 15. Cross-section drawn along line E–F′ in southeast Kansas (Source: Lee, 1940)



CROSS SECTION E-F'

WELLS SHOWN IN CROSS SECTION E-F'

Index no.	Company	Farm and well no.	Location		Index no.	Company	Farm and well no.	Location
1.	Mississippi Valley	Ringer no. 1	Sec. 19, T. 22 S., R. 7 W		6.	Merriman et al	Nelson no. 1	Sec. 4, T. 23 S., R. 6 E
2.	Allison & Fitzwilliams	Dukelow no. 1	Sec. 11, T. 22 S., R. 6 W.		7.	Farr & Kiskaddon	Badger no. 1	Sec. 33, T. 25 S., R. 10 E
3.	Braden et al	Willems no. 1	Sec 6, T. 22 S., R. 4 W		8.	Trees	Edwards no. 1	Sec. 22, T. 30 S., R. 15 E
4.	McBride	Friesen no 1	Sec. 20, T. 22 S., R. 3 W.		9.	Unknown	Lynn no. 1	Sec. 10, T. 33 S., R. 17 E.
5.	Patton	Haase no. 1	Sec. 18, T. 24 S., R. 2 E.		10.	St Louis Sm. & Ref Co.	Ballard no. 1	Sec. 10, T. 35 S., R 24 E

No. 9 is no 2 of cross section C-C' and no 21 of cross section F-F'
No 7 is well no 9 of cross section B-B'

states further (p. 65) that because of the well developed unconformity at the base of the rocks assigned to the Warsaw in Kansas, and the lack of evidence for unconformity in the rocks above the base, that the Warsaw is believed to be of Meramec age. The interval between the oolite and the overlying unconformity is herein interpreted as representing the L and K bed subunits of the Baxter Springs Member as described by McKnight and Fischer (1970).

This author agrees with Lee's interpretation (1940) that the Short Creek is an Osage unit overlying lower Osage strata with conformity. In the northeastern Oklahoma study area the Short Creek is overlain with conformity by the Baxter Springs Member of McKnight and Fischer (1970). The Osage sediments are herein interpreted as representing a progradational package which developed in response to a regressing Osage sea. Regressive sedimentation ceased as sea level began to rise in earliest Meramec time.

The Baxter Springs Member

The Baxter Springs Member was named by McKnight and Fischer (1970, p. 40) for exposures that occur at its type location along the Spring River, about 1000 feet south of the Oklahoma-Kansas State line. This member consists of three different subunits of conspicuously different lithology, comprising the J, K, and L beds of Fowler and Lyden (Fowler, 1942). McKnight and Fischer (1970, p. 40) report that the three usually occur in sequence but that the middle subunit

(K) changes character locally, overlapping the lower subunit (L), and apparently grading into it laterally.

All three subunits contain glauconite and phosphatic pebbles indicating similarities in the environments of deposition. The upper subunit, the J bed of Fowler and Lyden (Fowler, 1942), is generally only a few inches thick. Glauconite is abundant and is nearly diagnostic for the bed. McKnight and Fischer (1970, p. 40) report that their interpretation regarding the identity of the unit that in certain areas cuts-down disconformably and truncates the underlying unit or units differs from that of Fowler and Lyden (Fowler, 1942). They state (p. 40) that "we believe this to be the middle unit, or K bed, whereas they [Fowler and Lyden] believe it to be the upper unit, or J bed."

In a written communication to McKnight and Fischer (1970, p. 50), Gordon states that fossils collected from the J bed subunit are more closely related to K bed than to any other part of the Mississippian section. He thus believes that there is no faunal evidence for a marked hiatus beneath J bed as postulated by some geologists. Gordon has observed that *Marginirugus magnus* is abundant in the Baxter Springs Member, and its virtual restriction to the Member and to the underlying Short Creek Oolite Member makes it convenient to regard these beds as constituting the "*Marginirugus magnus* zone." Beds containing *Marginirugus magnus* were formerly included in the Keokuk by most geologists but, since the work of Van Tuyl (1925, p. 184-203), these beds have been included in the Warsaw. Gordon concludes, then, that the Baxter Springs Member appears to be at least partially equivilant to the lower part of the type-Warsaw section.

As previously discussed, Lee (1940) has concluded that the Short Creek and the overlying sediments, up to the J bed subunit, belong to the Keokuk (Osage). Lee's conclusions are based on his interpretation of an unconformity at the base of the J bed subunit (p. 63), and a similarity of the chert below the Short Creek to that above it (p. 62), and he states (p. 65) that the fauna of the Osage and Meramec strata is very similar.

L Bed

The L bed subunit of the Baxter Springs Member is typically a thick unit of pale chert with local interbedded fine-grained limestone. Local occurrences of sparsely oolitic, and glauconitic chert are present in the basal few inches. The unit is present in the main part of the mineralized area of the Picher field but is truncated at the base of the K bed along an irreglar southeast-northwest line traversing the western part of the mining field (McKnight and Fischer, 1970, p. 40).

McKnight and Fischer (1970, p. 46) state that bioherms are probably developed near the western margin of the L bed subunit. The L bed subunit overlies the Short Creek Oolite with conformity, and is overlain with both conformity and angular discordance (McKnight and Fischer, 1970, p. 43) by the K bed subunit.

K Bed

According to McKnight and Fischer (1970, p.43) the K bed subunit of the Baxter Springs Member occurs in two different facies. They refer to an eastern phase consisting of alternating limestone and chert, which resembles the Joplin Member (p. 43). Approximately on the western fringe of the L bed subunit, the K bed subunit becomes shaly and is referred to by them as the western phase (p. 43, 45). McKnight and Fischer (1970, p. 45) report that both phases contain local occurrences of glauconitic oolite.

McKnight and Fischer (1970, p. 47) report that most exposures demonstrate that the shaly western phase of K bed is younger than L bed, but some others indicate a contemporaniety of the two. These authors believe (p. 47) that the lower part of the western phase of the K bed subunit is equivalent in age to the L bed subunit occurring further east.

This author agrees with the conclusion reached by McKnight and Fischer (1970) concerning the age relationships of the L and K bed subunits. Furthermore, as interpreted herein, the basal portions of the L and K bed subunits are in part equivalent to the Short Creek Oolite. It is believed here that the L and K bed subunits were deposited on the inner and outer shelves of a regressing late Osage sea. The deeper outer shelf waters were separated from the shallower waters of the inner shelf by the prograding oolitic shoal of the Short Creek.

The Meramec Series

J Bed Subunit

The J bed subunit of the Baxter Spings Member is a highly glauconitic coarse-grained to shaly limestone, commonly only a few inches thick but reaching a thickness of as much as five feet in the Tri-State mining area (McKnight and Fischer (1970, p. 49). McKnight and Fisher (1970, p. 49) report the occurrence of numerous small phosphatic pebbles and scattered fish teeth in basal portions of the J bed subunit.

The upper two inches of the K bed subunit and the base of the J bed subunit are commonly traversed by small tubes (McKnight and Fischer, 1970, p. 49) which are interpreted by them as borings made by some organism. The borings are filled with the glauconitic material found in the J bed subunit, suggesting the development of a hard ground in the upper K bed subunit. Hardgrounds are believed to develop in settings characterized by low rates of sedimentation (Leeder, 1982, p. 291).

McKnight and Fischer (1970, p. 49) believe that the J bed subunit is conformable on the K bed or L bed subunits. Where both K and L beds are absent, as in some areas on the southwestern fringe of the mining field, they report that the J bed subunit rests conformably on the Short Creek Oolite

Member. As interpreted by Lee (1940) and herein, however, the J bed subunit represents the basal strata of the Meramec series, and rests with unconformity on all lower units.

<u>The Moccasin Bend Member</u>

The Moccasin Bend Member of the Boone Formation was originally described by McKnight and Fischer (1970, p. 50) for the locality on the Spring River six miles east of Miami, Oklahoma. The unit comprises the lettered units from B to H of Fowler and Lyden (Fowler, 1942), from the top down. McKnight and Fischer (1970, p. 51) report that the distinctions are not sharp and may fail, the boundaries commonly being gradational. In general, there is a lower part comprising the G and H beds, and an upper part comprising the B-F beds.

In a written communication to McKnight and Fischer (1970, p. 54, 55) Gordon reports the occurrence of several long-ranging Osage brachiopod species, and several early Meramec species. Gordon has correlated the Moccasin Bend Member with the Warsaw Shale (Meramec).

The Moccasin Bend Member is believed to overlie the Baxter Springs Member conformably and is overlain in part of the Picher mining field by the Quapaw Limestone of Warsaw or Salem age with uncertain relations (McKnight and Fischer, 1970, p. 55). The author has concluded, however, that although the Moccasin Bend Member (Meramec) overlies the J bed subunit of the Baxter Springs Member with conformity, the lower subunits of the Baxter Springs are separated from the J bed subunit by unconformity. An erosional unconformity is indicated by a number of workers who site the truncation of older strata against the J bed deposits. Where the Quapaw Limestone is absent the Moccasin Bend is overlain unconformably by the Hindsville Limestone (Chester), or the Krebs Group of Pennsylvanian (Des Moines) age (McKnight and Fischer, 1970, p. 55).

CHAPTER IV

STRUCTURE OF THE TRI-STATE AREA

Regional Structural Setting

Northeastern Oklahoma occupies the southwestern flank of the Ozark Uplift, a structure which extends into Missouri, southeastern Kansas, and northern Arkansas. Formations strike in an arcuate pattern and are nearly horizonal, exhibiting a regional dip of 25 to 50 feet per mile (McKnight and Fischer, 1970, p. 72), away from the axis of the structure. The regional dip is interrupted by a series of northeast-trending faults and folds, and a series of folds trending northwest (Figure 16).

Huffman (1958, p. 89) believes that deformation in northeastern Oklahoma is closely associated with the developing Ozark geanticline. He reports (p. 89) that southward tilting in pre-Chattanooga time is evidenced by the northward truncation of many older units, with subsequent overlapping by the Chattanooga Shale (Figure 17). He states further (p. 89) that renewed southward tilting in both pre-Hale (Morrow) and pre-Atoka time is indicated by the truncation of the Pitkin (Chester), and the Bloyd (Morrow)

Figure 16. Regional structure of the Ozark Anticline; contours are drawn on the top of Cambro-Ordivician strata (Source: Nodine-Zeller and Thompson, 1977)

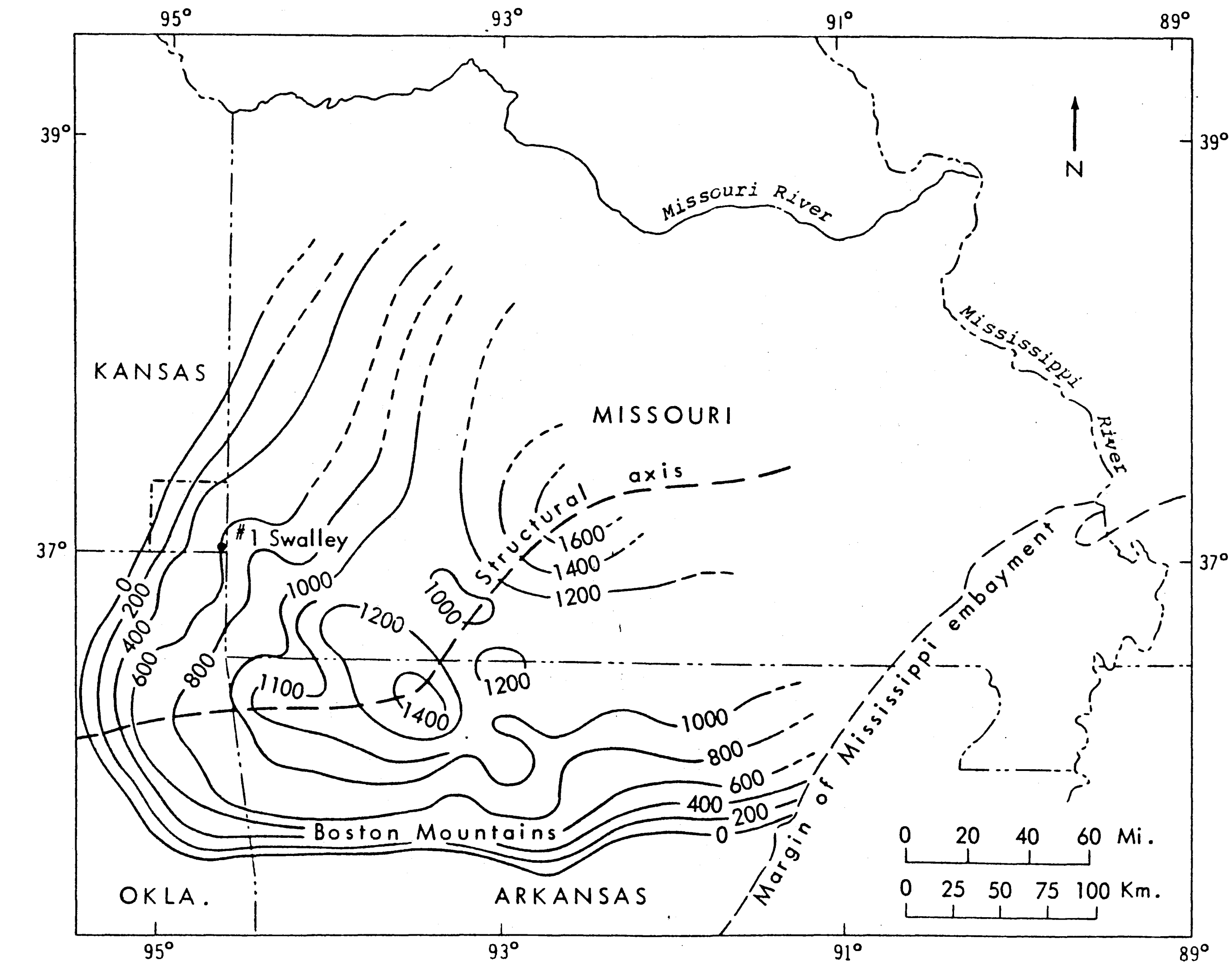
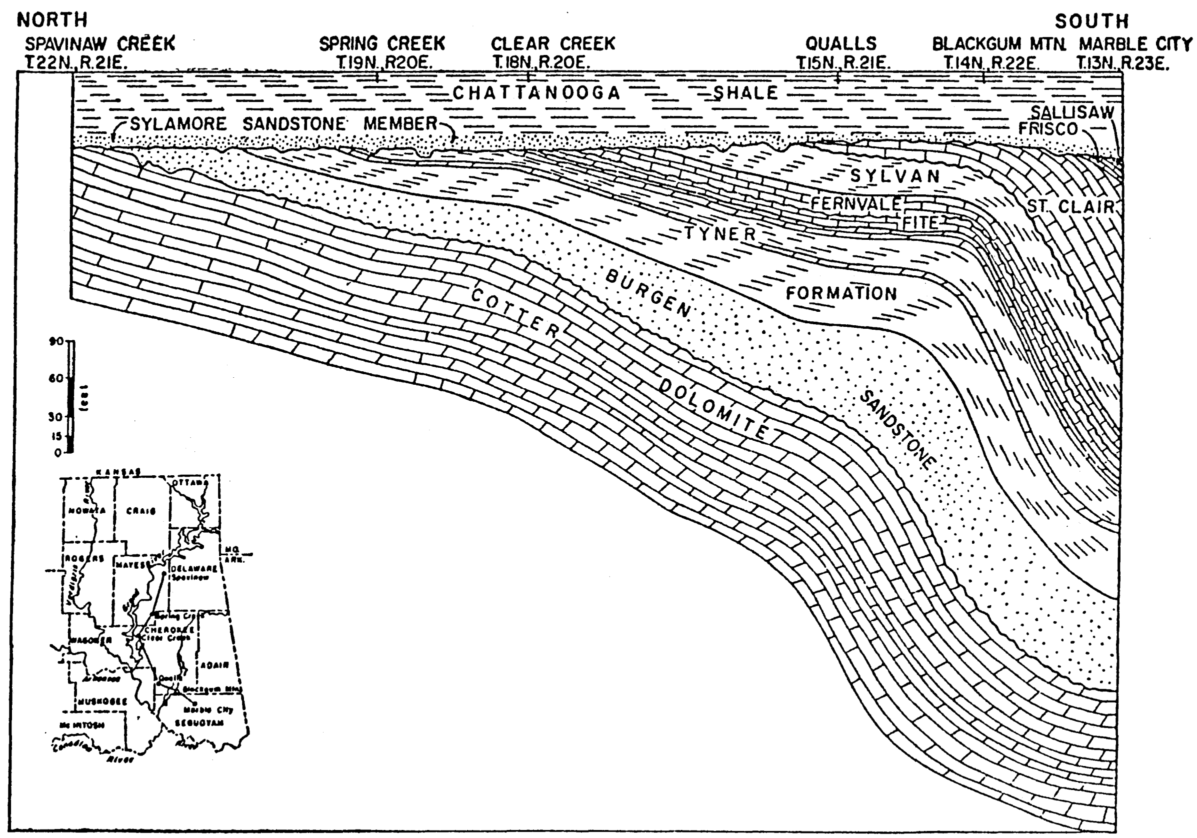

95°
93°
91°
89°
39°
37°
N
Missouri River
Mississippi River
KANSAS
MISSOURI
Structural axis
#1 Swalley
1600
1400
1200
1000
1100
800
600
400
200
0
Boston Mountains
Margin of Mississippi embayment
OKLA.
ARKANSAS
0 20 40 60 Mi.
0 25 50 75 100 Km.

Figure 17. Cross-section drawn along line in northeast Oklahoma to represent pre-Chattanooga tilting (Source: Huffman, 1958)


NORTH
SOUTH
SPAVINAW CREEK
T.22N., R.21E.
SPRING CREEK
T.19N., R.20E.
CLEAR CREEK
T.18N., R.20E.
QUALLS
T.15N., R.21E.
BLACKGUM MTN.
T.14N., R.22E.
MARBLE CITY
T.13N., R.23E.
CHATTANOOGA SHALE
SYLAMORE SANDSTONE MEMBER
SALLISAW
FRISCO
SYLVAN
ST. CLAIR
FERNVALE
FITE
TYNER FORMATION
BURGEN SANDSTONE
COTTER DOLOMITE
90
60
30
15
0
feet
KANSAS
OTTAWA
NOWATA
CRAIG
ROGERS
MAYES
DELAWARE
MO.
ARK.
WAGONER
CHEROKEE
ADAIR
MUSKOGEE
McINTOSH
SEQUOYAH

Formations (Figure 18).

According to Huffman (1958, p. 89), major deformation occurred in Des Moines time. He reports that the parallelism of faults and folds in the area with those of the Arkansas Valley syncline suggests a genetic relationship, and believes (p. 89) that tensional stresses are responsible for the deformation in northeastern Oklahoma. It is Huffman's opinion that tensional stresses occurred as a result of stretching across the positive Ozark structure, during the loading of the McAlester basin to the south (p. 89).

Local Structural Setting

The low angle of regional dip to the northwest exhibited by the Mississippian and Pennsylvanian strata in the study area is not uniform, but is interrupted by local folding. Features formed as the result of diastrophic stresses are often modified by slumpage following the dissolution of the carbonate strata (McKnight and Fischer, 1970, p. 72). The contributions of each process may be difficult to assess.

Several important structures interpreted as resulting from diastrophic stresses are reported in the literature (Fowler and Lyden, 1934; Huffman, 1958; McKnight and Fischer, 1970; Denison, 1981). Figure 19 illustrates some of the most important structures in the northeastern Oklahoma study area, including the Miami Trough, the Seneca Graben, and several smaller faults and folds. McKnight and Fischer (1970) have

Figure 18. Cross-section drawn along line in northeast Oklahoma to represent Early Pennsylvanian tilting (Source: Huffman, 1958)

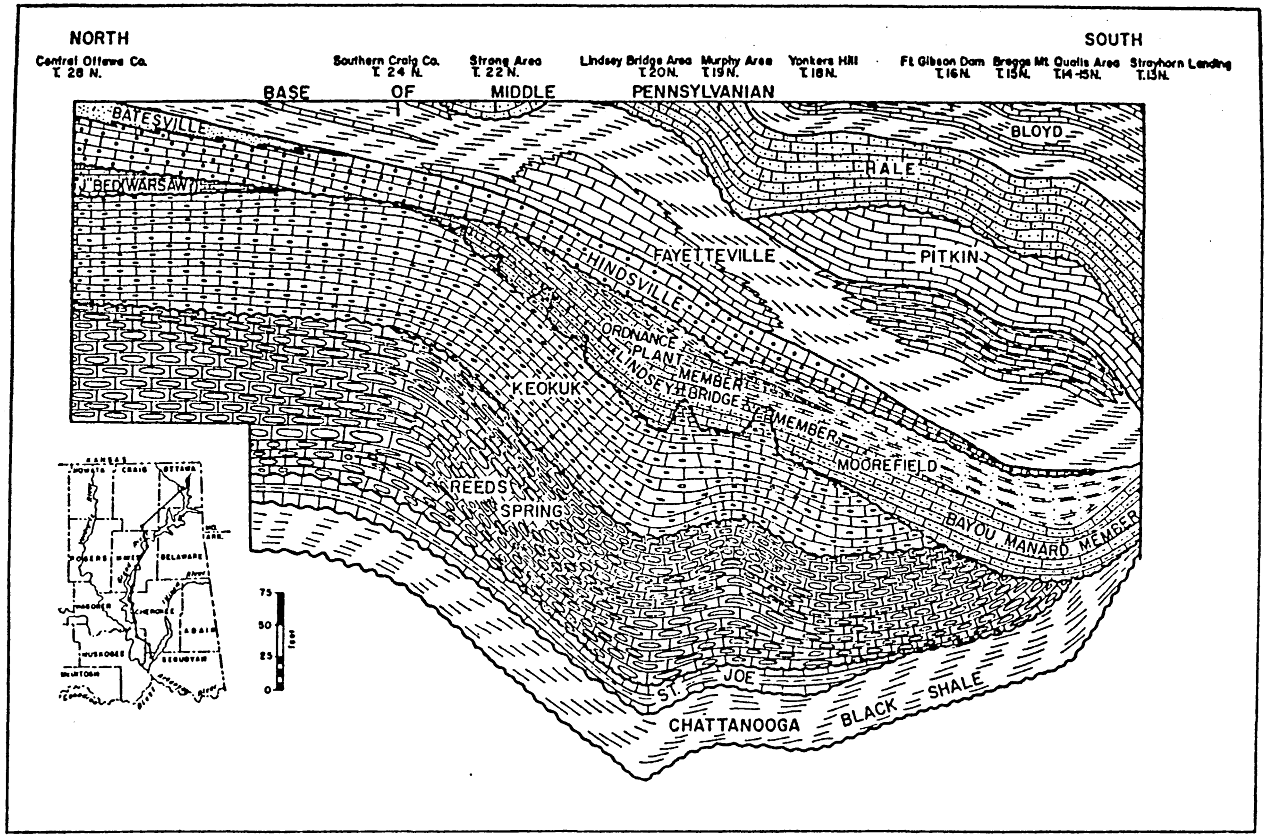
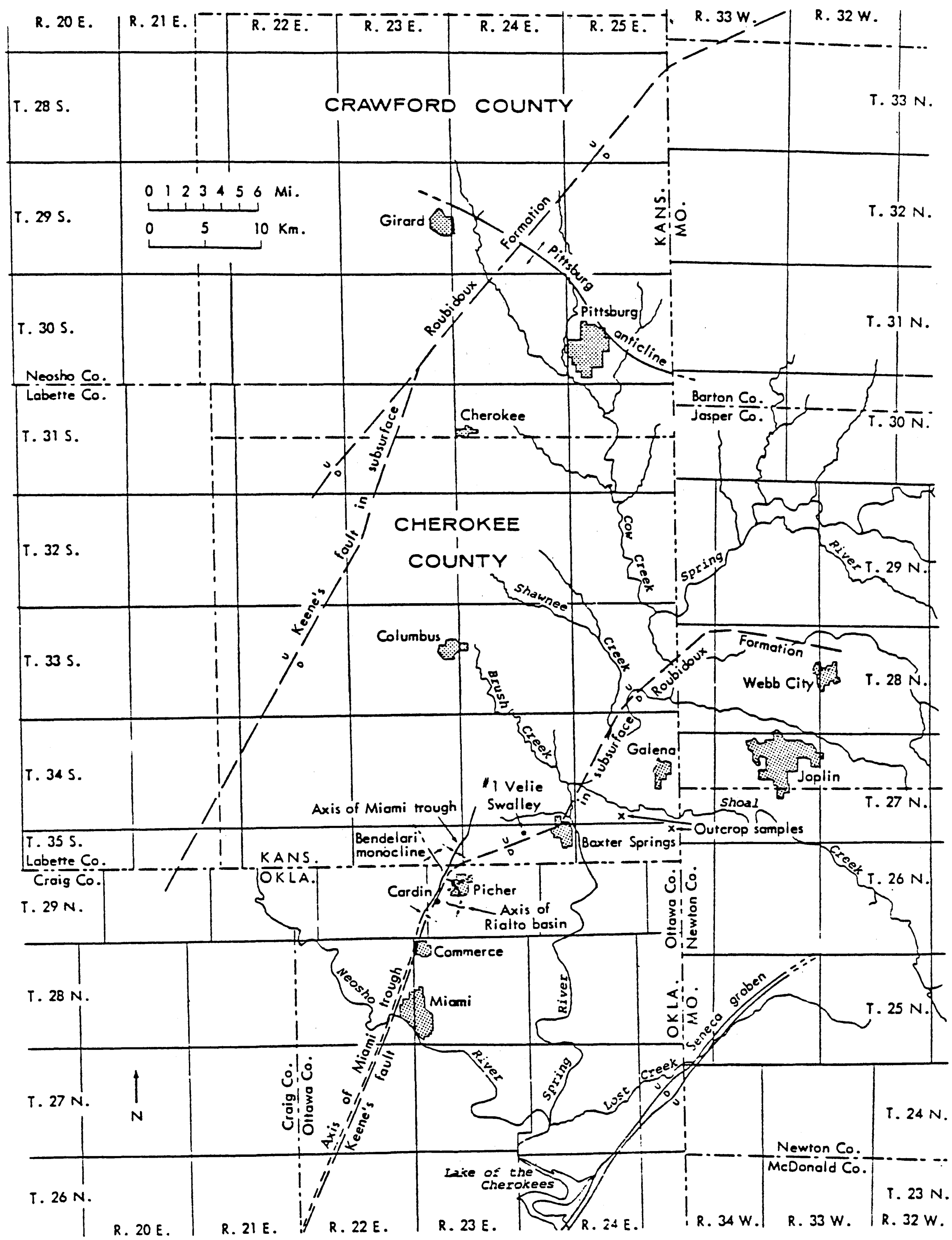

NORTH
SOUTH
Central Ottawa Co. T. 28 N.
Southern Craig Co. T. 24 N.
Strong Area T. 22 N.
Lindsey Bridge Area T. 20 N.
Murphy Area T. 19 N.
Yonkers Hill T. 18 N.
Ft. Gibson Dam T. 16 N.
Braggs Mt. T. 15 N.
Qualls Area T. 14-15 N.
Strayhorn Landing T. 13 N.
BASE OF MIDDLE PENNSYLVANIAN
BATESVILLE
"J" BED (WARSAW)
BLOYD
HALE
FAYETTEVILLE
PITKIN
HINDSVILLE
ORDNANCE PLANT MEMBER
LINDSEY BRIDGE MEMBER
KEOKUK
MOOREFIELD
REEDS SPRING
BAYOU MANARD MEMBER
ST. JOE
CHATTANOOGA BLACK SHALE
75
50
25
0
feet
KANSAS
NOWATA
CRAIG
OTTAWA
ROGERS
MAYES
DELAWARE
WAGONER
CHEROKEE
ADAIR
MUSKOGEE
SEQUOYAH
McINTOSH

Figure 19. Detail map of local structures (Source: Nodine-Zeller and Thompson, 1977)



CRAWFORD COUNTY
CHEROKEE COUNTY
0 1 2 3 4 5 6 Mi.
0 5 10 Km.
Girard
Pittsburg
Cherokee
Columbus
Galena
Joplin
Webb City
Baxter Springs
Picher
Cardin
Commerce
Miami
Roubidoux Formation in subsurface
Keene's fault in subsurface
Pittsburg anticline
Axis of Miami trough
Bendelari monocline
Axis of Rialto basin
#1 Velie Swalley
Outcrop samples
Neosho trough
Axis of Miami trough
Keene's fault
Seneca graben
Cow Creek
Shawnee Creek
Brush Creek
Spring River
Shoal Creek
Neosho River
Spring River
Lost Creek
Lake of the Cherokees
Neosho Co.
Labette Co.
Craig Co.
Ottawa Co.
Barton Co.
Jasper Co.
Newton Co.
McDonald Co.
KANS.
MO.
OKLA.
N
R. 20 E.
R. 21 E.
R. 22 E.
R. 23 E.
R. 24 E.
R. 25 E.
R. 33 W.
R. 32 W.
R. 34 W.
T. 28 S.
T. 29 S.
T. 30 S.
T. 31 S.
T. 32 S.
T. 33 S.
T. 34 S.
T. 35 S.
T. 33 N.
T. 32 N.
T. 31 N.
T. 30 N.
T. 29 N.
T. 28 N.
T. 27 N.
T. 26 N.
T. 25 N.
T. 24 N.
T. 23 N.

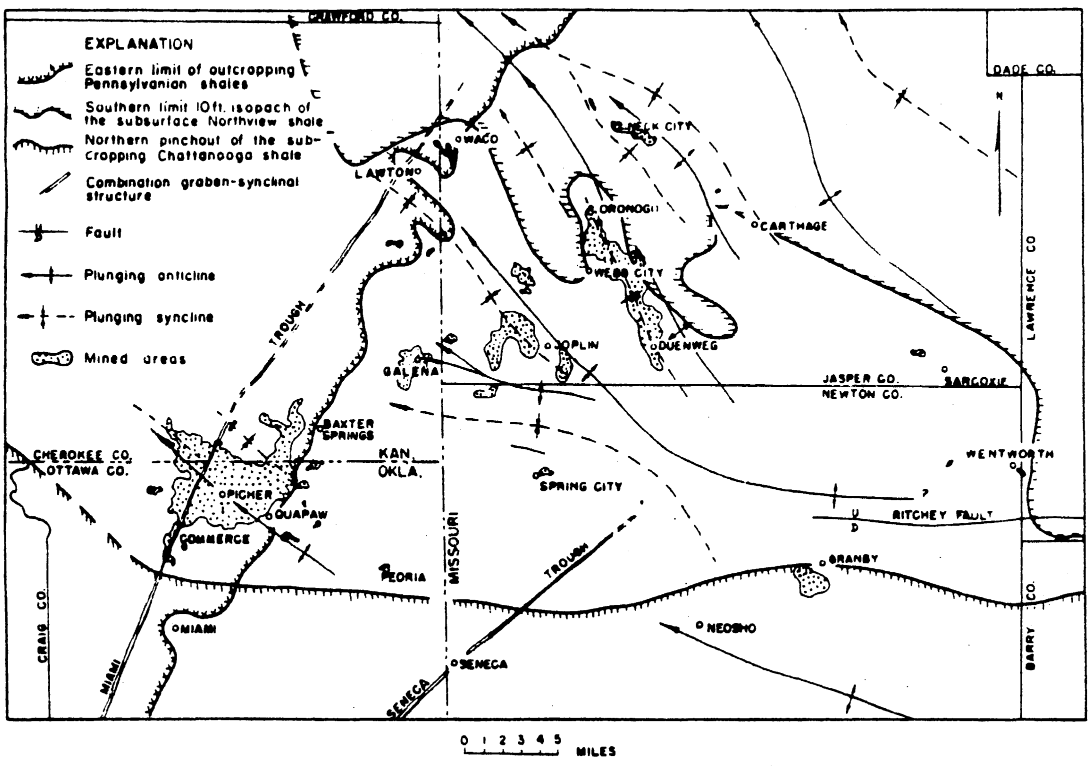
emphasized the association of the Miami Trough and mineralization in the Tri-State District, reporting (p. 91) that the structure influenced the localization of some ore bodies, and may have provided a conduit for the ascension of mineralizing fluids (p. 92).

Deep drilling has shown that the Miami Trough extends into the Precambrian basement (Brockie et al., 1968). Several northwest-trending structures are known, including the Picher anticline, the Bendelari monocline, and the Joplin anticline (Figure 20). The Bendelari monocline is believed by McKnight and Fischer (1970, p. 136) to extend into the Precambrian basement. The Picher anticline was named by Brockie et al. (1968, p. 412), who reported that deep drilling indicates that both the Picher anticline and the Joplin anticline are surface expressions of faults at depth.

Miami Trough

The Miami Trough has been described by McKnight and Fischer (1970, p. 74) as a "linear combination of syncline and graben...except that synclinal sag...prevails over true graben block faulting." The structure crosses the western portion of the study area with an average trend of N24E. McKnight and Fischer report (p. 74) that, when studied in detail, the trough exhibits irregular en-echelon offsets between adjacent basins, and any small faults which may be present. They also state (p. 74) that there is no noticeable displacement between the two blocks on either side of the

Figure 20. Map of local structures developed in the Tri-State District (Source: Brockie et al., 1968)


EXPLANATION
Eastern limit of outcropping Pennsylvanian shales
Southern limit 10ft. isopach of the subsurface Northview shale
Northern pinchout of the subcropping Chattanooga shale
Combination graben-synclinal structure
Fault
Plunging anticline
Plunging syncline
Mined areas
CRAWFORD CO.
DADE CO.
WACO
LAWTON
ORONOGO
CARTHAGE
WEBB CITY
DUENWEG
JOPLIN
GALENA
JASPER CO.
NEWTON CO.
SARCOXIE
BAXTER SPRINGS
CHEROKEE CO.
OTTAWA CO.
KAN.
OKLA.
PICHER
QUAPAW
COMMERCE
SPRING CITY
WENTWORTH
RITCHEY FAULT
GRANBY
PEORIA
MISSOURI
TROUGH
NEOSHO
MIAMI
SENECA
CRAIG CO.
LAWRENCE CO.
BARRY CO.
0 1 2 3 4 5 MILES

trough. Recent workers (Nodine-Zeller and Thompson, 1977) have reported the existence of Keene's fault, which closely parallels the Miami Trough in Oklahoma, but swings northeast into southeast Kansas, and southwest Missouri (Figure 19).

The Miami Trough is reported by McKnight and Fischer (1970, p. 74) to vary in width from 300 to nearly 2000 feet with vertical displacement reaching nearly 300 feet; 200 feet of which is throw across the bounding faults. In one location (the Blue Goose No. 1 mine), where the graben characteristics are most pronounced, the two bounding faults dip toward the graben block at 60 to 70 degrees (McKnight and Fischer, 1970, p. 74).

Seneca Graben

The Seneca Graben is a persistent, linear structure which trends northeast from its origin near Pryor, Oklahoma, to its termination near Seneca, Missouri (Figure 19). The average strike along the structure is between N40E and N45E. McKnight and Fischer (1970, p. 73) have described the structure as a complex feature in which bounding faults are not continuous, but are replaced in many places "first on one side and then on the other, or both" by sharply dipping strata, forming a tight synclinal sag. They further report (p. 73) that even where bounding faults exist, the strata dip for some distance toward the graben. Huffman (1958, p. 90) reports that these strata dip 10 to 25 degrees toward the axis of the structure.

McKnight and Fischer (1970, p. 73) report that strata within the graben block are largely unbroken and horizontal, although dips may approach 40 degrees. Huffman (1958, p. 90) reports maximum structural displacement to be less than 300 feet, bringing Atoka, Hale (Morrow), and Fayetteville (Chester) strata into contact with the Boone Formation.

A recent study by Patterson (1986, p. 119) indicates that the Seneca Graben may represent a right-lateral wrench fault system developed in response to Ouachita collisional events. Patterson cites several features (p. 119) as evidence of wrenching, including horizonal slickensides, mixed stratigraphic offsets, propeller-blade fault planes, and a flower structure.

As evidence of a right-lateral displacement along the Seneca structure, Patterson (1986, p. 120) refers to the occurrence of strike-slip faults parallel to the trend of the Seneca Graben (about N40E), right-lateral faults oriented at N60E to N80E, left-lateral faults oriented at N60W to N80W, with veins and normal faults trending east-west, and folds and a thrust fault which trends north-northwest. He reports (p. 120) that the structural sag associated with the feature may have a pull-apart origin.

Bendelari Monocline

The Bendalari monocline crosses the heart of the Picher mining field, trending in a northwesterly direction (Figure 19). Hagni (1976, p. 460) has described the Picher field as occurring at the intersection of the Miami Trough and the Bendelari monocline. McKnight and Fischer (1970, p. 136) report the alignment of many linear ore-runs in directions which parallel either the Miami Trough or the Bendelari monocline (Figure 21).

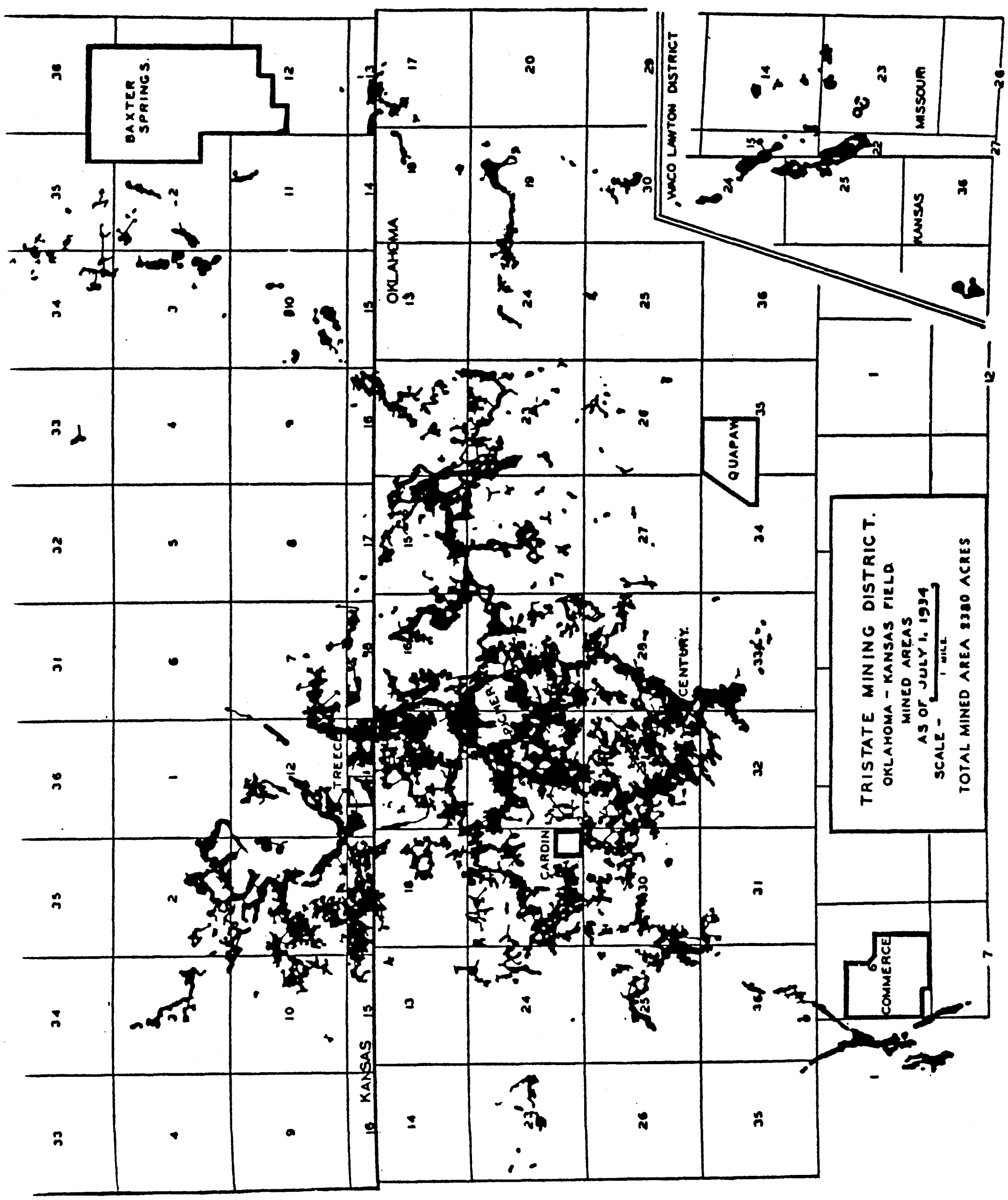
McKnight and Fischer (1970, p. 75) describe the northwest block of the structure as being downthrown, with vertical stratigraphic displacement reaching 100 to 140 feet, and structural dips reaching about 20 degrees. They also report (p. 75) that Chester strata underlying the basal Pennsylvanian unconformity are much thicker on the downdropped block of the monocline, indicating that the structure was developed after deposition of the Chester and before, or during, the erosion which marks the base of the Pennsylvanian.

Geology of the Ore Bodies

The lead and zinc sulfide ore deposits of the Tri-State District are recognized as being of the Mississippi Valley Type (McKnight and Fischer, 1970). The worldwide group of deposits of the Mississippi Valley Type was discussed in detail by Ohle (1959) and many similarites were pointed out. These similarities include formation within a framework of generally mild structural deformation, a carbonate host lithology, simple mineralogy, and the absence of igneous intrusives (McKnight and Fischer, 1970, p. 140).

McKnight and Fischer (1970, p. 92) report that the ores

Figure 21. Map of underground mine workings developed in the Tri-State District (Source: Fowler and Lyden, 1934)


TRISTATE MINING DISTRICT.
OKLAHOMA - KANSAS FIELD
MINED AREAS
AS OF JULY 1, 1934
SCALE - 1 MILE
TOTAL MINED AREA 2380 ACRES
BAXTER SPRINGS.
OKLAHOMA
KANSAS
MISSOURI
WACO LAWTON DISTRICT
QUAPAW
CENTURY
CARDIN
PICHER
TREECE
COMMERCE

are believed to have been formed from hydrothermal solutions derived from a deep-seated magma. These authors believe that the solutions ascended along the Miami Trough and other fractures extending into the basement. The solutions then migrated along fractures and other conduits in the Lower Paleozoic strata until arriving in favorable beds of Mississippian age. McKnight and Fischer (1970, p. 92) state that the sites of ore depostion were partially prepared by fracturing, chert brecciation, and some collapse of of the beds due to leaching of carbonate, prior to the deposition of Pennsylvanian beds. They believe (p. 92) that mineralization occurred at some later time, possibly during the Cretaceous, or even later.

All strata in the Boone Formation have been mineralized to some extent within the Picher field, as have Chester strata, and basal Pennsylvanian beds (McKnight and Fischer, 1970, p. 134). Certain beds have proven to be far more productive than others, however, particularly the Joplin Member (essentially the M bed subunit of Fowler and Lyden, 1932).

CHAPTER V

DEPOSITION OF UPPER OSAGE STRATA

General Features

Recent work by Gutschick and Sandberg (1983) in the characterization of the continental margins, and shelfedges around the western, southern, and eastern sides of the conterminous United States has proved to be very useful in an understanding of regional sedimentation patterns during the Mississippian. Their work concerns 1.5 million years of Middle Mississippian time (the duration of the *anchoralis-latus* conodont zone). This time corresponds to the middle Osage, latest Tournaisian, or Mamet foram zone 9 (p. 79). Gutschick and Sandberg report that this time was chosen because it shows a maximum eustatic rise of sealevel, and is characterized by progradation away from the craton of an extensive carbonate platform with passive shelfedges. This time is just prior to the time of Short Creek deposition.

Gutschick and Sandberg (1983, p. 88) report that shelf sedimentation occurred throughout Osage time, but that only the Burlington Limestone and time-equivilant strata represent the *anchoralis-latus* Zone. Sedimentation during late Osage time, including the Short Creek Oolite, resulted in the deposition of the Keokuk Limestone which, according to Lane (1978, p. 172), is probably representative of a progradation of the Burlington Shelf during early Visean time.

Figure 22 is a paleogeographic and lithofacies map of the conterminous United States at the time of the *anchoralis-latus* Zone, as reported by Gutschick and Sandberg (1983, p. 84). Note especially the proximity of the shelfedge to the study area in northeastern Oklahoma, and that the Ozark geanticline is interpreted as being emergent. Figure 23 is a paleoceanographic and paleobathymetric map of the conterminous United States during the same time. Note especially the circulation patterns of surface sea currents, and directions of upwelling. According to this interpretation, the study area in northeastern Oklahoma is the site of upwelling deep marine waters, and occurs on a shelf with water depths ranging between 25 and 100 meters. The setting is tropical, as the study area occurs at about 10 degrees south latitude.

It is interesting to note the orientation of the continent during this part of the Mississiappian. As illustrated in Figures 22 and 23, the orientation of the North American craton during middle Osage time was about 30 degrees counterclockwise of its present position. This indicates that limestones of the Keokuk shelf, including the Short Creek Oolite, were deposited along a trend of roughly 5 to 10 degrees west of the north.

Paleo-trade winds in the equatorial, southern hemisphere

Figure 22. Paleogeographic and lithofacies map of the conterminous United States drawn for *anchoralis-latus* time (Source: Gutschick and Sandberg, 1983)

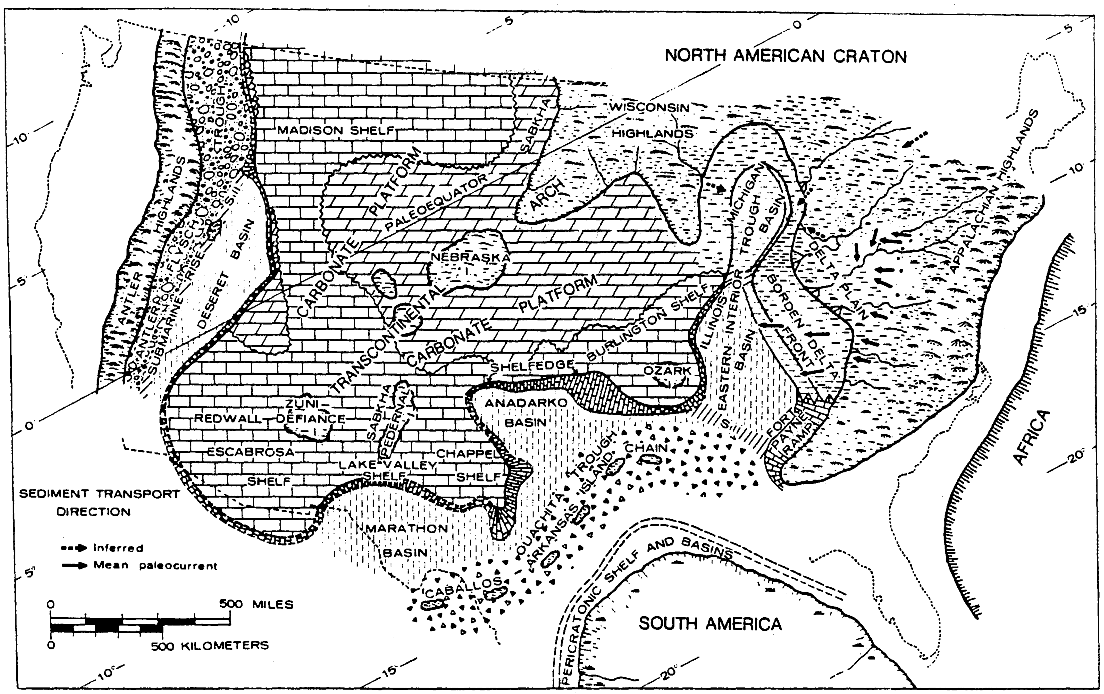
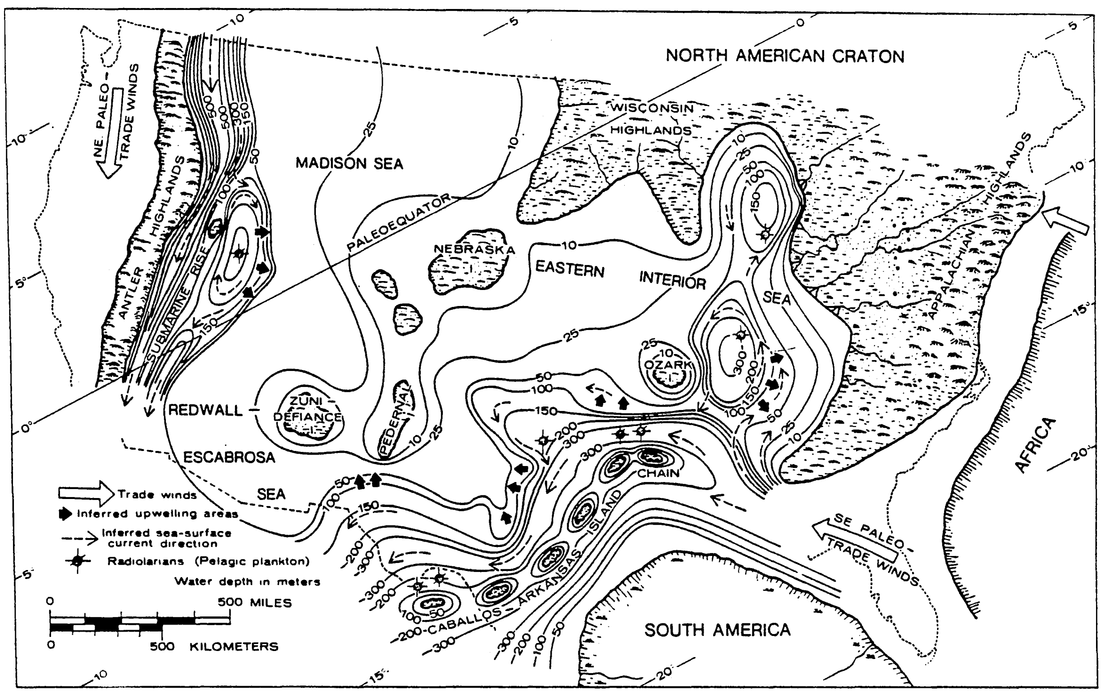

NORTH AMERICAN CRATON
MADISON SHELF
SABKHA
WISCONSIN
HIGHLANDS
ARCH
PALEOEQUATOR
CARBONATE PLATFORM
TRANSCONTINENTAL
NEBRASKA
PLATFORM
CARBONATE
ANTLER HIGHLANDS
FLYSCH TROUGH
ANTLER SUBMARINE RISE
DESERET BASIN
MICHIGAN BASIN
INTERIOR TROUGH
ILLINOIS
BURLINGTON SHELF
BORDEN FRONT
DELTA
DELTA PLAIN
APPALACHIAN HIGHLANDS
SHELFEDGE
OZARK
EASTERN BASIN
FORT PAYNE RAMP
ANADARKO
BASIN
ZUNI
REDWALL
DEFIANCE
ESCABROSA
SHELF
SABKHA
PEDERNAL
LAKE VALLEY
SHELF
CHAPPEL
SHELF
CHAIN
ISLAND
ARKANSAS
OUACHITA
TROUGH
MARATHON
BASIN
CABALLOS
PERICRATONIC SHELF AND BASINS
SOUTH AMERICA
AFRICA
SEDIMENT TRANSPORT DIRECTION
Inferred
Mean paleocurrent
0
500 MILES
0
500 KILOMETERS
10°
15°
20°
5°
0

Figure 23. Paleoceanographic and paleobathymetric map of the conterminous United States drawn for *anchoralis-latus* time (Source: Gutschick and Sandberg, 1983)


NORTH AMERICAN CRATON
NE. PALEO-TRADE WINDS
MADISON SEA
WISCONSIN HIGHLANDS
ANTLER HIGHLANDS
SUBMARINE RISE
PALEOEQUATOR
NEBRASKA
EASTERN INTERIOR SEA
APPALACHIAN HIGHLANDS
OZARK
ZUNI-DEFIANCE
PEDERNAL
REDWALL - ESCABROSA SEA
CABALLOS - ARKANSAS - ISLAND - CHAIN
AFRICA
SE PALEO-TRADE WINDS
SOUTH AMERICA
Trade winds
Inferred upwelling areas
Inferred sea-surface current direction
Radiolarians (Pelagic plankton)
Water depth in meters
0 500 MILES
0 500 KILOMETERS

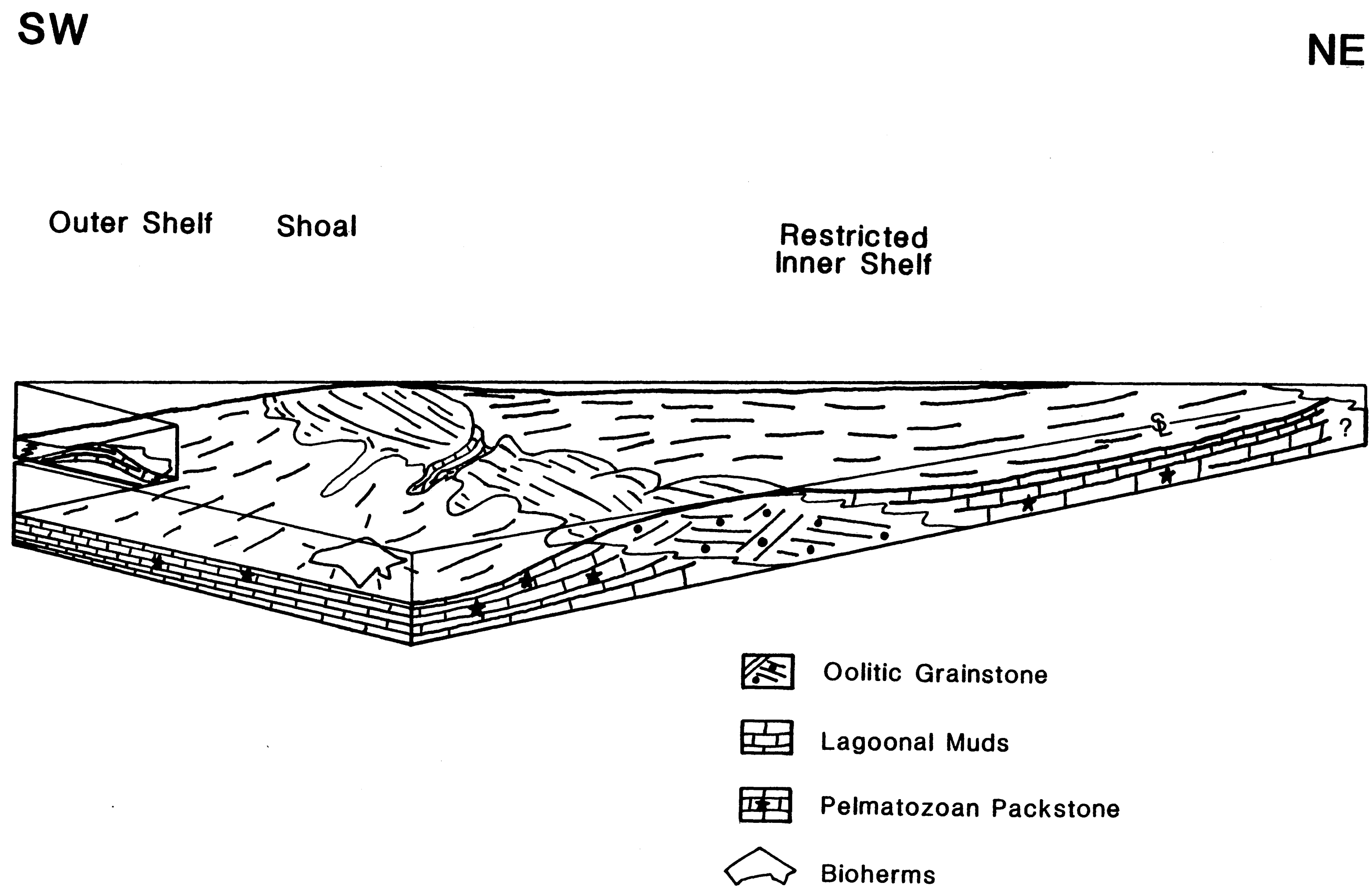
setting would have been from the southeast, as a result of the Corialis force (Figure 23). According to the principal of the Ekman spiral, as discussed by Leeder (1982, pp. 231-232), surface water currents would trend 45 degrees to the west of the prevailing wind direction, in the southern hemisphere. With a southeastern paleo-trade wind, surface currents in the Oklahoma study area would have been roughly to the west and, therefore, away from the Keokuk shelf (Figure 23). The movement of surface waters away from the shelf may have been responsible for upwelling deep marine waters in the area.

Development and Recognition of Facies

The Short Creek Oolite is a very well sorted calcarenite developed in the high energy conditions of the upper subtidal to lower intertidal zones. In the northeastern Oklahoma study area it is overlain by, and laterally replaced by, the bioturbated and intraclastic mudstones and bioclastic wackstones of the Baxter Springs Member. The oolitic facies is here interpreted to have developed as a shoal which served to restrict marine circulation to large areas of the inner shelf. The Baxter Springs Member is composed of two distinct facies, including inner and outer shelf facies.

Figure 24 is a conceptualized depiction of the environment of sedimentation which prevailed during early Short Creek time. As lateral dimensions are poorly known, no scale is implied. It is the intent of this diagram to

Figure 24. Idealized diagram of the sedimentary environment which prevailed near the end of Short Creek deposition


SW
NE
Outer Shelf
Shoal
Restricted Inner Shelf
?
Oolitic Grainstone
Lagoonal Muds
Pelmatozoan Packstone
Bioherms

illustrate the various micro-environments developed during this time, and their effects on sedimentation. The diagram is constructed along a line of section (northeast to southwest) which is believed by the author to approximate a line perpendicular to the depositional strike in the northeastern Oklahoma study area.

Oolitic Shoal Facies

The Short Creek Oolite is here interpreted to have been deposited as an oolitic shoal, which developed in upper subtidal to lower intertidal conditions. Ooid formation and shoaling occurred in zones of relatively high energy above the active wave-base. Progradation of the oolitic shoal onto the crinoid-bryozoan meadows of the Joplin Member occurred in response to regressing sea levels.

As a result of strongly agitated conditions muds are absent, having been winnowed away, and the resulting calcarenite is extremely well sorted. Bedding in the oolite is typically massive but areas of medium to large-scale planar cross-bedding have been observed in outcrop. Planar cross-bed sets are a result of the migration of straight-crested dunes and current ripples (Leeder, 1982, p. 88, 89). The oolite is commonly glauconitic, particularly near the top of the unit. Glauconite commonly forms in agitated shallow marine settings characterized by low sedimentation rates, where it is often a replacement of fecal pellets (Tucker, 1981, and Berner, 1971).

Ooids have preferentially nucleated about pelmatozoan skeletal debris, and less commonly about bryozoan, brachiopod, and bivalve skeletal debris. Peloids are occasionally observed as ooid nucei, as are rare detrital quartz grains. Skeletal debris other than that utilized as ooid nuclei is rare in the Short Creek, except in occasional locations where thin layers of highly fossiliferous sediment occurs within the oolite. These layers are laterally discontinuous, and lack a distinctive geometry. They probably represent storm deposits or tidal washover lobes, with pelmatozoan debris derived from the prolific outer shelf crinoidal-bryozoan meadows developed within the Joplin Member.

The cortical fabrics of the ooids in the Short Creek are variable, consisting of concentric, or a combination of concentric and radial fabrics. According to Reijers and ten Have (1983) cortical fabrics may be useful in the interpretation of depositional environments. They report that concentric fabrics are developed in shallow, agitated settings, while radial fabrics develop in slightly deeper, quieter settings, and mixed fabrics are developed in a variable hydrodynamic setting.

Mixed-fabric ooids in the Short Creek display a tendency for radial development near the center of the cortex, grading to a concentric fabric near the outer margin of the cortex. Reijers and ten Have (1983, pp. 194-195) report that the radial cortical fabric reflects relatively weak agitation, at a time when the comparitively small ooid is in constant suspension. As agitation increases, concentric layers are added and, finally, the ooid is deposited as sediment. Reijers and ten Have suggest that such an increase in agitation may be a result of a regressing sea.

Inner Shelf Facies

The bulk of the L and K bed subunits of the Baxter Springs Member are here interpreted as representing a back-shoal or lagoonal facies developed across a broad area of the inner shelf during late Osage time. These sediments are predominantly mudstones and bioclastic wackestones, commonly containing micritic intraclasts. They are believed here to be a result of sedimentation in the quiet upper subtidal to lower intertidal waters shoreward from the oolitic shoal-barrier. The sediments overlie the Short Creek Oolite in the northeastern Oklahoma study area, as a result of the progradation of the oolitic shoal during sea level regression.

Conditions of restricted marine circulation are indicated by the low faunal diversity and density exhibited by the inner shelf sediments. Bioclastic debris observed in thin section is limited to ostracodes and occasional gastropods. In addition, peloids of probable fecal origin have been identified. These muddy sediments have been completely homogenized by burrowing organisms in most of the samples studied, but occasional poorly developed laminae are preserved. These laminae are rich in organic material and probably represent colonization by blue-green algae. It is relatively common to observe the development of a fenestral fabric in these sediments. These fenestrae are now cemented by sparry calcite, and lend additional support to the suggestion of algal mat growth in the lower intertidal zone.

There is no convincing evidence for the existence of a supratidal facies in the northeastern Oklahoma study area. Consequently the distance from the paleoshoreline remains problematic in this area. The local development of sparsely oolitic sediments in the K bed subunit (McKnight and Fischer, 1970, pp. 45, 46) indicates, however, that the subunit was periodically exposed to the higher energies available in the upper subtidal to lower intertidal zones. Furthermore, the occurrence of micritic intraclasts suggests that the muddy bottom was occasionally subjected to periods of higher energy, as during storms, or during periods of time marked by larger than average tidal ranges.

McKnight and Fischer (1970) have interpreted the K bed subunit to consist of two distinct phases, named by them as the eastern and the western facies (p. 43). They describe the eastern facies as consisting of a fine to coarsely crystalline crinoidal limestone (p. 44), and the western facies as consisting of a shaly, thin-bedded limestone (p. 45). Accumulations of a coarse crinoidal limestone have been observed by this author to occur just above the Short Creek Oolite in one outcrop in the northern portion of the Oklahoma study area. These deposits are believed here to represent localized accumulations of poorly sorted bioclastic debris deposited on the shoreward side of the prograding oolitic shoal, possibly during storm surges. The shaly western phase occurs as an outer shelf facies, as discussed below.

Rare blebs of length-slow chalcedony (quartzine) are observed in some samples, and may represent the replacement of evaporitic sulfate minerals (Folk and Pittman, 1971). The relative scarcity of such occurrences has led the author to believe that the Oklahoma study area is relatively removed from the paleoshoreline, and that the tropical setting was not an arid one. All of the inner shelf samples studied contain small amounts of detrital quartz. These grains make up a maximum of only two to three percent of the bulk volume, and their very small size (silt) may suggest that they are of eolian origin.

The basal portions of the L bed subunit are extremely cherty, with only nodular limestones remaining. These nodules are commonly surrounded by a siliceous to clayey matrix. The clays in this setting have probably been concentrated through the effects of pressure solution acting on the fine-grained lime muds. At one locality, a green shale about 1.5 feet in thickness is well exposed, suggesting the fluvial transport of terrigenous clastics, with subsequent deposition in quiet subtidal waters of the inner shelf. The local occurrences of terrigenous clastics resulting from deposition by a probable fluvial mechanism lends some support to the author's belief that the environment was relatively humid.

Outer Shelf Facies

Sediments of the Baxter Springs Member make up a second important facies on the outer shelf of the late Osage sea. McKnight and Fischer (1970, p. 46) report that local bryozoan or crinoidal bioherms occur in the L bed subunit, west of the Picher, Oklahoma mining field. Harbaugh (1957) also reports the scattered occurrences of such bioherms but has restricted his interpretation of the age represented to, simply, the upper Keokuk Limestone. In both of these publications the bioherms are described as Waulsortian type mounds and suggest, therefore, sedimentation on the distal outer shelf.

McKnight and Fischer (1970, p. 46) point out that the biohermal L bed subunit thins west of the Picher, Oklahoma mining field, and is eventually replaced by sediments of the K subunit. They state further (p. 43) that the contact between the limestone of the eastern facies and the shaly limestone of the western facies of the K subunit occurs near the L bed margin, along an irregular northwest to southeast line which traverses the western portion of the mining field (p. 40). This change in lithology from crystalline limestone to a shaly limestone in an area with known biohermal deposits suggests deposition in quiet subtidal waters on distal portions of the outer shelf.

Environmental Summary

The Short Creek Oolite and the closely associated Baxter Springs Member are believed to have been deposited during a regression of the epeiric Mississippian sea during late Osage time. The Short Creek Oolite was deposited as a shoal in the high energy of the upper subtidal to lower intertidal zones. The most important facies of the L and K bed subunits of the Baxter Springs Member in the northeastern Oklahoma study area is interpreted as a back-shoal or lagoonal deposit, developed in the restricted, upper subtidal to lower intertidal waters of the inner shelf. These fine-grained sediments overlie the oolite in the study area, and were deposited in response to progradation of the oolitic shoal. A restricted setting is indicated by the very low faunal diversity and density exhibited.

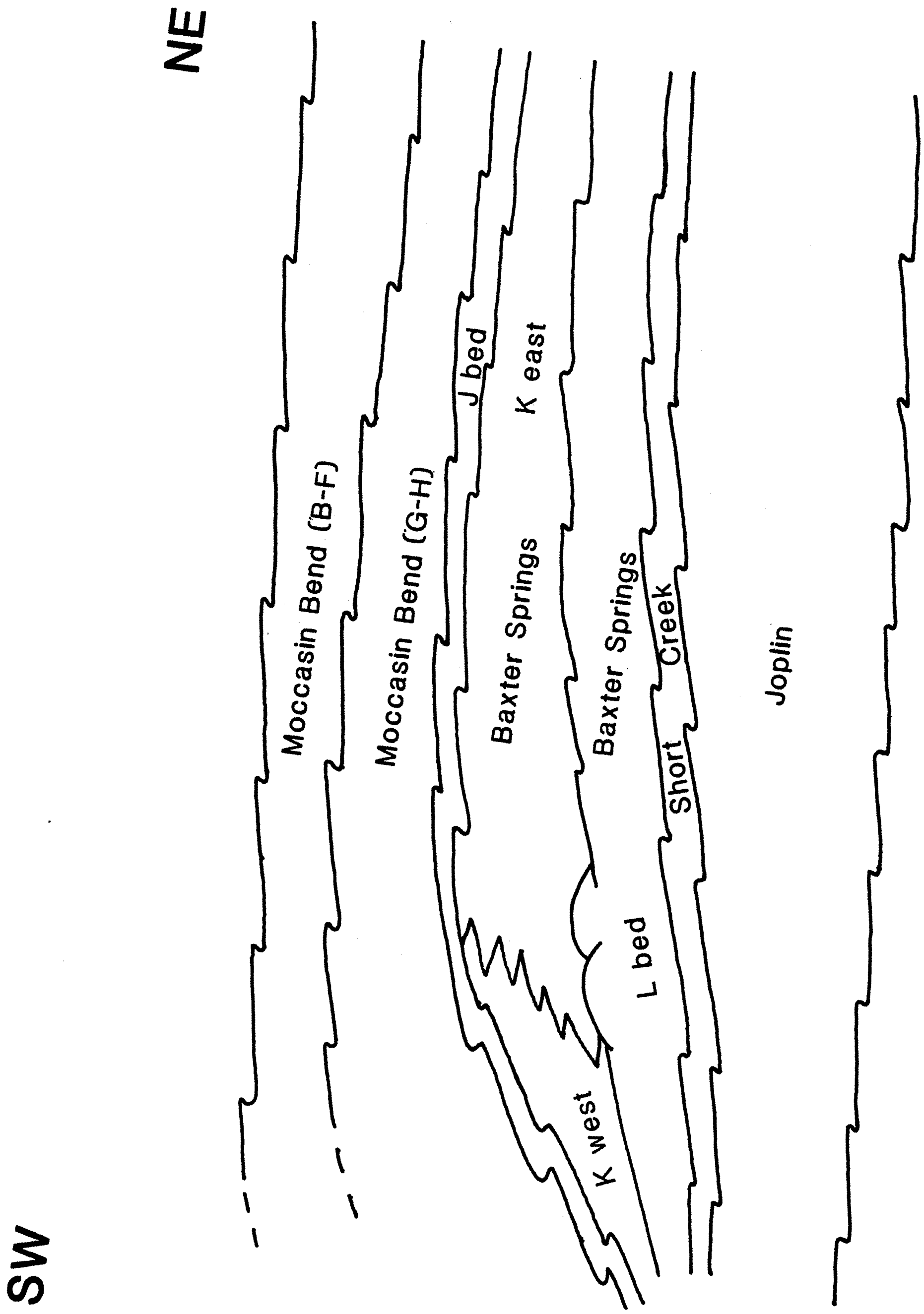
Bryozoan-crinoidal bioherms are developed in the L bed subunit near its western margin. Beyond the western margin, of the L bed subunit, the K bed subunit becomes shaly. This change in lithology from crystalline limestones to shaly limestones, in an area of known biohermal sedimentation, suggests deposition on distal portions of the outer shelf.

A widespread transgression marks the end of regressional shoaling-upward sedimentation in the late Osage. The basal deposit of Meramec age is now referred to as the J bed subunit of the Baxter Springs Member. The J bed subunit is extremely glauconitic and phosphatic, and has been observed to truncate many older Mississippian units (Lee, 1940, and

Huffman, 1958).

Figure 25 is a cross-section presented in order to summarize the various late Osage facies discussed above. As lateral and vertical constraints are poorly known, no scale is implied. The line of section (northeast to southwest) is believed by the author to approximate a line approximately perpendicular to the depostional strike of the late Osage strata in the northeastern Oklahoma study area.

Figure 25. Idealized cross-sectional representation of local facies developed in the upper Boone Formation


NE
SW
Moccasin Bend (B-F)
Moccasin Bend (G-H)
J bed
K east
Baxter Springs
Baxter Springs
Creek
Short
Joplin
L bed
K west

CHAPTER VI

PETROGRAPHY OF THE SHORT CREEK OOLITE

General Petrographic Features and Classification

The Short Creek Oolite is a well-sorted calcarenite whose allochemical composition is dominated by ooids. Non-coated skeletal debris is also observed, but is less important volumetrically, as are peloids, and occasional oolitic intraclasts. Detrital quartz silt is rarely observed and may occur as ooid nuclei. Lime muds are absent in most samples examined, although it may become an important constituent in upper portions of the section.

The samples examined classify as calcarenites with grain sizes ranging between 62 and 2000 microns, by the method outlined in Tucker (1981). Samples examined constitute oosparites or oobiosparites according to the compositional classification of Folk (1962). By the textural classification of Dunham (1962), these samples represent oolitic packstones or grainstones, to oolitic skeletal packstones or grainstones.

The oolite in all samples examined has been pervasively cemented by calcite. The calcite cement occurs most commonly as an equant, subhedral to anhedral mosaic, or as syntaxial overgrowths to echinoderm fragments. Replacement by silica may be important in the upper part of the section; silica replacement fabrics typically exhibit a microquartz morphology, but may grade to a megaquartz morphology. In the samples analyzed during the course of this study, primary porosities have been observed to be almost totally destroyed by pervasive cementation. Secondary porosity, which is essentially oomoldic, has been observed with some regularity.

Allochemical Constituents

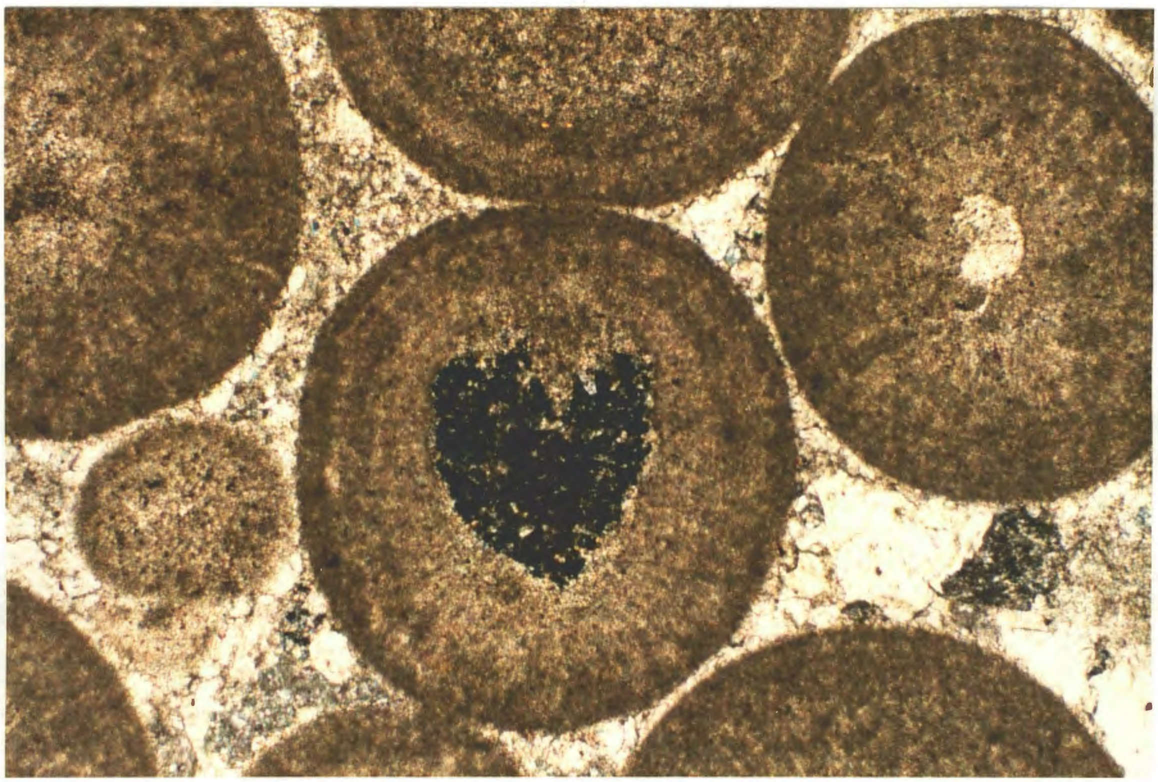
Ooids

The oolitic fabric is usually extremely well-sorted with ooids ranging in size from 0.125 to 0.625 mm, and averaging 0.5 mm. Ooids typically comprise an average of about 60 percent of the bulk volume.

The ooids have nucleated about skeletal debris, peloids and, rarely, detrital quartz or chert. Nucleation is preferential about pelmatozoan skeletal debris (Figure 26) but brachipod, bryozoan, bivalve, echinoid, and gastropod fragments, in approximate order of decreasing abundance, also serve as skeletal nuclei.

Cortical fabrics are variable, consisting of fine-grained material with a massive appearance, to well-defined concentric, or composites of concentric plus tangential

Figure 26. Photograph of ooid nucleation on pelmatozoan skeletal debris; crossed nicols, 100X



patterns. Of these fabrics, a concentric pattern is most commonly exhibited, although the concentric laminae may be vague (Figure 27). Where the composite fabric is developed, the tangential pattern always occurs at the center of the cortex, and is gradually replaced by a concentric pattern toward the outer margin of the cortex (Figure 28).

Much has been written concerning the possible relationships between the cortical fabric and original mineralogy of the ooid, or its environment of formation. Leeder (1982), Medwedeff and Wilkinson (1983), and Reijers and ten Have (1983) provide a good background for the reader interested in studying the basis for such interpretations.

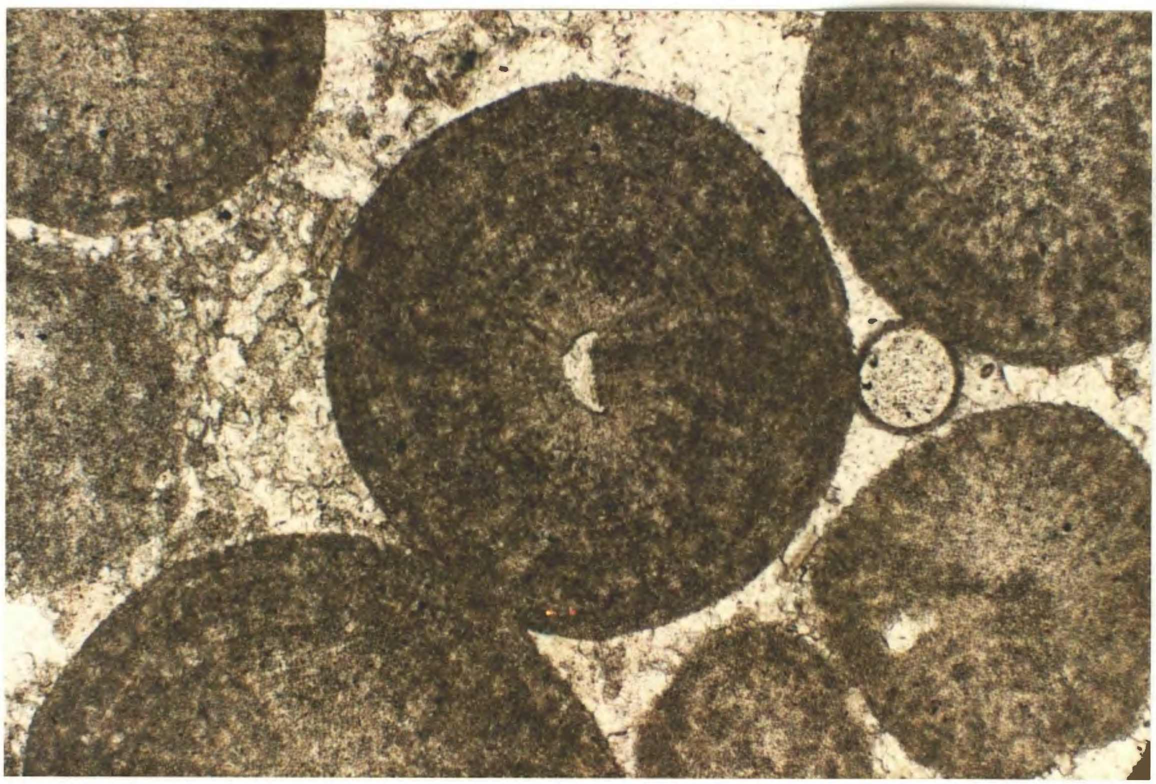
Superficial Grains

Superficially coated skeletal debris occurs in many of the Short Creek samples examined. These coats might be confused with micrite envelopes, except that the coats may exceed 100 microns in thickness. The development of superficial coats is most common in association with pelmatozoan debris, but may also be associated with brachiopod or bivalve debris.

Superficial coatings are typically developed about large skeletal fragments. The diameter of pelmatozoan debris, for example, may reach or exceed 0.5 mm. The development or preservation of superficial grains appears to be more important in portions of the Short Creek section which exhibit less than excellent grain-size sorting, and a greater than

Figure 27. Photograph of ooid cortex illustrating concentric fabric; plane polarized light, 100X

Figure 28. Photograph of ooid cortex illustrating composite tangential plus concentric fabric; plane polarized light, 100X



average content of skeletal debris.

Aggregate Grains

Aggregate grains, or grapestones, occur occasionally in the Short Creek samples examined. The aggregates themselves may reach about 1 mm in diameter, and are composed of small ooids, peloids, and skeletal debris which are surrounded by a fine-grained calcite matrix. Ooids in the aggregate average only about 0.25 mm in diameter, as do the associated peloids.

Peloids

Peloids occur in the Short Creek as lithified fecal material (pellets) and as micritized skeletal debris. Often this distiction is not clear, so the general term peloid is preferred.

Fecal pellets are rounded lumps of micritic material which average about 0.25 mm in diameter. The contribution of pellets to the nucleation of ooids in the Short Creek is suspected to be significant, although their petrographic identification is problematic.

Micritized skeletal debris occurs throughout the Short Creek section. These grains are recognized as skeletal debris, but the destruction of detail is so great that their biological affinities remain unknown or uncertain. Grain sizes are variable, as a function of the size of the skeletal debris from which they are formed. Most are small, ranging in size from 0.2 to about 0.4 mm.

Skeletal Debris

Non-coated skeletal debris in the Short Creek includes fragments of echinoderms, brachiopods, molluscs, bryozoans, forams, trilobites, ostracodes, and sponge spicules. These fragments commonly exhibit a high degree of abrasion, indicative of significant transport or reworking.

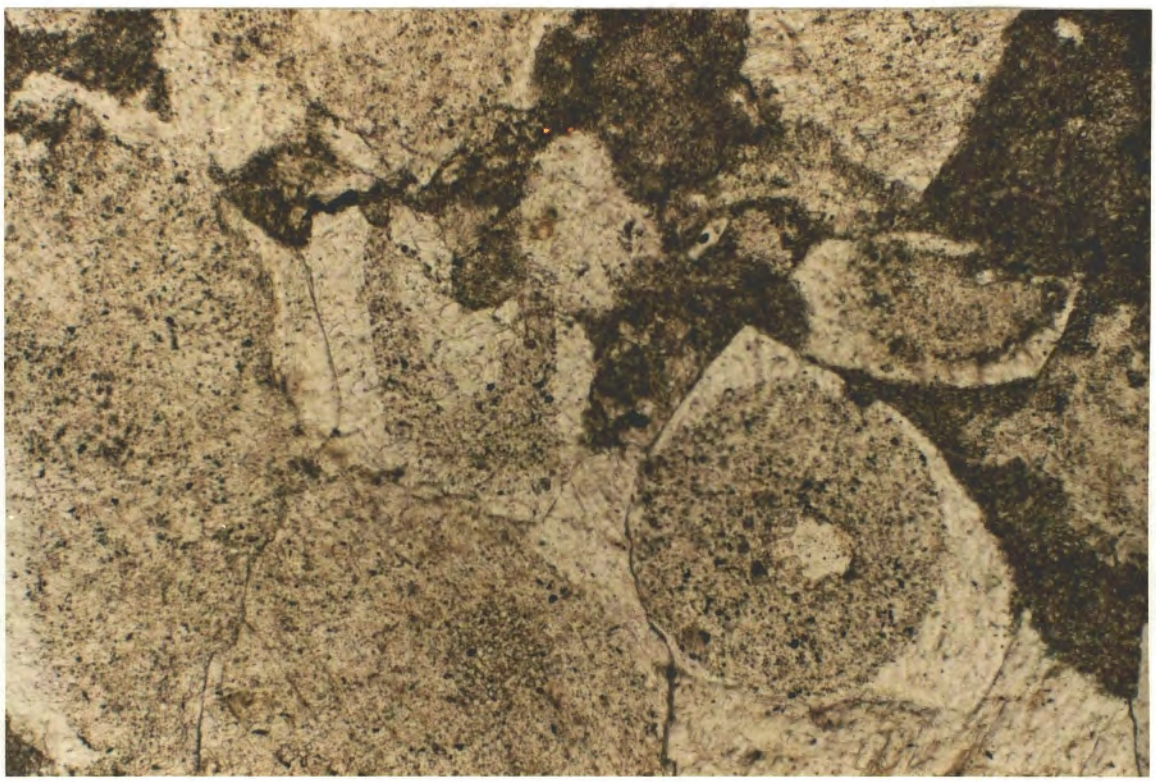
Echinoderms

Pelmatozoan fragments are the most common bioclastic grains in the Short Creek, ranging from 10 to 40 percent of the bulk volume. In many cases this percentage would be significantly higher if those fragments which serve as ooid, or superficial grain, nuclei were considered. It should be noted that in most of the Short Creek samples examined, the bulk percentage of pelmatozoan debris ranges between 10 and 20. Higher concentrations of pelmatozoans occur sporadically throughout the section in thin lenses of less well-sorted bioclastic sediments.

Syntaxial overgrowths of calcite are commonly developed around pelmatozoan grains (Figure 29). In samples with relatively abundant pelmatozoan debris, the syntaxial overgrowths may become the dominant cement of the Short Creek.

Bioclastic grains tentatively identified as echinoid fragments are rarely observed, contributing only in trace quantities to the bulk volume. These grains are identified on the basis of mud-filled pores which once served to anchor

Figure 29. Photograph of syntaxial calcite overgrowths on pelmatozoan skeletal debris; plane polarized light, 100X



the spines of the organism.

Brachiopods

Brachiopod debris occurs throughout the Short Creek, with bulk volume percentages ranging from 0 to 5. The fragments are always disarticulated, and usually reflect a high degree of abrasion. They may occur as debris less than 1 mm in length to debris, or entire valves, which are 20 to 30 mm in length.

Brachiopods have long been utilized by workers in the area as tools for stratigraphic correlation. Several species occur within the samples examined, but no attempt to identify or classify the various forms has been made by this author.

Molluscs

Bivalve and gastropod skeletal debris occurs throughout the Short Creek section, in very small quantities. Average bulk volume percentages of each organism is about 2. It is common for gastropod debris to occur in slightly higher quantities than bivalve debris in the samples examined.

Gastropods occur as small planispiral forms, and as larger uniserial forms. The originally aragonitic tests are now composed of blocky, equant neomorphic calcite, and the chambers may be filled with cements or lime mud (Figure 30).

Bivalve skeletons are disarticulated and abraded, and range in size from small fragments about 0.4 mm to large fragments several millimeters in length. The bivalve debris

Figure 30. Photograph of neomorphosed, spar-filled gastropod fragment; plane polarized light, 100X

identified occurs as single-layer aragonite (originally), or aragonite plus calcite multi-layers. In all cases, the originally aragonitic layers are now composed of blocky, equant neomorphic calcite.

Bryozoans

Bryozoans of the Short Creek are fenestrate forms, and occur throughout the sediment. They comprise from 0 to about 5 percent of the bulk volume in the samples examined. The bryozoan skeletal debris occurs as slender, fibrous fragments which commonly exhibit extensive abrasion (Figure 31). Primary intragranular porosity is rarely preserved within the zoecia. This porosity is generally destroyed as a result of calcite cementation, or infilling by fine-grained sediments.

Forams

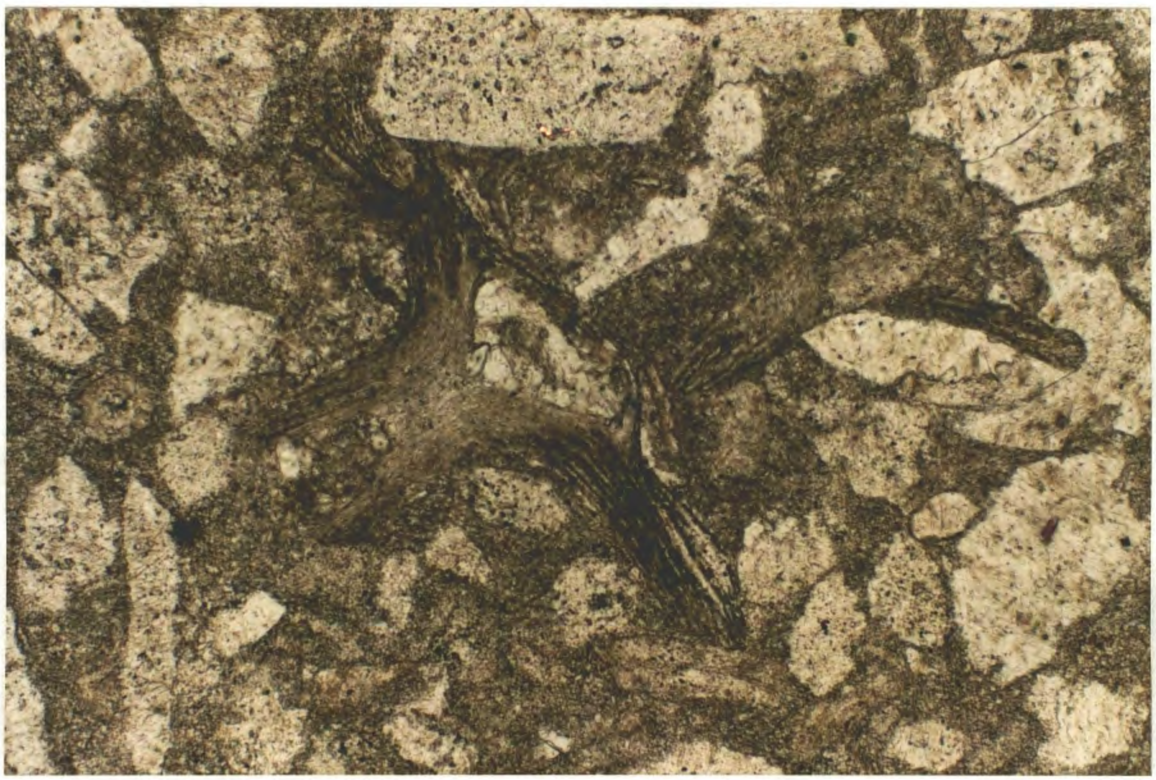
Forams are occasionally identified in the Short Creek samples examined. Several different foram morphologies have been identified, with uniserial or possible biserial forms occurring in the greatest numbers.

Miscellaneous Skeletal Debris

Trilobites are rarely identified as non-coated skeletal debris or ooid nuclei. The fragments are broken and abraded, but usually exhibit the typical undulosic extinction in cross polarized light.

Ostracodes are rarely encountered in the samples exam-

Figure 31. Photograph of bryozoan skeletal debris; plane polarized light, 100X



ined. The shells are thin and often disarticulated, but are rarely broken.

Skeletal grains tentatively identified herein as sponge spicules occur in many of the samples examined. The spicules are monaxons, and typically display a central canal filled with lime mud. The spicules are believed to have been originally opaline in composition, and have since been replaced by low magnesium calcite.

Terrigenous Clastic Constituents

Detrital Quartz

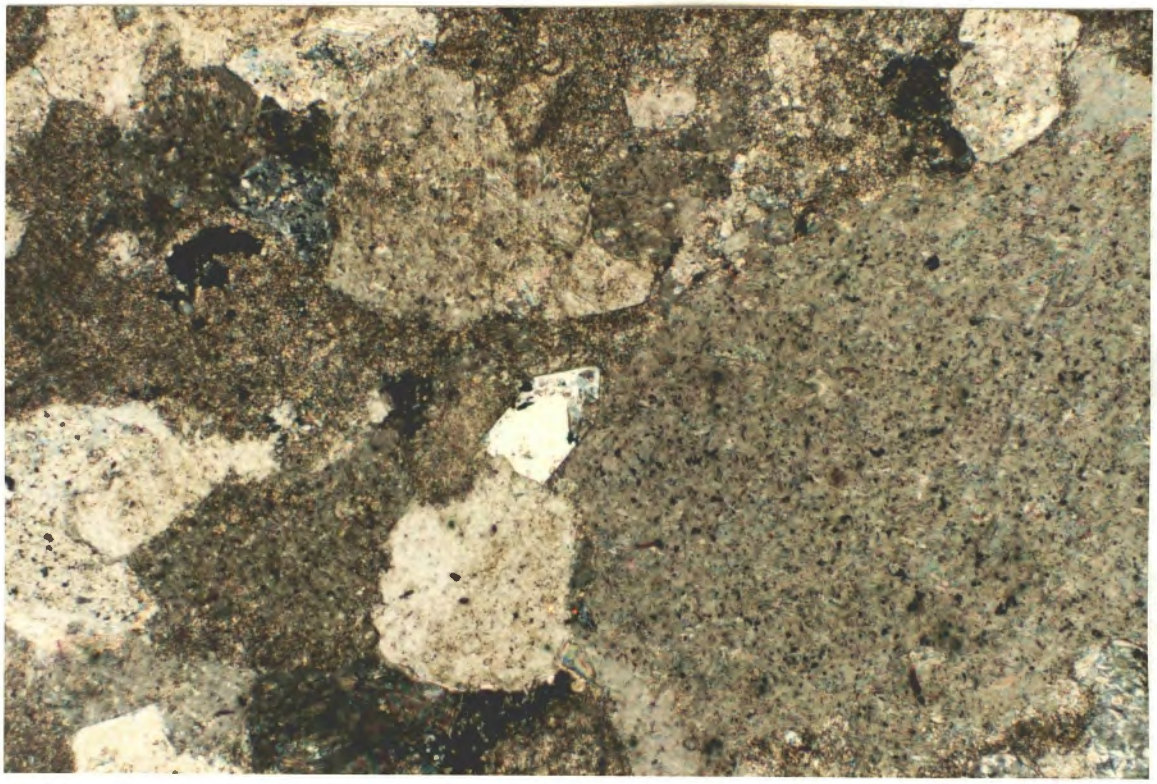
Very fine-grained sand to silt-sized particles of detrital quartz are common in the samples examined, although they never exceed 1 to 2 percent of the bulk volume. The grains are well-rounded and may reflect eolian transport. The detrital quartz grains are commonly surrounded by syntaxial quartz overgrowths which exhibit euhedral terminations (Figure 32). Detrital quartz is occasionally observed serving as ooid nuclei.

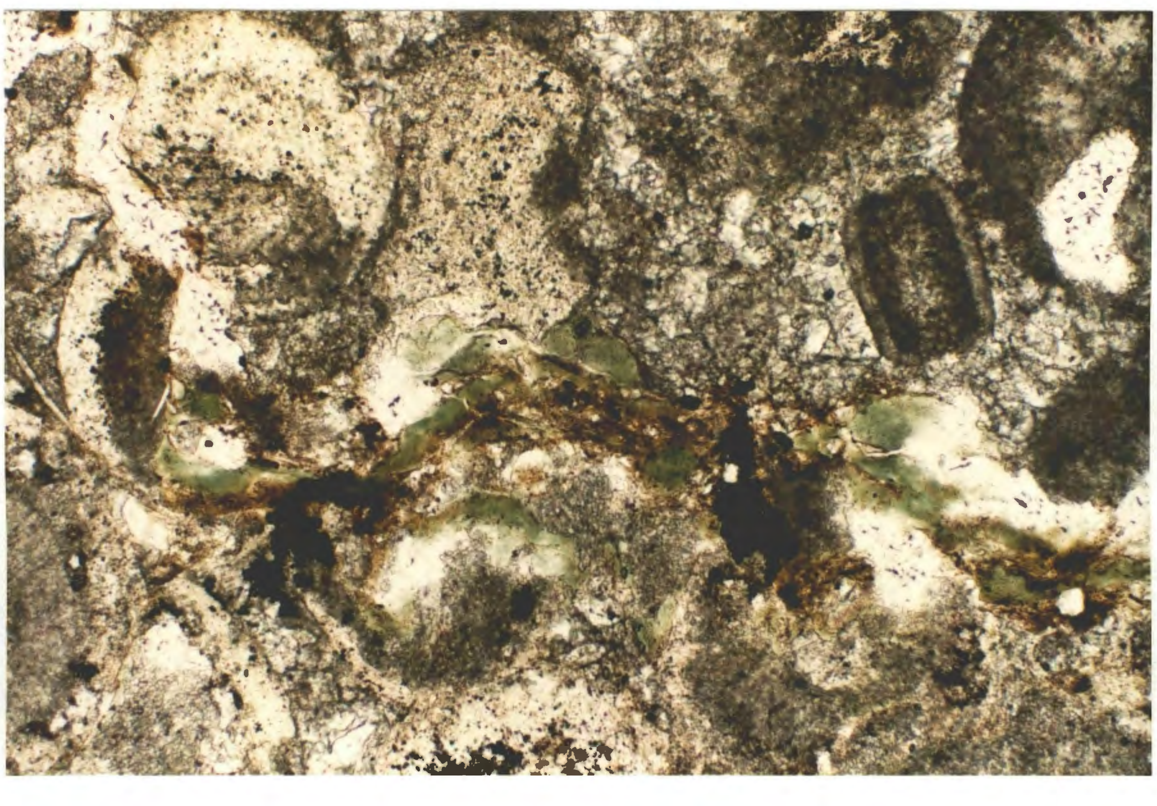
Detrital Clays

Samples of the Short Creek examined are essentially free of detrital clays. Clays of probable detrital origin have been observed, however, occurring along stylolites which are developed in the upper portions of the Short Creek section (Figure 33). This insoluble residuum does not occur in

Figure 32. Photograph of detrital quartz grain displaying syntaxial quartz overgrowth; crossed nicols, 100X

Figure 33. Photograph of stylolitization and associated concentration of insoluble, clayey residuum; plane polarized light, 100X





quantities sufficient to permit mineralogical identification by X-ray diffraction, but its low birefrengence and yellow-brown color in plane light suggests an illitic or chloritic composition.

Diagenetic Constituents

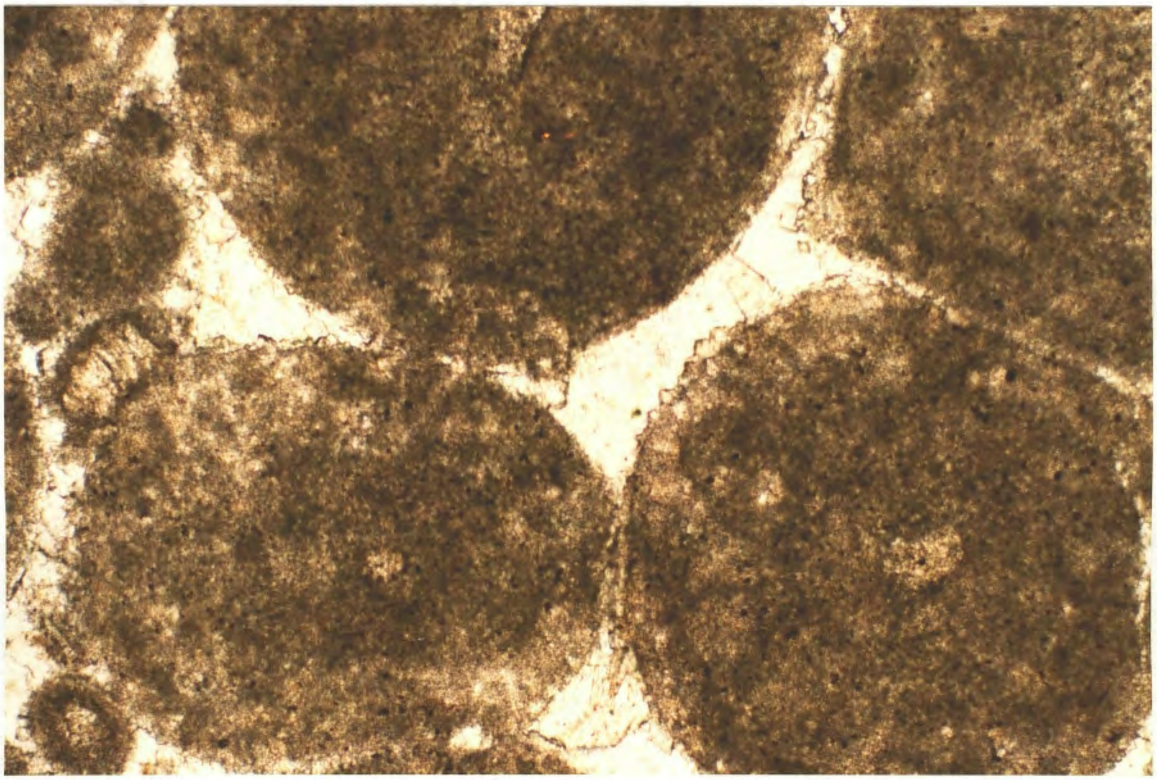
Calcite Cements

In the samples of the Short Creek examined during the course of this study, primary intergranular and intragranular porosities have been observed to be almost totally destroyed by the precipitation of calcite cements. The cements constitute an important portion of the bulk volume of the samples analyzed, and range from about 12 to 25 percent. Cement fabrics observed include a medium to coarse-grained, blocky and equant, low magnesium calcite spar, syntaxial calcite overgrowths, and an irregularly developed early, isopachous cement.

Early Cements

An early, bladed, cement fabric has been identified in several samples examined. The cement has an irregular distribution and cannot be demonstrated in every sample. The morphology of the cement is significant in that it is bladed, and not acicular. Individual crystals display a slight elongation parallel to the C-Axis, and a euhedral to sub-hedral rhombic termination (Figure 34). Crystals range in

Figure 34. Photograph of early, calcitic rim-cements; note rhombic habit and euhedral termination; plane polarized light, 100X



length from 2.5 to 5 microns, and are oriented so that the C-axis is normal to the substrate. Although petrographic evidence is limited, these cements appear on ooids most commonly.

Equant Cements

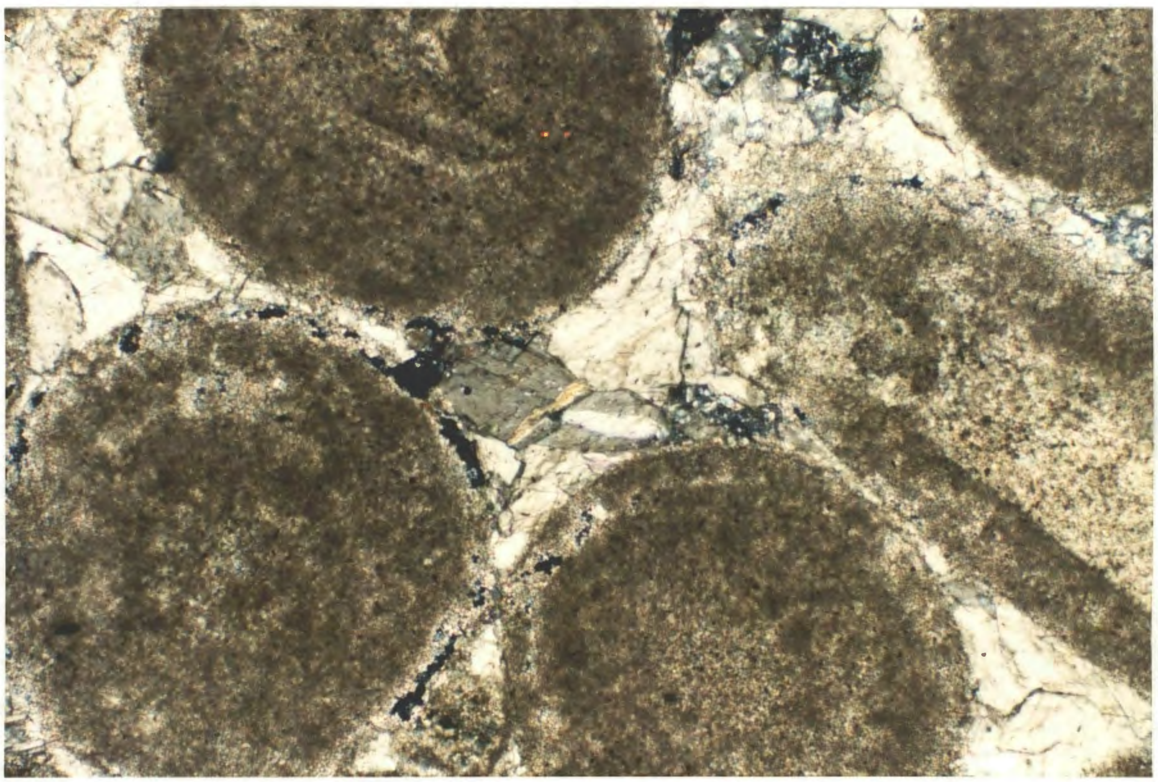
The most common cement fabric in the Short Creek is a medium to coarse grained, blocky and equant, calcite spar. Crystal sizes range between 0.25mm and 0.4mm, with an average of about 0.30mm in diameter. The crystals form a subhedral to anhedral mosaic and commonly exhibit well developed plane-compromise boundaries (Figure 35). They are rarely poikilotopic, but have been observed to replace peloids.

Staining with potassium ferricyanide indicates that the great bulk of these cements are composed of non-ferroan, low magnesium calcite. Somewhat ferroan, equant calcite cements are rarely observed in these samples. Where present, the ferroan calcite cements tend to exhibit a gradational increase in ferrous ion content, toward the pore-interior.

Syntaxial Calcite Overgrowths

Uncoated echinoderm skeletal debris is nearly always surrounded by syntaxial calcite overgrowths. When echinoderm debris is abundant, as in local portions of the Short Creek section, these syntaxial overgrowths may become the dominant cement type. Individual overgrowths are typically subhedral, and multiple overgrowths form a very coarse-grained subhedral

Figure 35. Photograph of equant, subhedral mosaic of calcite cements; crossed nicols, 100X



mosaic commonly exhibiting well developed plane-compromise boundaries and enfacial junctions. These syntaxial cements are commonly poikilotopic, including small bits of skeletal debris, peloids, or detrital quartz during precipitation.

Dolomite Cements

A baroque dolomite which lines fracture surfaces has been observed to occur, rarely, in the upper 1 to 2 inches of the Short Creek section at Outcrop 1 (NE1/4, Sec.29, T27N, R24E). This material is believed to represent a late stage of cementation, and its extent is limited to fractures. Staining with potassium ferricyanide indicates that the dolomite is not appreciably ferroan.

Silica

Silica in the Short Creek Oolite is largely limited to replacement fabrics, and has not been observed to occur as a true cement, except as syntaxial overgrowths on detrital quartz fragments. Nodules of silicified oolite occur sporadically throughout the a typical Short Creek section, particularly near its top. In addition, non-nodular silica repiacements are common near the top of the unit. Chalcedony is occasionally observed in the Short Creek, although it appears to be limited to the upper portions of the unit.

Replacement Silica

Silicification is preferential and has been observed to affect ooids, bryozoan skeletal debris and, probably, lime mud. Calcite cements are not usually affected, nor is echinoderm skeletal debris.

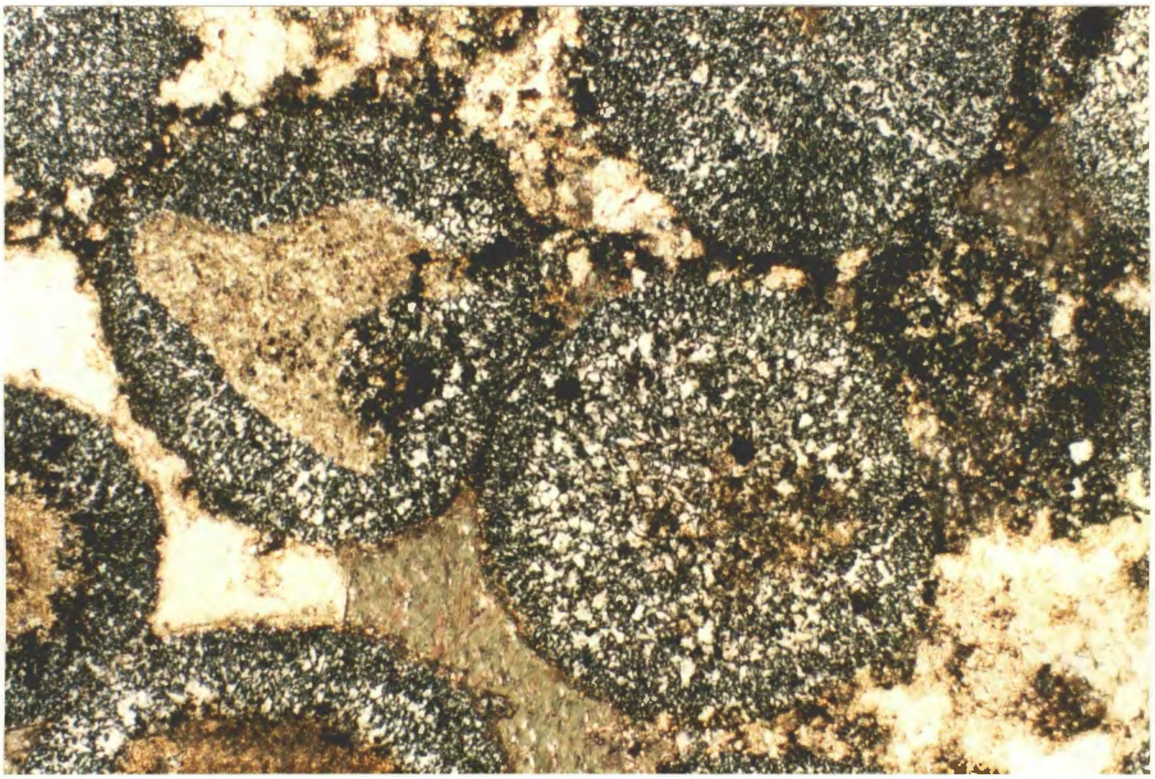
Silicification of the ooids is progressive, beginning at the outer cortex margins. The replacement may be partial or complete, and the replacement fabric is variable. Silica typically exhibits a microquartz fabric near the outer margin of the cortex, and may grade to a megaquartz fabric as the nucleus is approached (Figure 36). Normally, the original cortical fabric is destroyed during replacement, but a vague concentricity is occasionally preserved. Replacement silica is usually colorless, but may become highly colored (yellow-brown) as a result of contamination by organic matter from the ooid cortex.

Silicification has been observed to terminate abruptly in contact with micrite which occurs sporadically in the upper Short Creek. Micrite is largely limited to the uppermost several inches of the Short Creek, where it filtered into the oolitic sediment during the progradation of the overlying lagoonal facies. The interooid material now silicified was probably micritic, but its lower permeability served to locally limit the flow of diagenetic fluids.

<u>Chalcedony</u>

Small nodules of chalcedony are occasionally observed in the Short Creek samples examined. Although rare throughout most of the section, the frequency of their occurrence in-

Figure 36. Photograph of partially and completely silicified Short Creek ooids; crossed nicols, 100X



creases somewhat toward the top of the unit. The nodules themselves may reach 0.4 mm in diameter, and are composed of radiating fibers of 2 to 3 microns in width, and 100 to 200 microns in length.

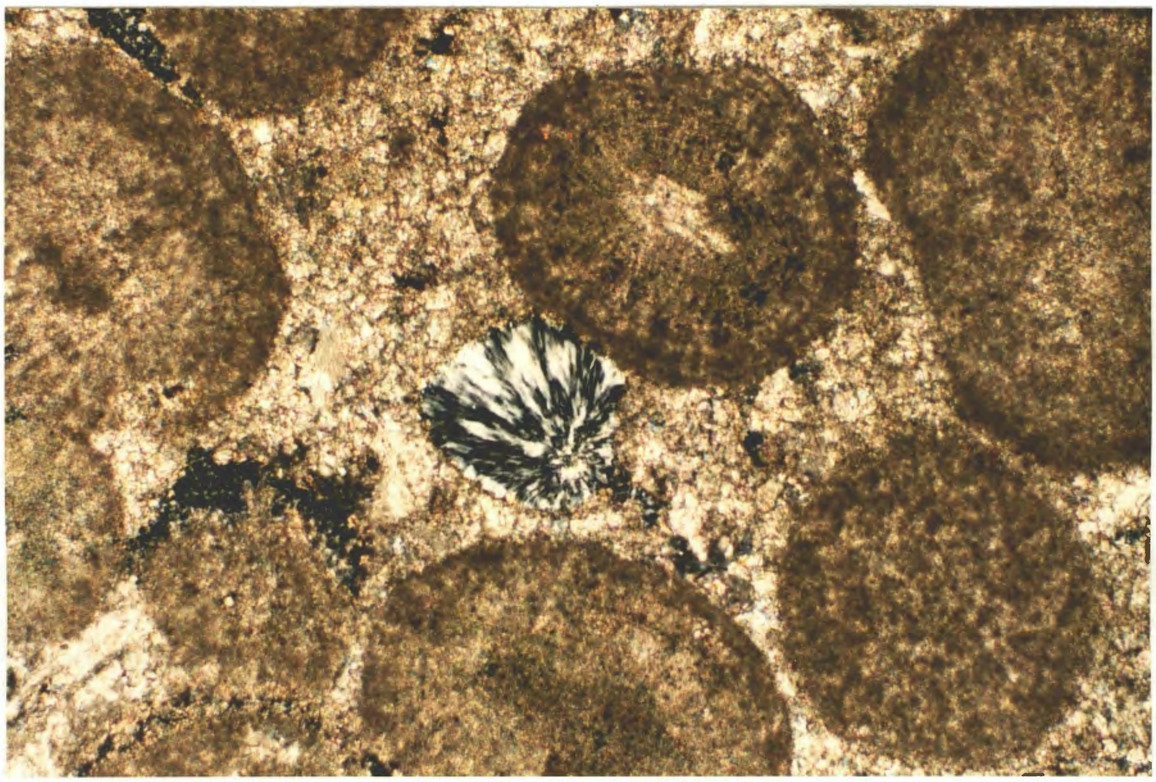
The chalcedony observed is a length slow variety (quartzine), which is believed by Folk and Pittman (1971) to represent replacement of sulfate evaporitic minerals (Figure 37). It is proposed herein that the evaporitic minerals probably originated within the back-shoal or lagoonal facies, and were transported into the oolitic shoal by storm or tidal currents. Silicification probably occurred within the Short Creek sediments after transport.

Glauconite

Glauconite occurs in trace quantities in many of the Short Creek samples examined. Its percentage of the bulk volume increases toward the top of the unit, where it may reach 5 to 10 percent. Glauconite occurs most commonly in intraooid areas (Figure 38), and it is commonly observed to replace the nucleus and inner cortex of the ooid. This replacement does not usually result in total destruction of the original cortical fabric; the tangential fabric of the inner cortex is often preserved.

Glauconite also occurs as discrete to rather indescriminate patches within the ooid. These patches tend to occur near the nucleus or inner cortex, but may occur elsewhere in the ooid. In interooid areas, glauconite occurs as small

Figure 37. Photograph of fibrous, chalcedony nodule; crossed nicols, 100X



rounded blebs which are believed to represent the replacement of fecal pellets.

In silicified ooids, silica may replace all parts of the ooid except those occupied by glauconite. In these ooids glauconite occurs near the center of the cortex and silica replaces the remainder of the cortex (Figure 39).

Glauconite may also occur along microstylolites in the upper portions of the Short Creek. This glauconite commonly occurs in association with a yellow-brown clay mineral which resembles illite or chlorite.

Pyrite

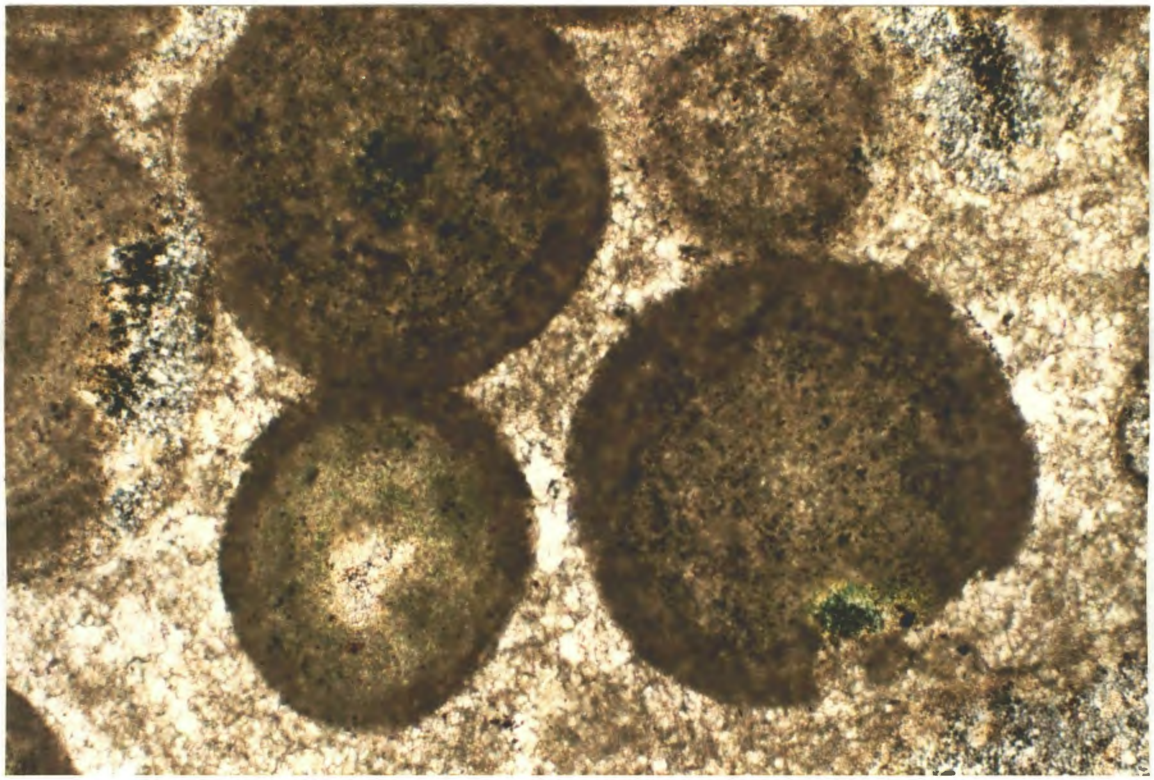
Pyrite occurs in very small quantities in many of the Short Creek samples examined. It typically appears as small, rounded nodules, or as anhedral to subhedral crystals.

Dolomite

Isolated crystals of rhombic micro-dolomite occur throughout the Short Creek section. The crystals average only about 100 microns in diameter, and occur only in trace quantities. Dolomite was detected by X-ray diffraction, although in most samples analyzed the peaks are ratty and of very low intensity (Figure 40). Minor dolomitization may have resulted during the neomorphism of high magnesium calcite to low magnesium calcite, as a result of Mg^{2+} release.

Figure 38. Photograph of ooid replacement by glauconite; crossed nicols, 100X

Figure 39. Photograph of ooid replacement by glauconite and silica; note that glauconitization occludes total replacement by silica; crossed nicols, 100X



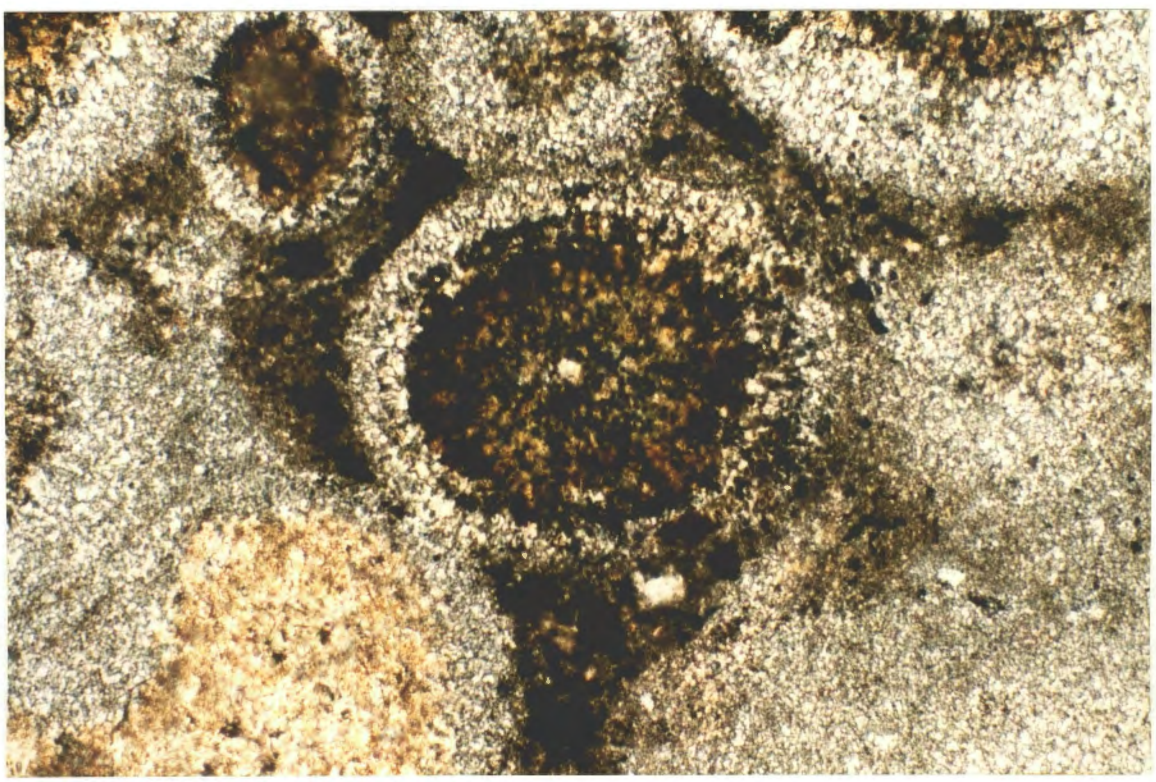
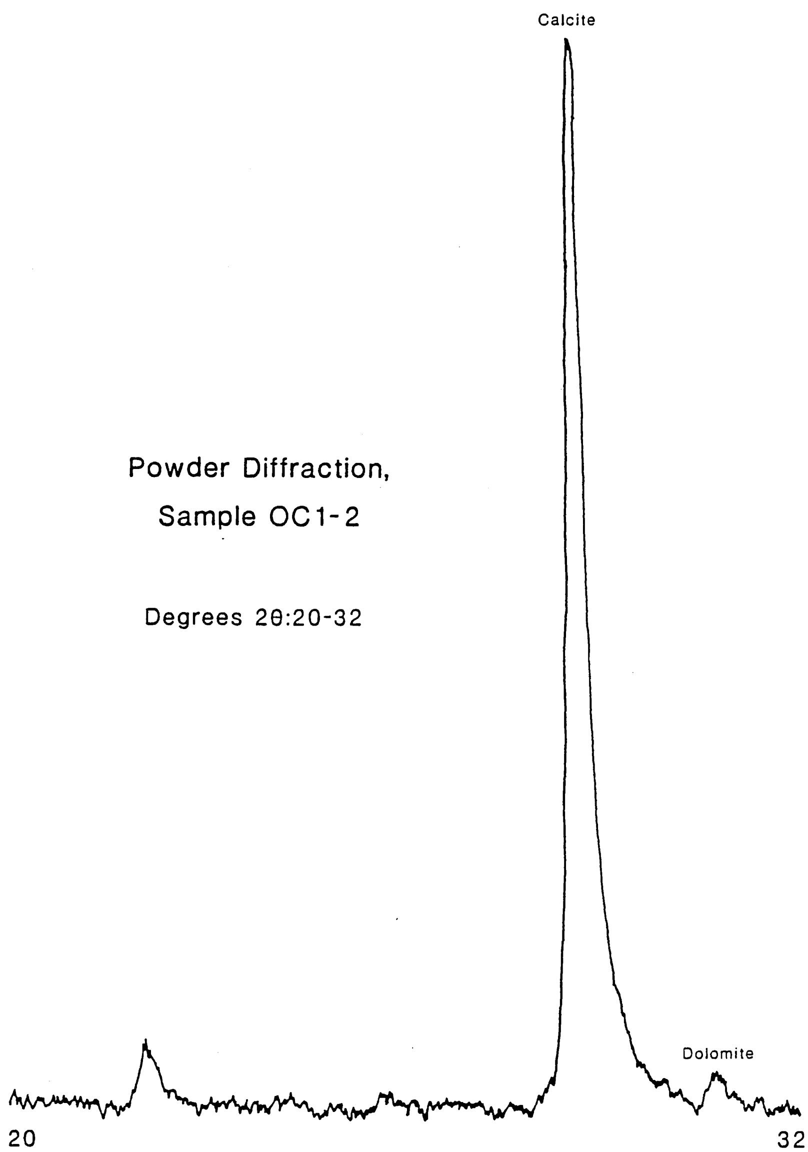


Figure 40. An x-ray diffraction curve from sample OC1-2; presented as an example typical of other samples of the Short Creek Oolite


Calcite
Powder Diffraction,
Sample OC1-2
Degrees 2θ:20-32
Dolomite
20
32

CHAPTER VII

DIAGENESIS OF THE SHORT CREEK OOLITE

Ooid Genesis

Despite the great amount of information available in the literature, it is fair to say that the processes of ooid genesis are imperfectly understood. The discussion which follows is presented in order to summarize some of the most important concepts, as they relate to the genesis of ooids in the Short Creek Oolite.

Cortical Fabric as a Function of Original Mineralogy

While some workers propose that all ooids are originally aragonitic (Shearman, et al., 1970), many argue that the original mineralogy of ooids is variable (Sandberg, 1975; Wilkinson and Landing, 1978; Medwedeff and Wilkinson, 1983; and others). According to MacKenzie and Pigott (1981), the relative abundances of aragonite versus the calcite phases was not constant through time. Furthermore, the primary mineralogy of the calcitic ooids was probably variable (Kettenbrink and Manger, 1971; and Brand and Veizer, 1983).

In a study of the Twin Creek Formation (Jurassic) of

Wyoming, Medwedeff and Wilkinson (1983) concluded that the ooids present were originally calcitic. They report (p. 110) that the gross fabric of the Twin Creeks ooids is typically radial with banded or concentric fabrics occurring, on occasion, as a function of ooid size. Where both fabrics occur together, the radial arrangement is nearest the nucleus.

Medwedeff and Wilkinson (1983) also studied modern aragonitic ooids from the Great Salt Lake, and found that (p. 113) these ooids exhibited "nearly identical relationships with respect to ooid size, banding density, and orientation of cortical crystals" to the calcitic ooids of the Twin Creek Formation. These authors state further (p. 113) that smaller calcite and aragonite ooids exhibit similar textural relationships, suggesting that primary cortical mineralogy is of limited significance in predicating cortical fabric.

Cortical Fabric as a Function
of Hydrodynamic Conditions

The idea that ooids come into contact with other grains more frequently, and with more force, as they grow larger was first suggested by Heller, et al. (1980). Heller believes that the roles of agitation and abrasion occurring during cortex accretion are related to ooid size, and significantly modify the cortical fabric during the progressive growth of the grain.

Reijers and ten Have (1983) have reached similar conclusions from their study of the Givetian-Frasnian Portilla

Limestone of northwest Spain. Ooids present in portions of this unit display variable cortical fabrics including radial, concentric, and a composite of the two. Ooids with these cortical fabrics occur in distinct zones throughout the study area (Reijers and ten Have, 1983, p. 193).

Reijers and ten Have (1983, p. 194) report that in warm, agitated, shallow marine settings with water which is saturated with respect to $CaCO_3$, slow precipitation around a nucleus results in the formation of cortices with a concentric fabric. Heller et al. (1980) reached similar conclusions regarding experimentally produced ooids, and ooids from modern and ancient settings.

In slightly deeper settings the sea will be weakly agitated, but may still be saturated with respect to $CaCO_3$. Here, according to Reijers and ten Have (1983, p. 194), slow precipitation around a nucleus results in the development of radial cortices. Various authors (Rusnak, 1960; Loreau and Purser, 1973; and Heller et al., 1980) have observed similar fabrics in ooids from comparable environments, both recent and ancient, and Davies et al., (1978) reproduced such ooid fabrics in the laboratory.

Composite cortical fabrics are interpreted by Heller et al., (1980) to reflect growth in settings with variable hydrodynamic behavior. Reijers and ten Have (1983, p. 194-195) report that radial crystal growth reflects a period of weak agitation in which the comparitively small ooid remains in suspension while radial growth occurs. These authors continue by stating that with increased agitation, such as might result during a slight regression of the sea, the grain could roll about accreting concentric layers with tangentially oriented crystals.

Short Creek Ooids

As was summarized above, determining the original mineralogy of the Short Creek ooids is quite problematic; cortical fabrics are probably better evidence of hydrodynamic conditions than of original cortical mineralogy. Certain deductions may be employed, however, to speculate on the original mineralogy of the Short Creek ooids.

An originally aragonitic mineralogy seems unlikely from petrographic observations in which aragonitic skeletal fragments have been neomorphosed to low magnesium calcite, with the resulting development of an irregular anhedral mosaic. It would seem that the ooids, if originally aragonitic, would exhibit neomorphic or corrosional effects as well.

On this basis, the ooids of the Short Creek are interpreted as being originally calcitic. It is not possible to know whether the phase was low magnesium calcite or high magnesium calcite. The precipitation of low magnesium calcite in Paleozoic seas is consistent with the findings of Brand and Veizer (1983).

The concentric, radial, or composite fabrics of the Short Creek cortices are very similar to those described by Reijers and ten Have (1983). It is probable that the environmental setting of the Short Creek approximated the setting deduced for the Portilla Limestone. Cortical fabrics of the Short Creek ooids are, then, believed to be indicative of the hydrodynamic energy predominant during their formation.

Diagenesis of the Short Creek Oolite

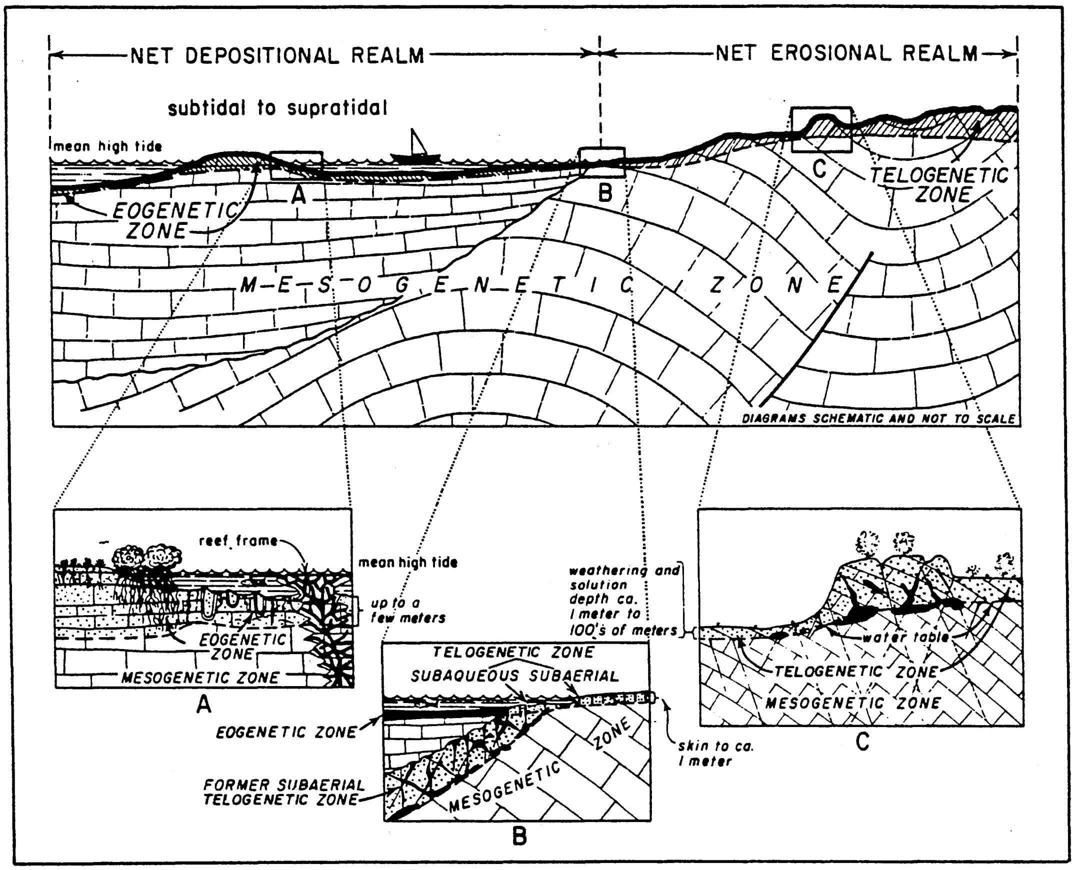
Discussion and Paragenesis

Diagenetic modifications in the Short Creek Oolite began with the irregular, syndepositional precipitation of a bladed carbonate cement. Selective silicification, glauconite formation, and the precipitation of pyrite occurred early in the shallow burial phase. Inversion of metastable aragonitic and high magnesium calcite constituents to low magnesium calcite occurred under conditions of shallow burial, as did the precipitation of equant and syntaxial calcite cements.

The unit was buried to greater depths where tectonic, or solution fractures were developed and subsequently filled by non-ferroan and ferroan calcites, and occasional baroque dolomite. Following uplift, selective dissolution of framework grains has resulted in the creation of secondary porosity which is essentially oomoldic.

Sediments of the Short Creek have been exposed to each of the three diagenetic zones described by Choquette and Pray (1970; Figure 41). Early processes in the Short Creek are eogenetic. As burial removed the sediment from contact with surficial fluids, diagenetic processes became mesogenetic.

Figure 41. The diagenetic zones of Choquette and Pray (1970) as utilized in this report


NET DEPOSITIONAL REALM
NET EROSIONAL REALM
subtidal to supratidal
mean high tide
A
B
C
EOGENETIC ZONE
TELOGENETIC ZONE
M-E-S-O-G-E-N-E-T-I-C ZONE
DIAGRAMS SCHEMATIC AND NOT TO SCALE
reef frame
mean high tide
up to a few meters
EOGENETIC ZONE
MESOGENETIC ZONE
TELOGENETIC ZONE
SUBAQUEOUS SUBAERIAL
EOGENETIC ZONE
FORMER SUBAERIAL TELOGENETIC ZONE
MESOGENETIC ZONE
skin to ca. 1 meter
weathering and solution depth ca. 1 meter to 100's of meters
water table
TELOGENETIC ZONE
MESOGENETIC ZONE

Telogenesis begins as the sediments are uplifted into the zone dominated by meteoric fluids.

Early Diagenesis

An early, bladed cement appears irregularly throughout the Short Creek section. This cement is preferentially developed on ooids, and is essentially isopachous. $CaCO_3$ was precipitated from marine waters under phreatic conditions in response to lowered levels of dissolved CO_2. The decrease in P_{CO_2} probably resulted from losses through agitation, and biochemical processes. Although irregular and sporadic, the early cements strengthened the sediment, and significantly reduced mechanical compaction in the early stages of burial.

The early, bladed cements are inclusion-free and contain no dolomite. Their relict bladed fabric and essentially equant rhombohedral termination suggest an original calcitic composition (Folk, 1974; Bathurst, 1975; Longman, 1980; Wilkinson et al., 1985). Aragonite is typically precipitated as acicular crystals, as is high magnesium calcite. The cement exhibits none of the morphological features associated with the neomorphism of aragonite to calcite, such as interlocking anhedral crystals of inclusion-rich low magnesium calcite (Wilkinson et al., 1985).

It is not possible to know whether the bladed cements were precipitated as high or low magnesium calcite. Slight elongation in the C-axis direction may suggest selective poisoning of lattice sites parallel to the other axes (Folk, 1974), indicating a significant Mg^{2+} activity, but apparently not one which might halt the precipitation of calcite altogether. This calcite was probably, then, at least somewhat magnesian.

Early biogenic processes, such as sulfate reduction and methane biogenesis probably occurred in the Short Creek, but were limited in effect because of a high rate of fluid exchange, and an overall aerobic setting. Small quantities of biogenic pyrite may have formed locally during this time, but most is believed to have formed during dewatering of the overlying lagoonal sediments during shallow burial.

Shallow Burial

The most important diagenetic modifications observed in the sediments of the Short Creek occurred during shallow burial of the unit. As the oolitic shoal continued to prograde, its sediments were progressively overlain by lagoonal muds of the Baxter Springs Member. Mechanical compaction occurred in both the oolitic facies and in the overlying muddy facies. Compaction, both mechanical and chemical, in the muddy sediment was important in the contribution of ionic and organic solutes which were necessary in the cementation and partial replacement of the oolitic sediment below.

Biogenic Processes

An early phase in the shallow burial history of the

Short Creek is related to biogenic processes occurring in the Baxter Springs. Bacterial reduction of nitrate and sulfate, along with the formation of ammonia and methane, in an anerobic setting, controlled to a large degree the solubility of several important mineral phases (Berner, 1971).

Early, biogenic pyrite is a common constituent of many Baxter Springs samples, and the ionic constituents necessary for its formation there were introduced to the Short Creek sediments, as the muddy facies was dewatered. Early pyrite forms framboidal, intergranular crystals in the Short Creek. Although pyrite occurs in only small quantities in the Short Creek, its distribution throughout the section is widespread.

Mechanical compaction is responsible for the spalling and flattening of the ooid outer cortex, as observed in many of the samples examined. Much of this compaction occurred before major cementation and replacement and, therefore, provides a basis for the relative dating of certain events.

Pore fluids in the muddy Baxter Springs sediments were distinctly alkaline, reflecting supersaturation with $CaCO_3$ and a high ammonia content (Berner, 1971; Krauskopf, 1979). Bicarbonate and CO_2 concentrations were elevated as a result of anerobic bacterial oxidation of carbohydrates (Berner, 1971). $CaCO_3$ solubilities may be increased in the presence of dissolved or suspended organic materials (Berner et al., 1970; Krauskopf, 1979; Mitterer and Cunningham, 1985), so precipitation of $CaCO_3$ was probably retarded in the organic-rich muds of the Baxter Springs. The retardation of $CaCO_3$

precipitation was important in reducing the loss of porosity and permeability, through cementation, and in creating a solution which was supersaturated with respect to $CaCO_3$.

Silicification

The Baxter Springs Member is extremely cherty, particularly near its base. Siliceous sponge spicules have been cited as the principal source of diagenetic silica in a number of other studies (Pittman, 1959; Wilson, 1966; Namy, 1974), and were probably the source of silica for the Baxter Springs and Short Creek cherts. Modern hexactinellid sponges (glass sponges) are mostly restricted to deep water, while Paleozoic forms were common at all depths (Thompson, 1982). Spicules observed in the Baxter and Short Creek samples have been replaced by a fine-grained, equant mosaic of low magnesium calcite. As silicification is known to predate the precipitation of equant, and syntaxial cements in the Short Creek, the few spicules observed probably escaped silica dissolution, and were replaced during the precipitation of calcite cements.

Whereas $CaCO_3$ solubilities are increased in the presence of organic material, the solubilities of various silica phases are decreased by the presence of organic materials (Lovering, 1972). Common electrolytes in the pore fluids of marine sediments, and in particular NaCl (Van Lier et al., 1960), tend to accelerate the equilibrium of silica in solution, resulting in dissolution of quartz by unsaturated solutions, and precipitation of quartz from supersaturated solutions (Lovering, 1972).

Siliceous spicules were dissolved or replaced, particularly in the Baxter sediments, to produce a fluid which was saturated or supersaturated with respect to silica. A solution which is supersaturated with respect to silica is metastable under moderately alkaline conditions (Lovering, 1972). Replacement of $CaCO_3$ by silica, and the precipitation of quartz in the Baxter and Short Creek sediments resulted, and was probably accelerated as the P_{CO_2} derived from biogenic processes increased. The increase in P_{CO_2} would tend to drive the pH of the solution down, thereby increasing the solubility of $CaCO_3$, and decreasing the solubility of silica; because silica was less soluble than $CaCO_3$, replacement occurred (Ames, 1961).

Silicification postdates early mechanical compaction in the Short Creek as evidenced by petrographic observations. This type of replacement commonly occludes the precipitation of the later, equant and syntaxial calcite cements. In addition to replacement silica, syntaxial quartz overgrowths were developed on sand to silt-sized fragments of detrital quartz, which are present throughout the section, and which occasionally serve as ooid nucei. The wide distribution of diagenetic silica, though not quantitatively important in much of the Short Creek section, is evidence of the high degree of permeability retained by the oolitic sediment during this time.

Glauconite

Based on petrographic evidence, glauconite formation began sometime before silicification. Glauconite has been observed to replace the cores of ooid cortices while silica has replaced the remaining outer cortex. The chemistry of glauconite formation is not well known, and glauconite is a poorly defined phase. Burst (1958) recognized four materials to which the term glauconite was applied: type I is a well-ordered, high potassium-mica structure and is the true mineral, glauconite. Other materials are poorly ordered, or are mixtures of clays which are unrelated to glauconite (Burst, 1958).

Modern occurrences of glauconite tend to be the more poorly ordered types (Bell and Goodell, 1967; Hower, 1961). Hower believes that long-term diagenesis results in the ordering of less stable forms into the true mineral phase. On this basis, the formation of glauconite in the Short Creek was most probably a long-term process which began soon after the shoaling oolitic bedform was partially stabilized, and continued well into the shallow burial history of the sand.

Neomorphism of Metastable Phases

The neomorphism of aragonitic and high magnesium calcite bioclastic grains was an important process occurring in the shallow burial stage. Originally aragonitic bivalves and gastropods clearly exhibit the curved or interpenetrating crystal boundaries, and the equant, anhedral mosaic textures typical of neomorphosed aragonite (Bathurst, 1975; Dorobek, 1987).

The neomorphism of high magnesium calcite grains, such as pelmatozoan debris, is controlled by the mol% of $MgCO_3$ (Walter, 1985). The replacement of high magnesium calcite by low magnesium calcite proceeds by means of a thin-film mechanism (Bathurst, 1975), and the degree of original texture preservation is high.

The release of Mg^{2+}, upon ordering of the high magnesium structure, may result in the formation of small dolomite rhombs which are scattered through the skeletal fragment, or in subsequent cements (Lohmann and Myers, 1977). Such dolomites have been observed in the Short Creek samples examined, but are rare. The scarcity of this dolomite occurrence is regarded herein as evidence of high rates of fluid exchange through the Short Creek sediments, which flushed the Mg^{2+} out of the system. Furthermore, the pores were probably filled with marine-derived fluids whose Mg/Ca was inappropriate for dolomite formation (Krauskopf, 1979).

Equant and Syntaxial Calcite Cements

The precipitation of equant and syntaxial calcite cements in the Short Creek began during conditions of shallow burial. Similar shallow burial cements are reported in the literature (Folk, 1974). The blocky, equant cement forms a medium to coarse-grained, subhedral to anhedral mosaic of, typically inclusion-free, low magnesium calcite. The blocky cements are not commonly poikilotopic but have been observed to replace peloids. Syntaxial cements form subhedral to anhedral overgrowths on echinoderm skeletal fragments. The syntaxial cements are typically inclusion-free, but are commonly poikilotopic.

Equant and syntaxial cements of the Short Creek are not zoned to the extent that compositional distinctions are apparent from staining with potassium ferricyanide. The staining of Baxter Springs samples has, however, revealed that cements in larger pores may become increasingly ferroan toward the center of the pore-volume. Ferroan calcite is commonly identified as a product of late burial diagenesis (Woronick and Land, 1985). It is possible that porosity remained open, locally, within the Baxter Springs so that the compositional evolution of the cements reflects the increasing burial of the sediment. On the basis of the relative scarcity of ferroan, shallow burial cements in the Short Creek, therefore, it is possible to say that depositional porosity in the Short Creek was largely occluded before such, ferroan cements were precipitated.

The chemistry of the pore fluids which bathed the Short Creek sands was modified through the time of shallow burial to reflect the evolution of the Baxter Springs fluids. As early biogenic processes neared completion in the Baxter Springs, the content of dissolved CO_2 and organic solutes in the Short Creek was decreased. It is also possible that the fluids of the Short Creek were influenced by meteoric waters which recharged the carbonate aquifer system in the area of its up-dip, on-shore truncation. The mixing of marine waters, or marine-derived connate fluids, with meteoric waters should serve to decrease the Mg/Ca of the fluid, and thereby promote the precipitation of calcite (Berner, 1971; Folk, 1974).

Pressure solution became significant in the fine-grained sediments of the Baxter Springs following initial dewatering, and provided an ample source of ions necessary for the precipitation of equant and syntaxial calcite cements in the Short Creek. Some workers (Dunham, 1969; Bathurst, 1975) reported that cementation models based on $CaCO_3$ from a remote source, had difficulty in deriving the cement volume exhibited by ancient limestones. On this basis, Dunham (1969, p. 161) calculated that between 10,000 and 100,000 pore volumes of water were necessary for complete cementation by $CaCO_3$.

Flow models indicate that waters of compaction in subsiding basins provide insufficient volumes of fluid for major cementation (Bonham, 1980). A problem of mass balance is, therefore, evident. According to Scholle and Halley (1985), this problem is largely circumvented by a model which uses a local supply of cementing material derived from the pressure solution of nearby sources. High-amplitude stylolites formed at the contact of the Short Creek and the Baxter Springs Members, as well as the coalescence of chert nodules in the Baxter Springs, and the microstylolitization of ooid contacts in the Short Creek are indicative of significant mechanical compaction and pressure solution (Scholle and Halley, 1985).

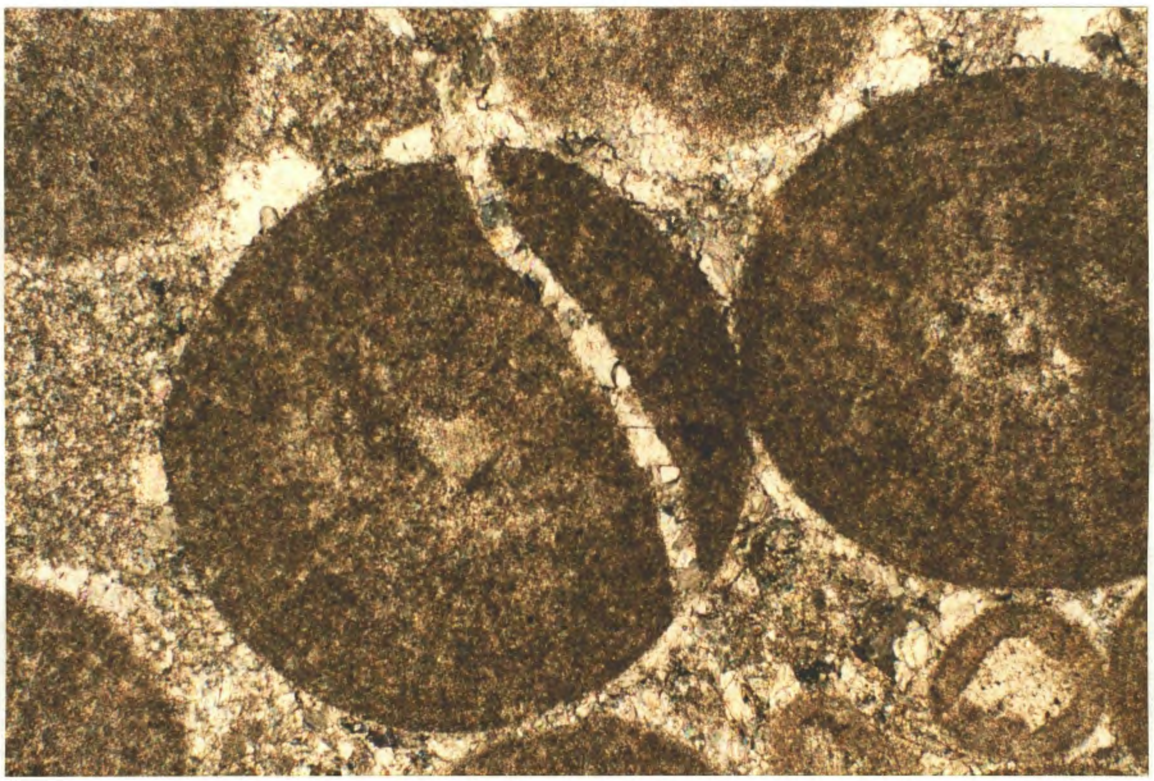
Deeper Burial

Non-ferroan and ferroan calcite cement, with occasional baroque dolomite occurs as fracture-filling precipitates in the Baxter Springs and, to a lesser degree, in the Short Creek sediments. Fractures in these rocks are subvertical in orientation, and were probably developed during deeper burial as a result of tectonic stresses, or collapse due to solution thinning of lower stratigraphic units (McKnight and Fischer, 1970). Fractures observed in the Short Creek are largely confined to upper portions of the section where silicification probably increased their brittle behavior.

Parted fracture planes in the upper Short Creek may be completely cemented, but are commonly only partially filled (Figure 42). Non-ferroan and ferroan calcite cements exhibit a blocky to drusy fabric, while rare baroque dolomite exhibits characteristic curved cleavage planes and undulosic extinction. Non-ferroan calcite is the most quantitatively significant late cement, but it may grade into increasingly ferroan calcite toward the interior of the pore space. On this basis, the precipitation of late, non-ferroan cements is believed to predate the precipitation of ferroan cements.

Baroque dolomite crystals are quantitatively insignificant in the Short Creek, but their presence, and the presence of ferroan calcite cements, is indicative of late,

Figure 42. Photograph of late, non-ferroan calcite, fracture filling cements; crossed nicols, 100X



deeper burial diagenesis (Woronick and Land, 1985). Radke and Mathis (1980) suggest that baroque dolomite is indicative of formation in temperatures between 60 and 150 degrees centigrade. Petrographic evidence is not conclusive regarding the relative timing of baroque dolomite formation, with respect to the other late cements. The precipitation of late calcite cements might, however, trigger the formation of baroque dolomite by increasing the Mg/Ca of the solution to a point where dolomite precipitation is encouraged or accelerated (Krauskopf, 1979).

The baroque dolomite crystals exhibit a rather dirty color indicative of the oxidation of ferrous iron (Tucker, 1981), possibly as a result of exposure to modern, oxygenated meteoric fluids during telogenesis. Indeed, most late dolomites are ferroan (Leeder, 1982, p. 300), but evidence from Short Creek examples is inconclusive; staining with potassium ferricyanide rarely indicates significant concentrations of the ferrous ion in these cements.

Late Diagenesis (Telogenesis)

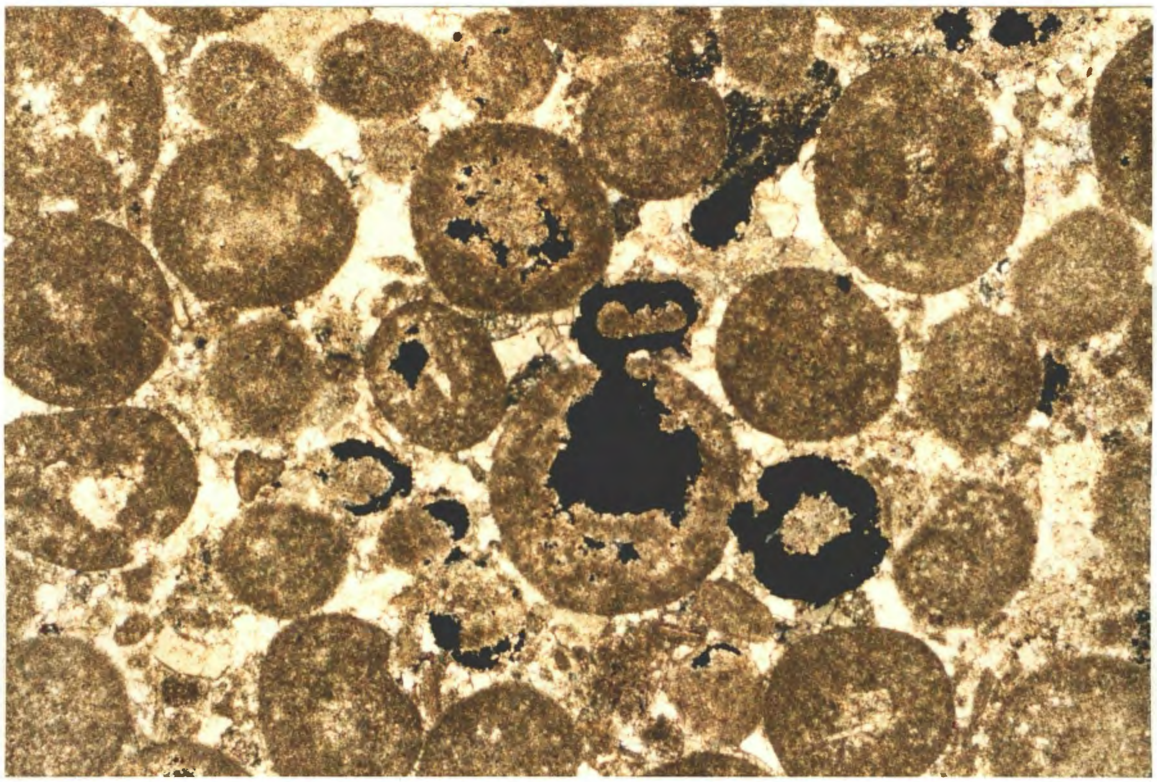
Very late in the diagenetic history of the Short Creek, the unit was exposed to meteoric fluids in response to uplift and/or erosional denudation of overlying Upper Paleozoic sediments. Meteoric pore fluids become acidic following perculation through an organic-rich soil horizon, and are generally distinctly undersaturated with respect to $CaCO_3$ (Krauskopf, 1979). Equilibrium of the pore fluid with the

$CaCO_3$ mineralogy must, therefore result in the dissolution, or replacement, of $CaCO_3$. As discussed previously, the presence of dissolved organic material, such as that derived from an organic-rich soil horizon, may retard this equilibration allowing the fluid to become supersaturated with respect to $CaCO_3$ (Lovering, 1972). Precipitation of very late, low magnesium calcites may result in remaining porosity.

There is no evidence to suggest that the Short Creek experienced cementation of the nature described above. In fact, it is probable that the tightly cemented Short Creek was essentially impervious to very late fluid movement. Selective dissolution and the creation of oomoldic porosity probably resulted as very late fracturing created avenues for the migration of meteorically-derived fluids which were undersaturated with respect to $CaCO_3$ (Figure 43). Such very late fractures may have formed following the relaxation of overburden stresses, or as a result of dissolution, or karstification, collapses in underlying stratigraphic units.

It is not possible to know the extent or distribution of secondary porosity development in the Short Creek as subsurface data are not available. The Short Creek is reported to produce small amounts of ground water in area wells (Reed et al., 1955), however, and because surviving primary porosity is extremely rare in the Short Creek samples examined, the probability of secondary porosity development in the subsurface appears to be high.

Figure 43. Photograph of secondary porosity development in the Short Creek Oolite; crossed nicols, 40X



Paragenetic Summary

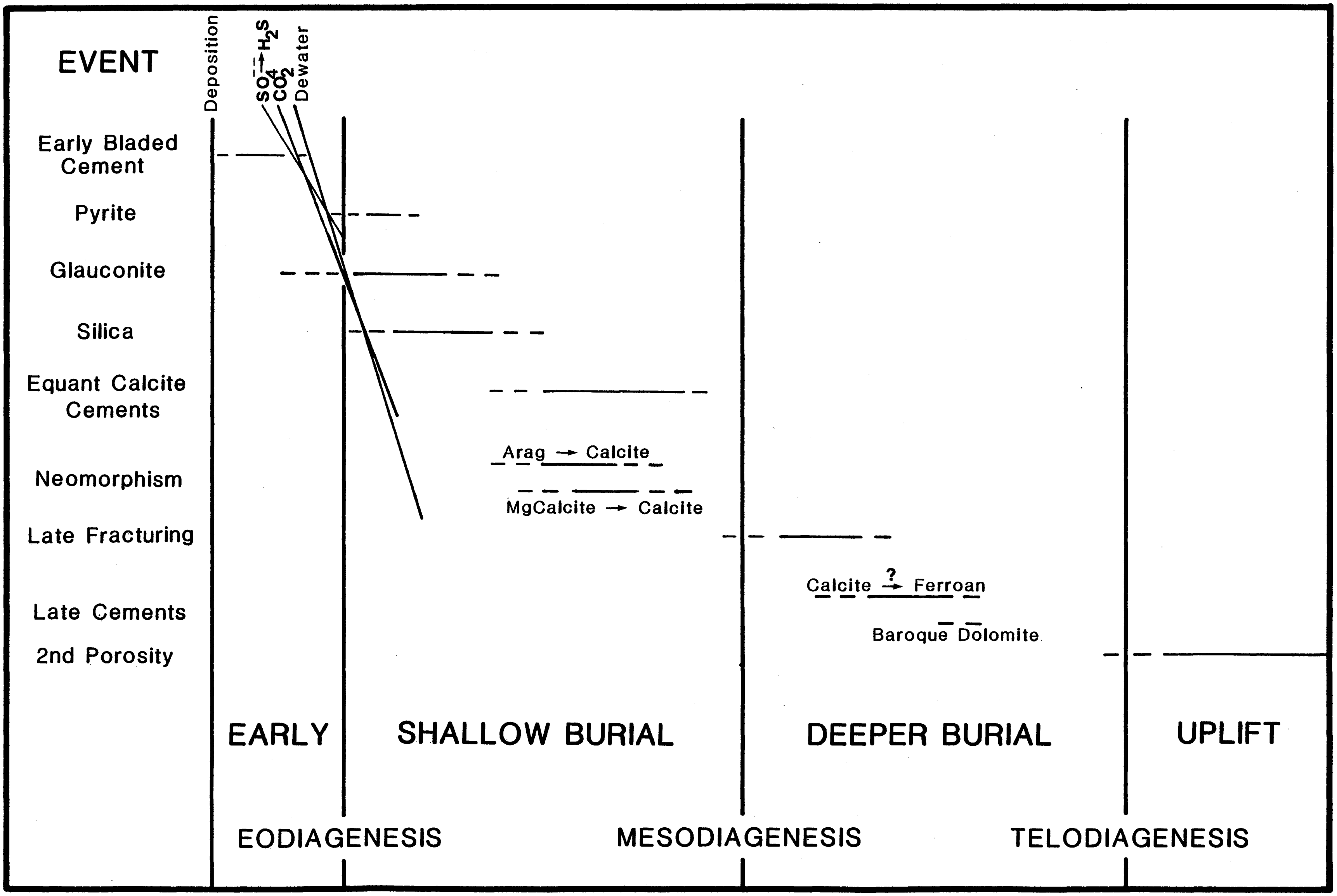
Chemical and physical processes which affected the Short Creek may be classified on the basis of their occurrence in early diagenesis, shallow burial, deeper burial, or late diagenesis (telogenesis). Distinctions are not always clear, and some processes may transcend these arbitrary boundaries (Figure 44).

Soon after deposition, or contemporaneously with it, an early, bladed, and essentially isopachous carbonate cement was precipitated under marine phreatic conditions. Equant but slightly elongate crystal morphologies suggest an original calcite mineralogy, although the calcite phase is unknown.

Mechanical compaction and early biogenic processes in the Baxter Springs resulted in a solution from which early, biogenic pyrite was precipitated in both the Baxter Springs and the Short Creek, as shallow burial began. Spicules of opaline silica were dissolved, particularly in the Baxter Springs, to the point of supersaturation with respect to quartz, while in the presence of dissolved organic material. Solution pH was moderately alkaline as a result of its saturation or supersaturation with respect to $CaCO_3$, and its possible high ammonia content.

Compaction was also affecting the oolite, and initialization of microstylolites or flattening at interooid contacts probably began during this stage of shallow burial.

Figure 44. A schematic representation of the paragenesis of diagenetic events which have modified the Short Creek Oolite since the time of its deposition


EVENT
Deposition
SO4 → H2S
CO2
Dewater
Early Bladed Cement
Pyrite
Glauconite
Silica
Equant Calcite Cements
Neomorphism
Arag → Calcite
MgCalcite → Calcite
Late Fracturing
Late Cements
Calcite ? Ferroan
Baroque Dolomite
2nd Porosity
EARLY
SHALLOW BURIAL
DEEPER BURIAL
UPLIFT
EODIAGENESIS
MESODIAGENESIS
TELODIAGENESIS

Pore fluids expelled from the dewatering Baxter Springs flowed freely into the porous and permeable Short Creek sediments. Ionic solutes transported from the Baxter Springs were responsible for most replacement and cementation of the Short Creek sediments during shallow burial diagenesis.

The formation of glauconite probably began near the end of early, marine diagenesis. The glauconite structure becomes more ordered as shallow burial diagenesis proceeds.

Silicification clearly postdates some compactional effects observed in the Short Creek, notably the spalling of outer cortical margins. Silicification apparently postdates glauconite formation, but has been observed to predate the precipitation of equant and syntaxial calcite cements.

The precipitation of equant and syntaxial calcite cement and the neomorphism of aragonitic and high magnesium calcite components occurred during later phases of the shallow burial stage. In addition, calcitization of any siliceous spicules which survived earlier dissolution began at this time. This precipitation and replacement occurred in response to lowered organic solute concentrations or, possibly, as a result of lowered Mg/Ca from the mixing of connate and meteoric fluids. The chemical modification of pore fluids in the Short Creek resulted in the creation of a solution which was supersaturated with respect to $CaCO_3$, at a slightly alkaline pH.

As the Short Creek sediments were buried deeper, they were subjected to fracturing by tectonic or solution-collapse mechanisms. Non-ferroan and occasional ferroan calcite cements were precipitated in the newly developed fracture porosity, along with rare baroque dolomite. It can be occasionally demonstrated that the non-ferroan calcite cements predate any ferroan phases present. The baroque dolomite, which is observed only rarely, is probably the latest phase to be precipitated in the Short Creek sediments. The formation of the late dolomite might begin only after the calcite cements have precipitated, increasing the Mg/Ca of the pore fluid sufficiently to encourage dolomite formation.

The Short Creek and other members of the Boone Formation are now exposed at the surface, in the study area, where they are in contact with meteoric fluids. Introduction of meteoric fluids into the tightly cemented Short Creek may have been facilitated by a stage of fracturing occurring in response to the release of overburden, or in response to the solution-collapse of underlying stratigraphic units.

The meteoric fluids are undersaturated with respect to $CaCO_3$, and selective dissolution has resulted in the creation of poorly interconnected oomoldic porosity. Water wells in the area which are completed in the Short Creek are reported to produce small quantities of water from the Short Creek, suggesting that the development of secondary porosity must be regional in scale.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Short Creek Stratigraphy

The age and stratigraphic correlation of the Short Creek Oolite have long been argued by a number of workers. Dispute is most commonly associated with the question of placement of the Osage and Meramec boundary, and its relation to the Short Creek. In summary, it is apparent that two principal interpretations exist. In the first, the boundary between the Osage and Meramec series is placed at the base of the Short Creek, and the contact between the Short Creek and the underlying Joplin Member is viewed as unconformable or disconformable. In the second, the boundary between the Osage and Meramec series is placed higher in the section, commonly at the J bed horizon of the Baxter Springs Member; the contact between the Short Creek and the underlying Joplin Member is viewed as conformable, if not gradational.

Interpretations derived as a result of this research lend support to the opinion that the boundary is properly placed at the J bed of the Baxter Springs Member, and that the contact between the Short Creek and the Joplin Members is conformable. Thin-section petrography revealed a gradational contact between the Short Creek and the Joplin at two locations, and a number of authors have documented the truncation of older strata associated with the deposition of J bed. Furthermore, interpretations concerning the environment of deposition infer that sediments deposited prior to the deposition of the Short Creek were inundated by a late Osage epeiric sea, thus, seeming to make unconformity at this time an unlikely possibility.

Structure of the Study Area

The study area resides on the southwestern flank of the Ozark Anticline, and the strata exhibit a gentle regional dip of 25-50 feet per mile to the northwest. The regional dip is interrupted by a series of northeasterly trending faults and folds, and a series of northwesterly trending folds. Structural events are believed to have great significance in the emplacement of ores throughout the Tri-State District.

Deposition of the Short Creek

The Short Creek oolite is believed to have been deposited as a shoal in a shallow, regressing, late Osage, epeiric sea. Conditions of moderate to high energy existed in the upper subtidal to lower intertidal setting of ooid formation and deposition. The oolitic shoal served to restrict normal marine circulation to large areas of the inner shelf.

Back-shoal or lagoonal sediments are muddy and exhibit a reduced faunal diversity. These muds are commonly homogenized by burrowing organisms, although laminae resulting from algal colonization is rarely observed. Skeletal debris observed in thin-section includes ostracodes, gastropods, and rare sponge spicules. Hexactinellid sponges were probably rather prolific, and their spicules are believed to have been a primary source of diagenetic silica.

Outer shelf facies are muddy and contain occasional crinoid-bryozoan bioherms. The biohermal deposits are scattered and poorly exposed in comparison to the deposits which are known to occur in the St. Joe or Reeds Spring Members.

Regressing conditions caused the Short Creek shoal to prograde onto the platform occupied by the Joplin Member, and itself be buried by prograding lagoonal sediments of the Baxter Springs Member. There is, therefore, contemporaneity of deposition of parts of these three members.

Petrography of the Short Creek

The Short Creek Oolite is a very well-sorted oolitic calcarenite. Mud has been winnowed away as a result of the high energies of ooid formation, and the sediment is best classified as an oolitic grainstone or an oosparite.

The ooids are very evenly sized at 0.5mm, and commonly nucleate about pelmatozoan debris. Uncoated pelmatozoan fragments usually exhibit well-developed syntaxial calcite cements. Non-coated skeletal debris comprises only a small percentage of the bulk volume of the sediment, but pelmatozoan, bryozoan, brachiopod, gastropod, and bivalve debris are fairly common. Rarely observed fragments include foraminifera, ostracodes, spicules, and trilobites. A trace of quartz silt occurs in every sample examined.

Ooid cortical fabrics are variable and individual cortices may exhibit concentric, tangential, or composite structures. Researchers have, for some time, explored the notion that cortical fabrics may represent a reflection of the original mineralogy of the ooid, or the hydrodynamic conditions of its formation. One current hypothesis proposes that the cortical fabric of the ooid is an excellent indication of its energy of formation, though not a valid means of determining the original mineralogy.

Ooids of the Short Creek are believed to have formed under variable hydrodynamic conditions; radial fabrics develop in lower energy settings during the time when the particle is small, while concentric fabrics develop during periods of higher energy from particles large enough to fall from suspension or collide with one another. A composite fabric indicates exposure to both regimes; in all cases where a composite fabric exists, the radial fabric occurs in the center of the cortex, and the concentric fabric occurs near the outer margin of the cortex.

Primary porosities of the sediment have been almost totally occluded as a result of pervasive cementation by calcite. Several cement morphologies have been identified, and include a sporadic early, isopachous cement, a later generation of equant and syntaxial cements, and a late series of calcite and dolomite cements associated with deep burial. Secondary, oomoldic porosity is sparsely but, apparently, widely developed in the sediment as a result of very late exposure to meteoric fluids.

Diagenesis of the Short Creek

Diagenetic modifications of the Short Creek sediment began soon after deposition with the precipitation of a thin, isopachous calcite cement. Precipitation occurred in the marine phreatic zone, sporadically, to yield an originally calcite cement. This sparsely developed cement appears to have reduced the effects of mechanical compaction during shallow burial of the sediment.

The shallow burial history of the oolitic sediment is closely tied to that of the overlying lagoonal muds. The products of early biogenic diagenesis in the lagoonal muds were delivered to the oolite during dewatering of the mud. High concentrations of organic molecules retarded the precipitation of $CaCO_3$ in both the muddy and the oolitic facies. These organic constituents probably accelerated the replacement of $CaCO_3$ by silica, with both the organic constituents and the silica largely derived from the dewatering lagoonal muds. Occasional pyrite was precipitated in the Short Creek at this time, and the formation of glauconite also began.

The production of organic constituents declined later in the period of shallow burial allowing $CaCO_3$ to supersaturate the solution. As a result, extensive calcite cementation occurred in the form of equant and syntaxial cements. These cements are responsible for the occlusion of almost all primary porosity.

Later in the history of the sediment, sub-vertical fractures were developed. These fractures are commonly filled by a late generation of cements which include ferroan and non-ferroan calcites, and baroque dolomite.

Exposure to meteoric fluids undersaturated with respect to $CaCO_3$ has become responsible for the creation of secondary, oomoldic porosity. These fluids were probably introduced by way of very late fractures formed through overburden releases or subsidence resulting from the dissolution of underlying strata.

Future Research

A great deal of work remains to be completed in the area. This work need not be limited, of course, to problems concerning the Short Creek Oolite Member of the Boone Formation, or even the Boone Formation itself. Perhaps the greatest hinderence to a more complete understanding of the geology in the area is the lack of mapping which has been done. This author proposes that mapping of the Boone Formation in the tri-state area be completed by mapping the members of the Boone Formation described by McKnight and Fischer (1970) in the USGS Professional Paper 588.

Once mapping is completed, the author proposes a thorough revaluation of Mississippian stratigraphy and correlation in the area, in light of modern concepts of facies development and distribution. The author suspects that the introduction of these modern concepts, along with strong biostratigraphic evidence, will serve to make sense of problems which have plagued workers for many years.

Still another problem which exists in the author's opinion is the underestimation of structural complexity observed in the area. The very small angles of regional dip may belie a structural complexity which has been misinterpreted by many early workers. Although fault and fold trends are distinct and conspicuous, only the work of Patterson (1986) has suggested a genetic relationship with wrench-faulting; it is the author's opinion that modern concepts of wrench-fault tectonics may explain some structural peculiarities which have heretofore been unsatisfactorally explained.

A great deal of work remains, obviously, in the study of petrography and diagenesis of the Boone Formation strata. Attention should be paid to an understanding of these aspects and, in particular, how they are related to facies development and the sedimentary environment.

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