

**KANSAS GEOLOGICAL SURVEY  
OPEN-FILE REPORT 83-29**

**DIAGENESIS OF MIDDLE CREEK AND BETHANY FALLS LIMESTONES,  
SWOPE FORMATION, UPPER PENNSYLVANIAN (MISSOURIAN),  
MIDCONTINENT NORTH AMERICA**

by

David Allen Nollsch

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SWOPE FORMATION, UPPER PENNSYLVANIAN (MISSOURIAN),  
MIDCONTINENT NORTH AMERICA

by

David Allen Nollsch

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science in Geology  
in the Graduate College of  
The University of Iowa

December, 1983

Thesis supervisor: Professor Philip H. Heckel

Graduate College  
The University of Iowa  
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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MASTER'S THESIS

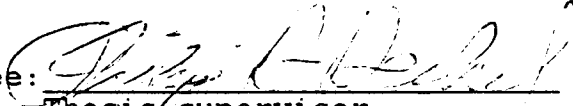
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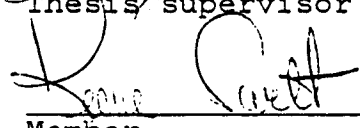
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## ACKNOWLEDGMENTS

Many people aided this thesis project, of whom the following deserve special thanks.

Dr. Philip Heckel suggested and supervised the thesis project and he and committee members Dr. Keene Swett and Dr. Robert Brenner edited the manuscript. Bruce Railsback provided additional samples from locality PLO, and discussions with him, Kim Knight, and Elaine Winfrey on diagenesis and carbonate petrology greatly benefited this thesis. John Groves provided insight into the identification and significance of various algae and encrusting organisms.

Ahmet Dogan contributed his knowledge of SEM operation and sample preparation, and much time educating and aiding the author during research with the SEM. Dr. John Edie directed microprobe analyses. Funding for SEM and microprobe studies was provided by the Graduate College. Ken Schmitz of Northern Illinois University, under the direction of Dr. Gene Perry, performed isotopic analyses utilizing funds from NSF grant EAR7911334. Further analyses were performed by Keith Egan of Oklahoma University with funding from a Shell Oil Fellowship. Dr. R. Sanders Rhodes

advised the author on editing the manuscript on the computer.

The Kansas Geological Survey provided financial support and a vehicle for fieldwork in Kansas, and the Iowa Geological Survey allowed the study of three cores in its possession.

Finally, I would like to thank my wife, Becky, and my family for their encouragement and support throughout the years.

## ABSTRACT

Diagenetic features within the transgressive Middle Creek and regressive Bethany Falls Limestones of the Swope Formation reflect 1) the downward migration of near-surface diagenetic environments during the regression that deposited the Bethany Falls and formed the soil of the overlying Galesburg Shale, followed by 2) the migration back upward of the diagenetic environments during the subsequent transgression that began deposition of the overlying cycle, culminating in the introduction of a deeper-burial connate environment. This reversal is demonstrated by the succession of cements in primary and secondary voids. Primary pores are filled by a generalized succession of: 1) fibrous marine cements, 2) irregular rims of mixing zone dolomite, 3) minor rims of blocky ferroan calcite, probably formed under local reducing conditions developed at the base of the stagnant-saturated meteoric phreatic zone, 4) nonferroan blocky calcite formed in the active-saturated meteoric phreatic zone, 5) return to ferroan calcite, and 6) ferroan dolomite formed in the deeper-burial connate environment. In contrast, secondary solution molds, formed in the undersaturated meteoric phreatic and vadose

environments during maximum regression, are filled only by cements (4), (5), and (6) of the sequence filling primary voids.

The absence of original structures within originally aragonitic grains near the top of the Bethany Falls suggests that meteoric water undersaturated with respect to  $\text{CaCO}_3$  entered this portion of the formation upon exposure, whereas minor preservation of original structures within aragonitic grains throughout the rest of the formation suggests that some meteoric water saturated with respect to  $\text{CaCO}_3$  replaced marine water before the introduction of undersaturated meteoric water lower in the formation.

The apparent leaching of originally aragonitic grains within the transgressive Middle Creek Limestone, the abundance of oomoldic porosity and local solution/collapse fabrics in oolitic grainstones, and the extensive development of meteorically derived microspar mottling, analogous to modern microspar nodules described by Steinen (1982), in wackestones and mudstones in the regressive Bethany Falls Limestone, all reflect extensive meteoric diagenesis of the Swope Formation. Dominance of meteoric diagenesis throughout the formation, occurrence of local caliche and solution channels at the top of the Bethany Falls, and well developed soils within the overlying Galesburg Shale suggest that the regression that closed the

Swope cycle may have been more extreme than that in most, if not all, other Upper Pennsylvanian cyclothem.

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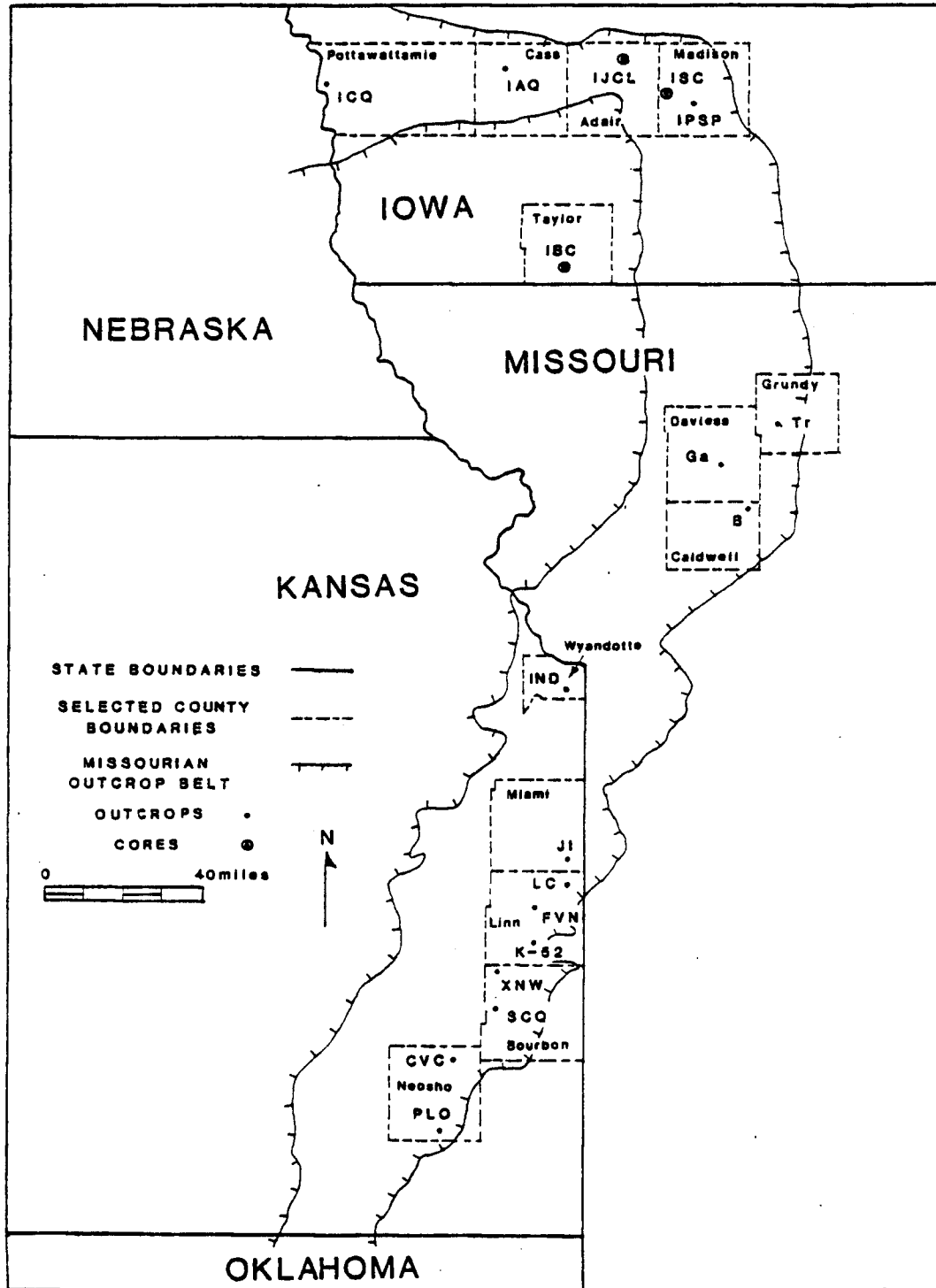
CHAPTER I  
INTRODUCTION

Pennsylvanian Midcontinent Cyclothem

Missourian (lower Upper Pennsylvanian) rocks of the Midcontinent crop out in southwestern and south-central Iowa, northwestern Missouri, and eastern Kansas (Fig. 1). These rocks are characterized by the stratigraphic alternation of laterally persistent sandy shale formations with laterally persistent limestone formations that contain thin shale members. The sequence dips gently westward at 15 to 30 feet per mile (Mossler, 1970).

Moore (1929) discovered the cyclicity of stratigraphic alternation in the Midcontinent and attributed the alternation to periodic widespread submergence by shallow seas. Wanless and Shepard (1936) proposed that the periodic submergence discussed by Moore was caused by eustatic sea-level changes due to the waxing and waning of Gondwanan glaciation. Work by Crowell (1978) demonstrates that Gondwanan glaciation was active throughout the Pennsylvanian and therefore would be a plausible cause of such sea-level fluctuations.

Figure 1. Map of study area showing Missourian outcrop belt and location of outcrops and cores. Exact locations of outcrops and cores are provided in Appendix A. Modified from Heckel (1978, 1980b).



Repetitive sequences of shale and limestone members were regarded as "cyclothems" by Moore (1936). Moore's "megacyclothem" ideally contains seven positional members including five limestones (Moore, 1931, 1936, 1949). Heckel (1977, 1978) proposed the basic eustatic "Kansas cyclothem", to simplify Moore's concept and better describe the more commonly occurring cyclothem in the Missourian, which rarely contain Moore's (1931) "lower", "super", or "fifth" limestones. The basic eustatic "Kansas cyclothem", as described by Heckel (1980a, p.200), comprises an ascending sequence of four positional members: 1) Outside Shale: a thick, sandy, nearshore to nonmarine shale, 2) Middle Limestone: a thin transgressive limestone, typically skeletal calcilutite, 3) Core Shale: a thin non-sandy offshore shale, commonly with a black phosphatic facies, 4) Upper Limestone: a thick regressive limestone typically skeletal calcilutite grading upward to various calcarenite and shoreline facies; 1) the Outside Shale repeated (Fig. 2). Heckel (1977) suggested that the outside shale represents the time of greatest regression, whereas the black phosphatic facies within the core shale, formed in anoxic bottom water below a circulation-restricting thermocline, and represents the time of greatest transgression. It should be noted that Zangerl and Richardson (1963) and most recently Merrill (1975) have

suggested that the black shales were deposited beneath algal "flotants" in a nearshore or lagoonal setting. However, Heckel's (1977) interpretation of the core shales based on the great lateral extent of the black shale facies, lithology, algal and invertebrate distributions, and conodont distributions (Heckel and Baesemann, 1975), is more convincing, and is supported by Schutter's (1983) study of clay mineralogy within both outside and core shales.

Heckel's (1977) basic eustatic "Kansas cyclothem" is applicable throughout the Midcontinent in Kansas, Missouri, Iowa, and Nebraska. Heckel's terminology for cyclothem will be used in this study.

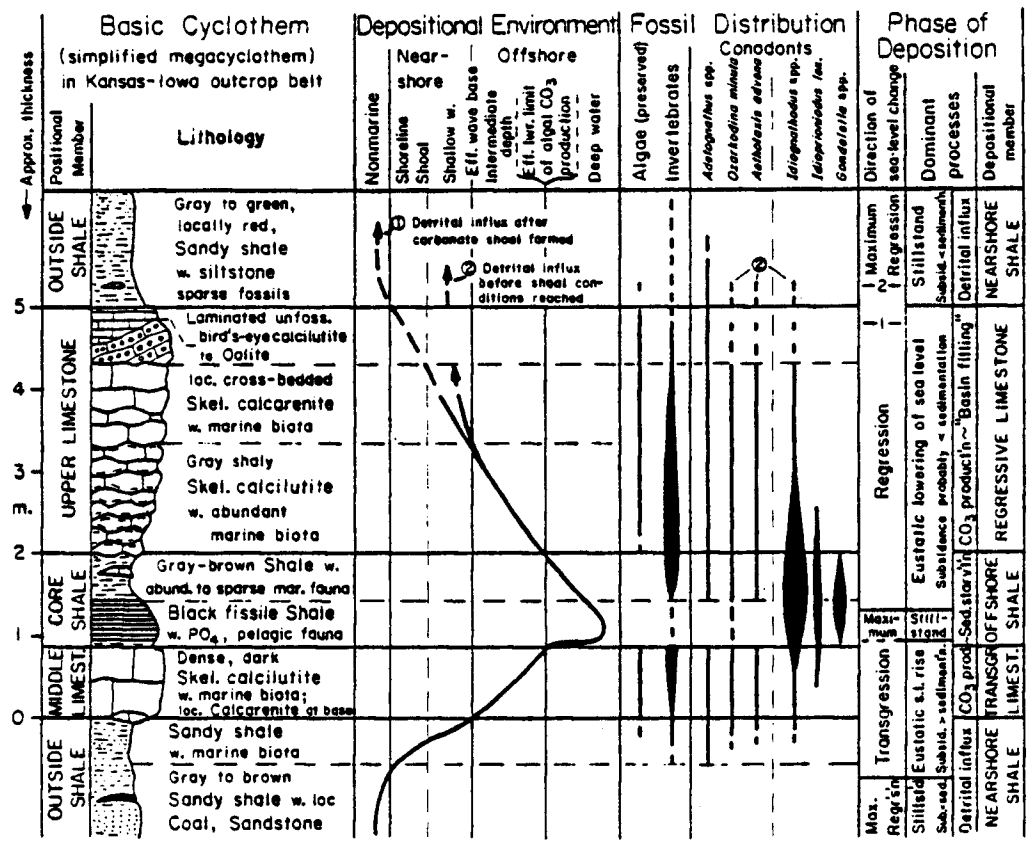
### Swope Formation

#### Stratigraphy

The Swope Formation, the subject of this study, and underlying Ladore Shale compose the middle of three cyclothem within the Bronson Subgroup at the base of the Kansas City Group (Fig. 3). The Swope Formation consists of three members, in ascending order: 1) Middle Creek transgressive limestone, 2) Hushpuckney offshore shale, 3) Bethany Falls regressive limestone.

The Swope Formation is underlain by the Ladore Shale, a nearshore to nonmarine "outside" shale, and underlies the terrestrial Galesburg Formation consisting of soil profiles

Figure 2. The basic eustatic "Kansas cyclothem" from Heckel 1977. Shows positional members, general lithologies, depositional environments, and phases of deposition of Upper Pennsylvanian cyclothems.



Basic Cyclothem  
(simplified megacyclothem)  
in Kansas-Iowa outcrop belt

Approx. thickness  
Positional Member

Lithology

Depositional Environment

Fossil Distribution

Phase of Deposition

Nonmarine  
Near-shore  
Shoreline Shoal  
Shallow w. Eff. wave base  
Intermediate  
Eff. lwr. limit of algal CO<sub>2</sub> production  
Deep water

Algae (preserved)  
Invertebrates  
Conodonts  
*Atrypa* spp.  
*Ozarkolina minima*  
*Atrypa edwardsi*  
*Idiogoniatites* sp.  
*Goniatites* spp.

Direction of sea-level change  
Dominant processes  
Depositional member

5  
4  
3  
2  
1  
0

OUTSIDE SHALE  
UPPER LIMESTONE  
CORE SHALE  
MIDDLE LIMESTONE  
OUTSIDE SHALE

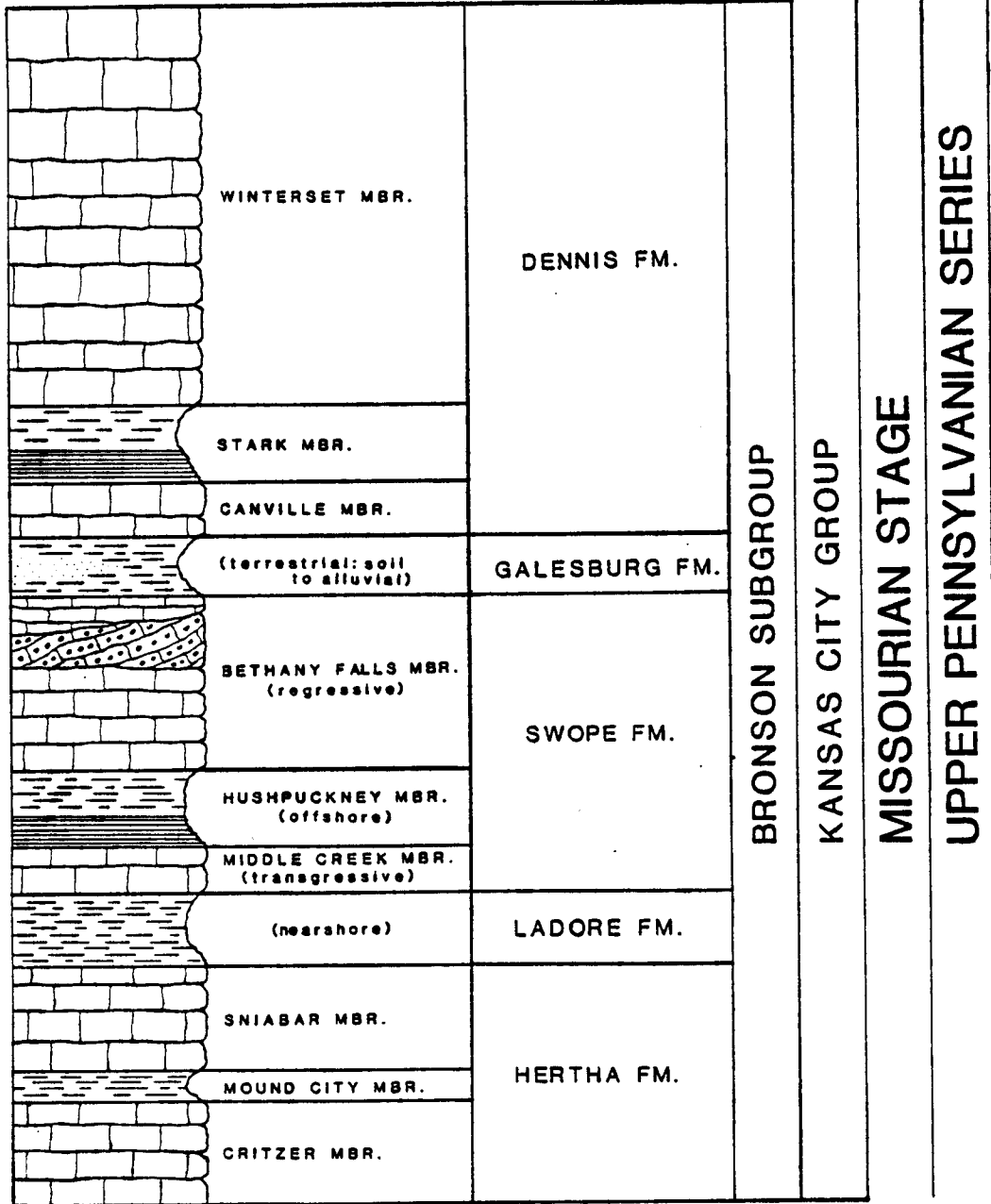
Gray to green, locally red, sandy shale w. siltstone sparse fossils  
Laminated unfoss. bird's-eye calcilutite to Oolite  
loc. cross-bedded Skel. calcarenite w. marine biota  
Gray shaly Skel. calcilutite w. abundant marine biota  
Gray-brown Shale w. abund. to sparse mar. fauna  
Black fissile Shale w. PO<sub>4</sub>, pelagic fauna  
Dense, dark Skel. calcilutite w. marine biota; loc. Calcarenite at base  
Sandy shale w. marine biota  
Gray to brown Sandy shale w. loc. Coal, Sandstone

Detrital influx after carbonate shoal formed  
Detrital influx before shoal conditions reached

Algae (preserved)  
Invertebrates  
Conodonts

Maximum of Regression  
Regression  
Eustatic lowering of sea level  
Subsidence probably = sedimentation  
Basin filling  
Stillstand  
Detrital influx  
Maximum of Regression  
Regression  
Eustatic lowering of sea level  
Subsidence probably = sedimentation  
Basin filling  
Stillstand  
Detrital influx  
Transgression  
Eustatic s.t. rise  
Subsidence probably = sedimentation  
Detrital influx CO<sub>2</sub> prod.  
Basin filling  
Stillstand  
Detrital influx  
NEARSHORE SHALE  
REGRESSIVE LIMESTONE  
TRANSGR OFFSHORE SHALE  
LIMEST.  
NEARSHORE SHALE

Figure 3. Stratigraphic column of the Bronson Subgroup. Shows stratigraphic nomenclature and gives basic environmental interpretation for members of the Swope and for overlying and underlying shale formations. Modified from Moore (1948).



and alluvium with local calichified horizons (Schutter, 1983).

#### Previous Work

The Middle Creek Limestone, Hushpuckney Shale, and Bethany Falls Limestone were grouped together in the Swope Formation by Moore (1936), when he reorganized the Bronson Subgroup.

Many general studies of Pennsylvanian cyclothem, including Heckel and Cocke's (1969) discussion of phylloid algal mound complexes and Hamblin's (1969) study of paleocurrents in calcarenites, included study of the Swope along with many other formations.

Payton (1964, 1966) carried out the first detailed petrologic study of the Swope Formation, along with the overlying Dennis Formation, in Missouri and Iowa. Mossler (1970, 1973) studied the petrology of the Swope in eastern Kansas and divided it into four major lithologic facies: 1) biomicrite facies, 2) mottled biomicrite facies, 3) oolite-pelletoid facies, 4) algal mound facies. These four major lithologic facies are readily distinguished petrographically and serve as a useful framework for the study of the Swope.

Early work on diagenesis of the Swope Formation was done by Mossler (1970, 1971), who determined a paragenetic

sequence of replacement by pyrite, sphalerite, calcite, dolomite, silica, kaolinite, and dickite within the rock. He emphasized dolomitization in the Swope, which did not conform to the syndepositional models of the time. Mossler did not, however, interpret the diagenetic environments in which these minerals formed. Scott (1970) discussed sedimentation and diagenesis of the Bethany Falls limestone, and most recently Watney (1980) discussed freshwater diagenesis in subsurface zones, including that equivalent to the Swope in western Kansas.

#### Depositional Facies

The carbonate members of the Swope Formation contain five general depositional facies. These include: 1) an algal wackestone to boundstone facies at the southern extent of the Middle Creek, 2) a skeletal wackestone facies throughout the rest of the Middle Creek and in the lower Bethany Falls, 3) an oolitic to pelletal grainstone facies in the upper Bethany Falls in Kansas and Missouri, 4) an osagia grainstone facies in the upper Bethany Falls in Iowa, and 5) a rubbly to laminated, locally birdseye-bearing, mudstone facies occurring along most of the outcrop belt at the top of the Bethany Falls (Fig. 4). These five depositional facies will be referred to throughout this study. Distribution of depositional facies within the Swope

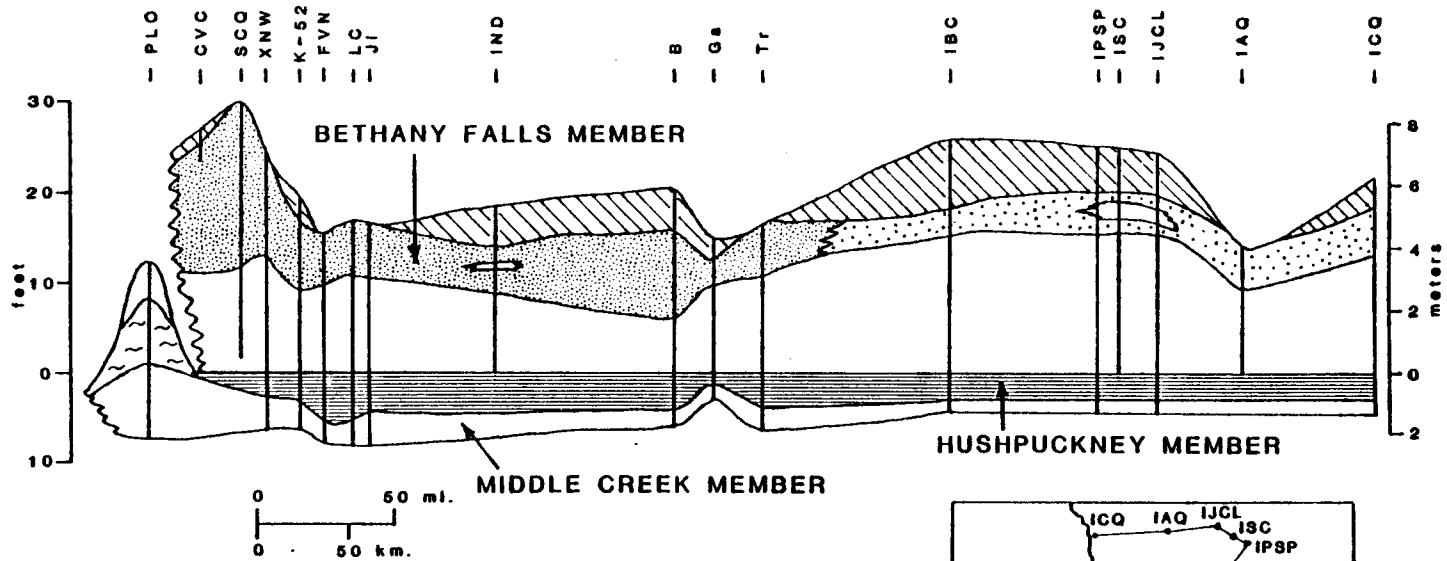
is typical of that described by Heckel (1977) for the basic Kansas cyclothem in his northern shoreward, open marine, and phylloid-algal-mound facies belts.







The five depositional facies given above are similar to those described by Mossler, who used Folk's (1959) classification, with the following exceptions: 1) The rubbly mudstone facies, treated separately in this study, was included in Mossler's biomicrite facies. 2) The skeletal wackestone facies includes both Mossler's biomicrite and mottled biomicrite facies. 3) The osagia grainstone facies did not occur in Mossler's study area and was therefore omitted by him. 4) A modification of Dunham's (1962) classification will be used in this study, rather than Folk's classification, because of the significance of original depositional fabrics as a limiting factor to what diagenetic textures may develop (e.g., moldic porosity will not develop in a barren mudstone no matter what pathway diagenesis takes).

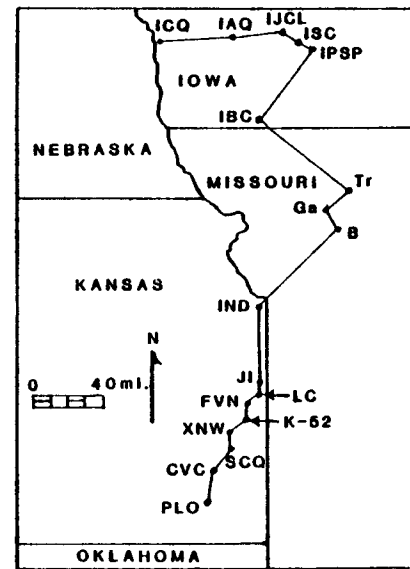
#### Purpose of Study

The purpose of this study is to apply recent advances in concepts of carbonate diagenesis to the Swope Formation, in order to decipher the diagenetic patterns within its carbonate members. The objectives are: 1) to determine the paragenetic sequences in samples at the individual

Figure 4. Stratigraphic cross-section of the Swope Formation showing major depositional facies. Vertical lines show extent of measured sections at each locality. Datum is top of Hushpuckney Shale Member, except at PLO. Compiled from Mossler (1970, 1973), Payton (1964, 1966), and author's field notes.



-  Rubbly Mudstone
-  Osagia Grainstone
-  Oolitic Grainstone
-  Skeletal Wackestone
-  Gray to Black Shale
-  Algal Boundstone



localities, 2) to interpret the diagenetic environments for various stages of diagenesis, 3) to describe and interpret different diagenetic fabrics and patterns within the depositional facies of the Swope, 4) to synthesize diagenetic patterns from all depositional facies in order to determine the history of migration of diagenetic environments through the Swope, 5) to test Heckel's (1983) model for carbonate diagenesis in Upper Pennsylvanian cyclothems, and 6) to determine trends in paleotopography through analysis of differences in diagenetic environments at different localities.

### Methods

#### Field

Stratigraphic sections at fifteen outcrops of the Swope Formation were measured using a hand level and Jacob's Staff (Fig. 1). Outcrops were selected for completeness of Swope exposure and even distribution along the outcrop belt of the Swope. Samples were collected at one foot (~30 cm.) intervals and at lithologic contacts.

#### Laboratory

Two hundred twenty thin sections and a number of polished slabs were prepared from samples of Middle Creek and Bethany Falls Limestones from the fifteen outcrops and three Iowa cores (Fig. 1).

All thin sections were studied with a polarizing petrographic microscope. About 75 selected thin sections were stained with alizarin red-S and potassium ferricyanide, using techniques described by Dickson (1965). Approximately one hundred thin sections with significant amounts of spar were studied with a Nuclide ELM-2A cathodoluminoscope operated between 9 and 12 kilovolts, with vacuum pressure between 50 and 90 millitorr, and with a beam current of 0.5 milliamps. Several thin sections were polished, and chemical analyses were obtained utilizing wavelength dispersive spectrometry (WDS) with an ARL EMX-SM electron microprobe operated at 15 kilovolts with a beam current of 200 nanoamps.

Selected samples were studied with a Scanning Electron Microscope (SEM) using both image and X-ray capabilities. SEM samples were either polished with 600 grit and ultrasonically cleaned, or freeze-fractured using liquid nitrogen. All SEM samples were coated with gold and palladium.

Twenty-five whole rock analyses of carbon and oxygen isotopes were performed by Mr. Keith Egan of Oklahoma University, and six carbon and oxygen isotope analyses were performed by Mr. Kennen Schmitz of Northern Illinois University. Samples for isotopic testing were washed in acetone, rinsed with distilled water and ultrasonically

cleaned to remove any organic residue resulting from contamination by kerosene-cooled rock saws. This washing process was then repeated and samples were allowed to dry at room temperature (heating may change the ratio of stable isotopes by allowing lighter isotopes to escape). Samples were then powdered with mortar and pestle, weighed, and packaged in glassine envelopes for shipment. Before powdering each sample, the mortar and pestle were cleaned thoroughly by grinding half of a glass coverslip and rinsing with distilled water.

#### Major Diagenetic Environments

Early work by Bathurst (1958, 1959) concentrated on description of diagenetic textures. Later works by Folk (1965, 1974) and Bathurst (1975) linking description and process were major steps forward in the study of carbonate diagenesis. Longman (1980) summarized carbonate diagenesis by describing four major near-surface diagenetic environments: marine phreatic, mixing zone, meteoric phreatic, and meteoric vadose, each of which produce characteristic diagenetic textures (Fig. 5). Zones within these diagenetic environments are based on inferred water circulation and saturation of water with respect to calcium carbonate. Application of Longman's diagenetic environments provides a means of understanding hydrologically controlled

diagenetic histories of carbonate sequences beyond simply reporting observed paragenetic sequences. Longman's (1980) four near-surface diagenetic environments and a fifth deeper-burial connate environment (Heckel, 1983; Longman, 1981) are briefly discussed below.

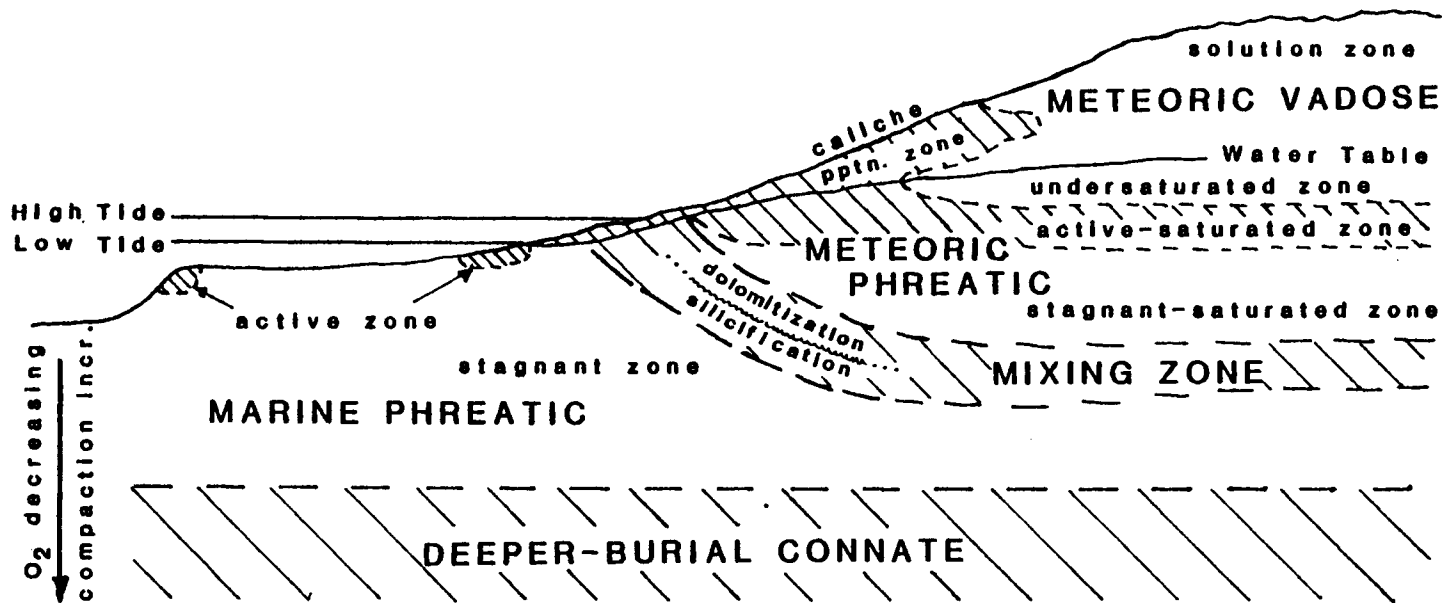
#### Marine Phreatic

In the marine phreatic environment all pores are filled with normal marine water. The marine phreatic environment may be divided into two zones on the basis of water circulation. The active zone has good water circulation near the sediment/water interface allowing much intergranular and cavity-filling cementation by isopachous fibrous aragonite and high magnesium calcite. Folk (1974) suggested that the fibrous crystal habit of calcite cements in the marine phreatic may be due to magnesium poisoning of sideward growth in the crystal lattice. The stagnant zone has poor water circulation, thus restricting cementation while allowing significant micritization of grains by boring organisms. There is a complete gradation between the active and stagnant zones within the marine phreatic environment.

#### Mixing Zone

The mixing zone is an environment between the marine phreatic and meteoric phreatic environments where pores are filled with a mixture of meteoric and marine waters. Bladed

Figure 5. Major diagenetic environments in a partly emergent carbonate terrain. Lined zones show where significant cementation occurs. Modified from Heckel (1983).



high magnesium calcite cementation (Longman, 1980) and silicification (Knauth, 1979) may occur within the mixing zone where the water is relatively marine (35-75% marine; Knauth, 1979). Where salinities are lower, in a range of 5-30% marine water, dolomite may replace calcite (Badiozamani, 1973). The formation of high magnesium calcite, silica, and dolomite within the mixing zone all are aided by greater water circulation and prolonged exposure of a sequence to mixing zone salinities.

#### Meteoric Phreatic

The meteoric phreatic environment lies below the terrestrial water table where all pores are filled with meteoric water. The meteoric phreatic may be divided into three zones on the basis of water circulation and calcium carbonate saturation. The undersaturated zone lies at the top of the meteoric phreatic where water introduced from above remains undersaturated with respect to calcium carbonate and causes solution of unstable grains. The active saturated zone has good circulation of pore waters saturated with calcium carbonate resulting in both extensive cementation by blocky calcite, coarsening toward pore centers, and neomorphism of unstable grains. The contact between the undersaturated and active saturated zones is gradational and includes conditions where aragonite may be

dissolved while calcite is precipitated. The stagnant saturated zone has poor circulation that restricts cementation, and this zone is characterized by neomorphism of unstable grains.

#### Meteoric Vadose

The meteoric vadose environment lies above the water table where both air and water fill pores. The meteoric vadose may be divided into a solution zone and a precipitation zone. In the solution zone, water undersaturated with calcium carbonate combined with atmospheric carbon dioxide dissolves unstable grains and enhances original pores to form molds and vugs. Locally within the meteoric vadose environment, zones of precipitation form where water becomes saturated with calcium carbonate, causing the precipitation of fine equant calcite in the form of meniscus or pendent cements. In more arid climates, caliche crusts may form at or below the surface of exposure due to evaporation and biologic processes.

#### Deeper-burial Connate

Heckel (1983) recognized compactional and cement characteristics of a deeper-burial connate environment. Within this environment high lithostatic pressures overpack uncemented calcarenites, with pressure solution occurring

along grain contacts, and pore water is squeezed from carbonate muds to form widespread stylolites. With increased depth of burial, reducing conditions prevail as organic matter decomposes, which allows ferroan calcite and dolomite cements to form.  $Mg^{++}$  released from clays and high magnesium calcite goes into the formation of dolomite, while aragonite and high magnesium calcite grains and cements are neomorphosed to equant blocky calcite.

#### Diagenetic Model for Pennsylvanian Cyclothem

Heckel (1983) combined the five major diagenetic environments discussed above with the hydrologic implications of his depositional interpretation (Heckel, 1977, 1980a) to create a generalized diagenetic model for the carbonate rocks in Pennsylvanian Midcontinent cyclothem. Migration of diagenetic environments through a cyclothem sequence were controlled by eustatic sea-level changes (Fig. 6). Transgressive limestones, offshore shales, and regressive limestones were all deposited in the marine phreatic environment. After deposition of the regressive limestone in a cycle, continued regression caused the downward migration through the sequence of first the mixing zone, and later the meteoric phreatic and meteoric vadose environments, as the overlying nearshore to nonmarine shale was deposited during maximum regression. With renewed

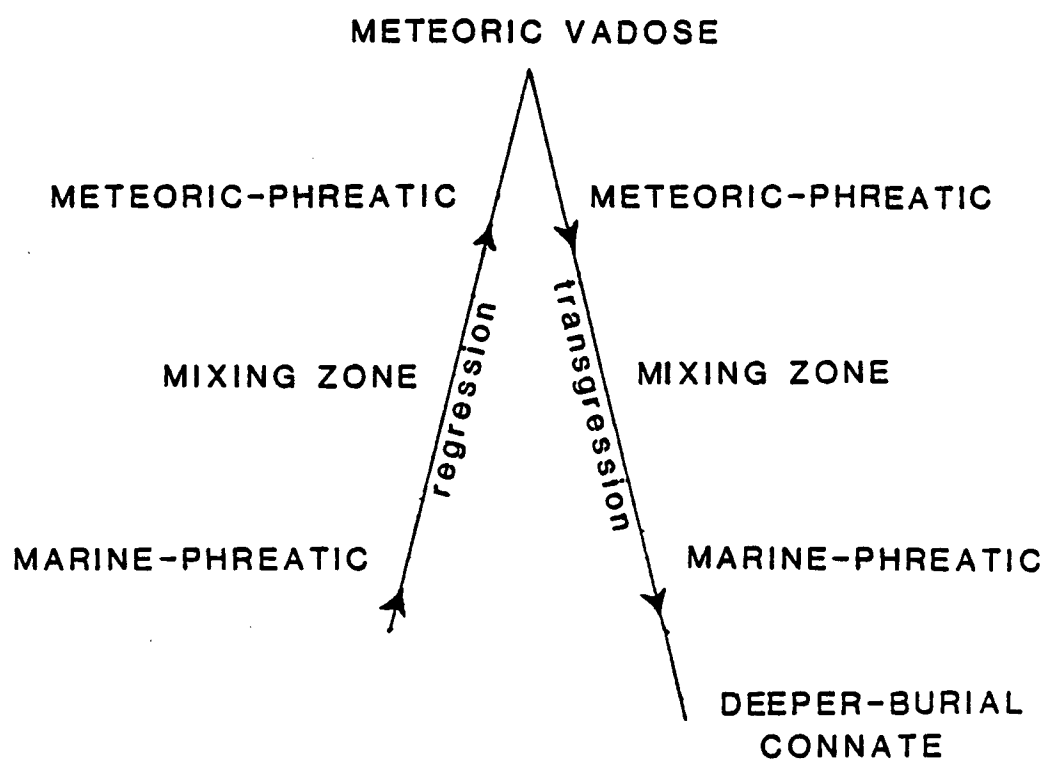
transgression and deposition of the transgressive limestone and offshore shale of the overlying cyclothem, the diagenetic environments migrated back upward through the original sequence in reverse order until the deeper-burial connate environment was introduced. The sequence was probably unaffected by regression of the seas during deposition of the regressive limestone of the overlying cyclothem, due to the thickness of overlying sediment, and likely remained in the deep-burial connate environment until recent exposure.

Considering this hydrologic setting it is important to note that: 1) the extent of the sequence reached by various diagenetic environments may vary greatly, as all environments may not have migrated through the entire sequence of rock, 2) a particular diagenetic environment may have passed through the same portion of the sequence twice (once during regression and again during the next transgression), and 3) the effect upon the sequence by various diagenetic environments would depend greatly on the rates of migration and the period of exposure to each environment.

According to Heckel's (1983) model, transgressive limestones should show pervasive overpacking of grains, discernible neomorphism of originally aragonitic grains, and ferroan calcite and dolomite cements. These characteristics

Figure 6. Migration of diagenetic environments in eustatic cyclothem setting. Migration of diagenetic environments during regression is reversed as transgression begins deposition of overlying cyclothem.

# MIGRATION OF DIAGENETIC ENVIRONMENTS



suggest movement of the transgressive limestones from the marine phreatic environment into a deeper-burial connate environment, and undergoing substantial compaction before lithification. In contrast, regressive limestones should show early marine cement rims, large-scale leaching of originally aragonitic grains, subsequent collapse of micrite envelopes, pervasive blocky calcite cementation, and filling of remaining voids by ferroan calcite and dolomite cements. These characteristics suggest the replacement of marine phreatic water by meteoric phreatic water, and possibly subaerial exposure, followed by movement back through the mixing zone or into the deeper-burial connate environment. In this model the offshore shale acts as an impermeable "seal" preventing meteoric waters from reaching the underlying transgressive limestone during regression.

CHAPTER II  
DESCRIPTION OF CARBONATE  
DIAGENESIS IN DEPOSITIONAL  
FACIES

This chapter describes diagenetically significant features and fabrics, such as grain preservation, cementation, and porosity, within each of the five major depositional facies of the Swope. Only basic interpretations will be made when they facilitate description; more elaborate interpretations of diagenesis within the Swope are discussed in Chapter V.

Paleontologic identification of grains are only as specific as is useful for this study, and generally are not carried below class level. Familial and generic identification are attempted only when differentiation at those levels becomes diagenetically significant, as is the case for algae. Due to the lack of preserved structure in green codiacean and many red algae, the term "phylloid" is used in this study, as suggested by Pray and Wray (1963), to encompass all indistinguishable leaflike forms. Phylloid algae within the Swope may include the codiaceans Eugonophyllum, Anchicodium, Ivanovia, Calcifolium, and the ancestral red coralline alga Archaeolithophyllum. When

conceptacles or buds are clearly apparent, Archaeolithopyllum may be distinguished from the codiaceans even though internal features no longer remain.

Silica and other noncarbonate minerals occurring within these facies are discussed in a later chapter. Terminology describing porosity in this study follow Choquette and Pray (1970).

#### Rubbly Mudstone Facies

The rubbly mudstone facies ranges from a very rubbly, roughly laminated, mottled mudstone in Kansas and Missouri to a finely laminated, birdseye-bearing mudstone in Iowa. The rubbly appearance (Fig. 7a) of the mudstone in Kansas and Missouri outcrops is due to weathering of resistant nodules of microspar within a matrix of less resistant shaley lime mud. Microspar nodules are dark gray in outcrop giving a mottled appearance to the rock when contrasted with the light gray matrix. Microspar mottles within the rubbly mudstone facies are similar to mottles found in the skeletal wackestone facies and are illustrated and discussed in greater detail with that facies. Near the top of the rubbly mudstone facies at locality IBC, microspar mottles occur surrounded by shale, suggesting the leaching of the lime mud matrix and downward infiltration of shale from the overlying Galesburg Formation to fill mudcracks and solution vugs

(Fig. 7b). Downward, the mudstone at locality IBC becomes a finely laminated birdseye mudstone typical of the facies at other Iowa localities.

#### Grain Preservation

The rubbly mudstone facies is unfossiliferous and free of grains except at the base where it is transitional with underlying grainstones. Ostracodes, ooids, and rare molluscs and echinoderms occur in limited numbers near the base of the mudstone facies. Originally aragonitic bivalves, gastropods, and ooids within this facies retain no relict structures and are composed of clear blocky calcite or ferroan calcite spar, increasing in crystal size toward the center of the grain, or by ferroan dolomite. Pelletal nuclei within ooids are typically "dropped" into a geopetal position (Fig. 7c). Spar characteristics, dropped nuclei in ooids, and the presence of remaining voids within some originally aragonitic grains strongly suggest that the spar within these grains is filling molds of the original grains.

#### Carbonate Cements

Original porosity within the rubbly mudstone facies was very low, and consisted of sparse intragranular voids within ostracodes, birdseye voids, and mudcracks. Intragranular and birdseye voids are filled by clear blocky calcite, while mudcracks are typically sediment filled. Some small

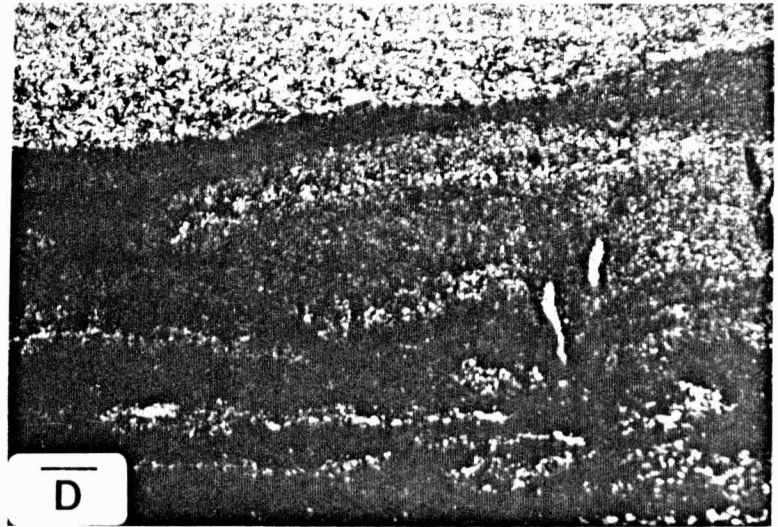
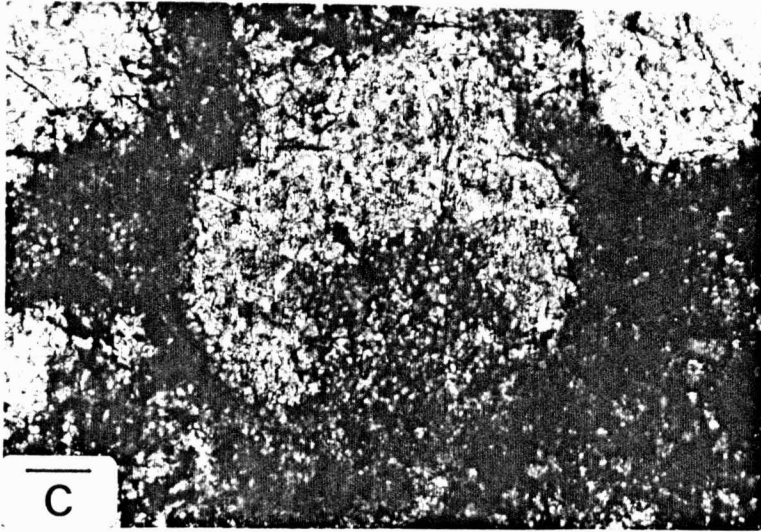
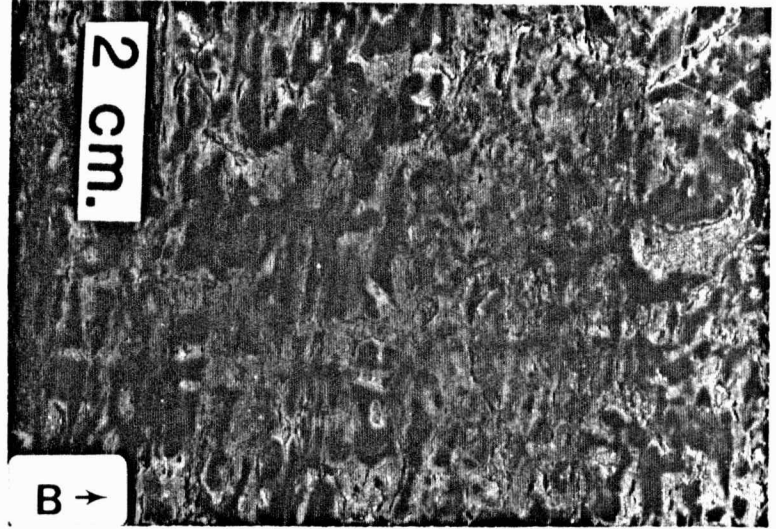
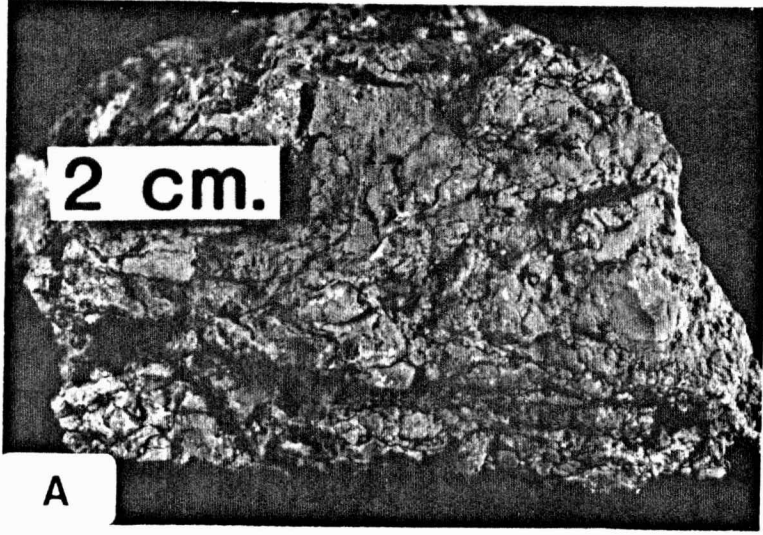
Figure 7. Diagenesis in the rubbly mudstone facies.

a) Rubbly mudstone at top of Bethany Falls at locality IND. Rubbly appearance of this facies in Kansas and Missouri is due to weathering of micritic matrix from around resistant microspar mottles.

b) Shale (light) from overlying Galesburg Formation fills mudcracks and solution vugs in this polished slab of top of rubbly mudstone facies at locality IBC.

c) Pellet nucleus has "dropped" to a geopetal position in this blocky calcite-filled oomold, indicating that ooid cortex was dissolved and resulting oomold filled by void-filling spar. This ooid occurs within a transitional oolitic wackestone at base of rubbly mudstone facies. (Plane-polarized light; Tr 5-t, s; Scale bar = 0.05 mm.)

d) Interbedded laminae of fine rhombs of nonferroan dolomite (dark) and microspar (light) within rubbly mudstone facies in western Iowa. (Plane-polarized light; ICQ 4-1, s; Scale bar = 1.00 mm.)



fractures, possibly mudcracks or syneresis cracks, within the rock are partly filled by possible pendent calcite cements.

Dolomite occurs in two forms in the rubbly mudstone facies. Very fine dolomite rhombs occur in laminae interbedded with microspar (Fig. 7d), and ferroan dolomite (along with lesser amounts of ferroan calcite) fills large vertical fractures and almost all molds.

Original intragranular and birdseye porosity, and the small amount of secondary moldic and fracture porosity have been mostly filled by carbonate cements.

### Osagia Grainstone Facies

#### Grain Preservation

A wide variety of grain types commonly occur as nuclei for osagia grains within this facies, including echinoderms, whole or fragmented gastropods, and fragments of brachiopods, bivalves, phylloid algae, dasycladacean algae, and trilobites. These grains often have fine algal or coarser sponge borings (Fig. 8a) and are micritized to varying degrees, although micritization is typically limited to a thin envelope around the exterior of grains. The laminated osagia coating on almost all grains is dominantly micrite and incorporates abundant encrusting foraminifers. The micritic portion may have been dominantly algal,

although no recognizable Girvanella were seen within the coatings. Generally, the osagia coatings are thicker on smaller grains, which somewhat equalizes overall grain size in the rock.

Abundant point and long contacts between coated grains, horizontal orientation of most elongated grains, and the occurrence of crushed brachiopods and echinoderms (common near the base of the facies) suggest that the sediment underwent compaction before significant cementation (Fig. 8b). Stylolites commonly occur along grain contacts near the base of the facies, rarely cutting across individual grains, and are often associated with large patches of spar where stylolites border the upper and lower boundaries of the spar and converge horizontally away from the spar. The volume-loss which resulted from pressure solution along stylolites may be estimated by the amount of grain destruction along stylolitized contacts, the amount of displacement of individual grains cut by stylolites, and by the amount of insoluble residue along stylolites. Evidence suggests that pressure solution generally removed less than two millimeters of limestone along individual stylolites, although collectively stylolites may represent a significant amount of pressure solution.

Unstable grains within the osagia grainstone facies include originally aragonitic gastropods, bivalves,

Figure 8. Diagenesis of osagia grainstone facies.

- a) Arrow points to sponge boring within a partially silicified brachiopod fragment. (Plane-polarized light; ISC 116.0; Scale bar = 0.50 mm.)
- b) Brachiopod valve (arrow) is crushed within osagia grainstone indicating that some compaction took place before lithification by intragranular cements. (Plane-polarized light; ICQ 2-t; Scale bar = 0.50 mm.)
- c) Osagia-coated dasyclad Paraepimastopora with micrite-filled pores preserved. Remainder of grain has been leached and filled with blocky calcite. (Plane-polarized light; IAQ 3-b; Scale bar = 0.20 mm.)
- d) Structureless gastropod of fine blocky calcite serves as nucleus of osagia grain. Lack of preserved structure and drusy crystal habit of calcite suggest that the gastropod has been leached and then void-filled. (Plane-polarized light; ICQ 3-4a; Scale bar = 0.20 mm.)
- e) Occurrence of same blocky calcite spar in both a broken, coated mollusc fragment (above A) and intergranular pores suggest early leaching of mollusc fragment and later void-filling of mold. Large mollusc fragment (B) contains a preserved central layer in an otherwise structureless grain. (Plane-polarized light; IBC 530.5; Scale bar = 0.50 mm.)
- f) Fragment of bivalve consisting of an outer ribbed layer of nonferroan calcite (C), which has been neomorphosed preserving detailed lamellar structure, and an inner leached layer filled by structureless clear blocky ferroan calcite (F). (Plane-polarized light; ISC 112.6, s; Scale bar = 0.50 mm.)
- g) Section of large gastropod mold filled by outer rim of bladed calcite, followed by blocky straight-sided calcite crystals increasing in size toward center of mold. (Cross-polarized light; ICQ 3-4b; Scale bar = 1.00 mm.)

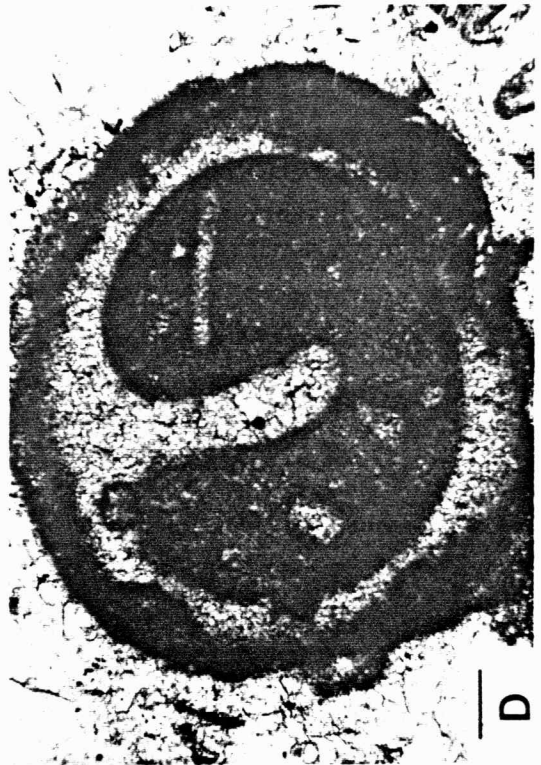
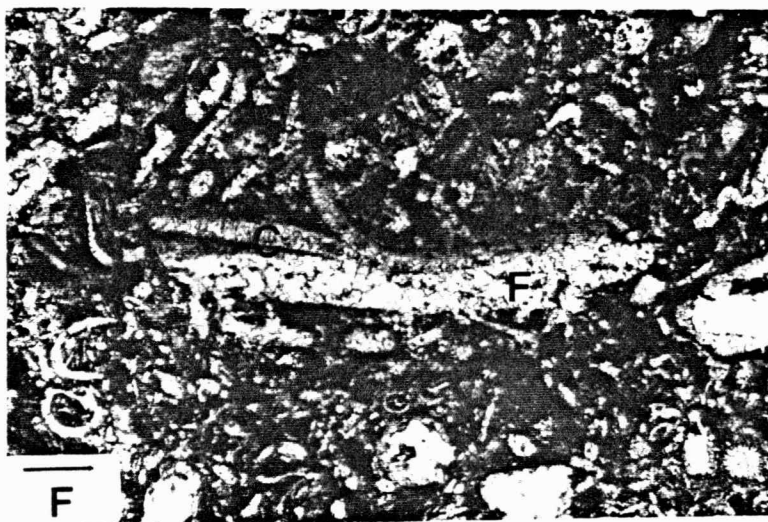


Figure 8  
cont.



fragmented phylloid algae, and dasycladacean algae. Blocky fragments of phylloid algal blades, consisting dominantly of clear blocky ferroan calcite, show no relict structure and were identified by their external shapes preserved by surrounding micrite envelopes and osagia coatings.

Micrite-filled pores of the dasycladacean alga Paraepimastopora (Johnson, 1963; Wray, 1977; J. R. Groves, pers. comm.), are typically well preserved within structureless clear blocky nonferroan or ferroan calcite that composes the remainder of the grains (Fig. 8c). These stout pores resulted from the disarticulation of branches from the central stem, and were open to the outside of the stem providing for their excellent preservation by external micrite filling or fine-grained cementation (Wray, 1977). Paraepimastopora occurs only within the osagia grainstone facies of the Swope where they often form nuclei of osagia grains. Preservation of Paraepimastopora is consistent throughout the osagia grainstone facies.

Preservation of molluscan grains within the osagia grainstone facies is somewhat variable, although generally poor, with grains consisting mostly of structureless blocky calcite (Fig. 8d, e). Relict structures were found within a small percentage of mollusc grains at localities ISC, IPSP, and at the base of the osagia grainstone at IBC. Relict structures commonly consist of a thin poorly preserved outer

layer or less commonly of several preserved inner layers. Rarely, the fine lamellar structure in the outer layer of a mollusc is preserved (Fig. 8f). Preserved layers in some grains have collapsed to a geopetal accumulation or have partially collapsed and are encompassed by clear blocky calcite or ferroan calcite. Preservation of molluscan structures is variable within the same thin section or even between various layers of the same grain. This variability is demonstrated by a bivalve from locality ISC in which the outer layer displays detailed preservation of its structure in nonferroan calcite, whereas the rest of the bivalve consists of structureless clear blocky ferroan calcite (Fig. 8f).

The task of identifying relict structures in molluscan grains was complicated by the abundance of Composita brachiopods, which appear similar to prismatic molluscs. In good samples Composita may be distinguished by an outer lamellar layer and by calcite spires extending into the prismatic layer (Scholle, 1978). However, in abraded or poorly preserved fragments of Composita the outer lamellar layer may be missing or micritized and spires may not occur in smaller fragments, making distinction from prismatic molluscs difficult. In such cases the presence of chalcedony, which preferentially replaces brachiopods throughout the Swope, and the presence of multilayering,

characteristic of molluscs, were used to distinguish Composita and molluscan fragments.

Molluscs throughout most of the osagia grainstone facies display no relict structure, and structureless molluscs are dominant even in thin sections where relict structures are preserved in some molluscan grains. These structureless molluscan grains were identified by gross morphologic characteristics including whorling of gastropods and curvature, tapered ends, and outline of ribs of bivalves. These morphologic characteristics are clearly evident within osagia coatings. Structureless molluscs consist of clear blocky nonferroan or ferroan calcite increasing in crystal size inward and becoming more ferroan in some cases. Thin rims of bladed calcite may occur along the outer edge of structureless grains (Fig. 8g). The characteristics of the spar in structureless molluscs suggest that it is void-filling cement (Bathurst, 1975), requiring the initial solution of molluscan grains followed by spar cement filling the molds preserved within osagia coatings.

#### Carbonate Cements

Original pore space in the osagia grainstone facies included intergranular and intragranular pores. Intergranular pores often have small rhombs of dolomite

scattered along their edges and are commonly filled by either syntaxial overgrowths of ferroan calcite on echinoderms or by clear blocky ferroan or nonferroan calcite. Syntaxial overgrowths commonly penetrate the osagia coating around echinoderms, extending well beyond the coating, and may even fill intergranular pores around several grains producing a poikilotopic texture within the rock. Syntaxial overgrowths on echinoderms are the dominant intergranular cement near the base of the facies, with overgrowths becoming smaller and filling less intergranular pore space upsection even though echinoderm abundance is similar throughout the facies. Clear blocky ferroan, and to a lesser degree nonferroan, calcite crystals fill the remaining intergranular pores near the base of the facies and are the dominant intergranular cement higher in the facies.

Large intragranular pores, such as those within large brachiopods, show the following sequence of cements from void edge to void center: 1) sparse outer rim of scattered dolomite rhombs, 2) thicker layer of ferroan calcite, 3) thin layer of nonferroan calcite, 4) and finally ferroan dolomite or occasionally ferroan calcite at the center. In many smaller intragranular voids, the later cements of this sequence are not present, and commonly there is no clear zonation between ferroan and nonferroan calcite cements but rather a "patchy" mix of the two.

Secondary porosity in this facies consists of molds of aragonitic grains at the core of osagia grains, molds of large uncoated gastropods near the top of the facies at locality ICQ, and of fractures cutting across grains and intergranular cements. Molds of aragonitic grains are filled by bladed to blocky nonferroan and ferroan calcite, as discussed above, with ferroan calcite at the center of molds where the two cements occur together. The excellent preservation of molds of large uncoated gastropods at locality ICQ, suggests that at least partial intergranular cementation of the surrounding osagia grainstone occurred before any solution of aragonitic grains. Fractures are filled by clear blocky ferroan calcite, and virtually no porosity remains in the osagia grainstone facies.

### Oolitic Grainstone Facies

#### Grain Preservation

Unstable grains within the oolitic grainstone facies include originally aragonitic ooids and molluscs. Molluscs are relatively sparse within this facies, occurring scattered among the abundant ooids and locally in lenses of skeletal debris. As in the osagia grainstone facies, preservation of molluscan grains is generally poor, with only a small randomly distributed proportion retaining relict internal layering within irregular crystals of cloudy

calcite. Molluscan grains are typically preserved as molds, often rimmed with hematite or filled with structureless blocky calcite and/or ferroan dolomite.

Preservation of ooids is extremely variable, including unfilled oomolds, cement-filled oomolds, micritized ooids, and ooids with well preserved concentric layering. Ooids typically have pellets as nuclei, although echinoderms and other skeletal fragments less commonly serve as nuclei. Well preserved ooids contain ghost concentric layering throughout a cortex consisting of irregular crystals of cloudy calcite and have centrally located nuclei (Fig. 9a) suggesting aggrading neomorphism (Folk, 1965; Bathurst, 1975). Structureless ooids either remain oomoldic, often rimmed by hematite, or are filled or partially filled by clear blocky calcite or ferroan dolomite, commonly with geopetal nuclei (Fig. 9b), indicating that the spar is void-filling (Bathurst, 1975). Ooids with outer concentric layers preserved around a central void of structureless blocky spar fill, some with dropped nuclei (Fig. 9c), also are common within the oolitic grainstone facies. Structureless blocky spar-filled oomolds or open oomolds with centrally located nuclei usually contain thin "bridges" of preserved cortex connecting the nuclei with the outer edge of the oomold. These thin bridges may extend from all orientations (top, side, bottom) and provide a means of

support for nuclei within oomolds (Fig. 9d). Structureless ooids with centrally located nuclei lacking an apparent means of support could possibly have thin bridges of preserved cortex supporting the nuclei in a third dimension, unobservable in thin section. Structureless ooids and open oomolds lacking nuclei are common, suggesting that their nuclei may have been unstable grains (e.g., mollusc fragments), which were dissolved with the aragonitic cortex. Bipartite or "half moon" ooids (Mossler, 1970; Carozzi, 1963), consisting of "dropped" nuclei and adjacent preserved inner cortex, with blocky spar filling the remaining upper portion of oomolds, are abundant at locality CVC, but were rarely observed at other localities.

Although one of the ooid types described above may dominate a particular thin section, the other common types (excluding bipartite ooids) are generally present. This heterogeneity of ooid preservation on a small scale is demonstrated in Figure 9e, where an ooid with concentric layers preserved in blocky calcite, an oomold filled with structureless clear blocky calcite, one filled with ferroan dolomite, and several open oomolds all occur within a several millimeter square area. In spite of the heterogeneity of ooid preservation, it is possible to classify samples as dominantly structureless (leached), dominantly neomorphosed (structure preserved), or as

Figure 9. Grain preservation in oolitic grainstone facies.

a) Concentric layering is well preserved within the cortex of a neomorphosed ooid (N). A second ooid (S) has only several outer concentric layers preserved, with a blocky calcite-filled center. Rhombs of ferroan dolomite replace part of both the pelletal nuclei and blocky calcite in the second ooid. (Plane-polarized light; JI 2frt, s; Scale bar = 0.20 mm.)

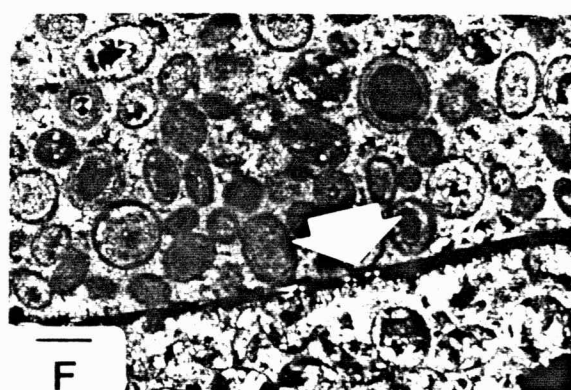
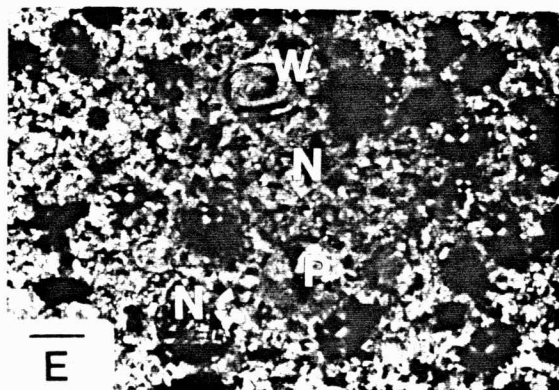
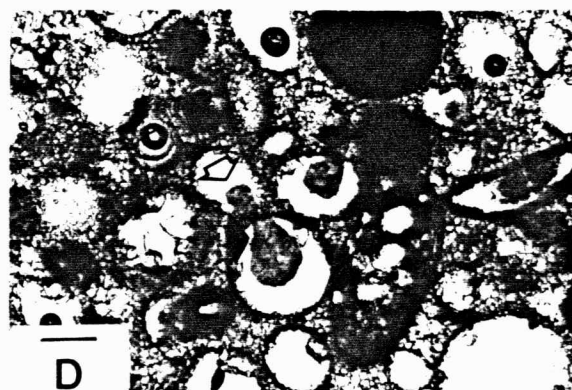
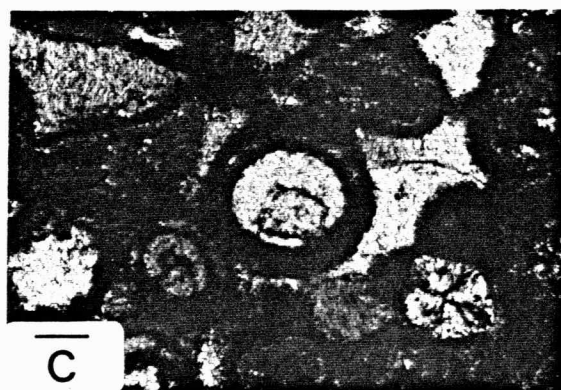
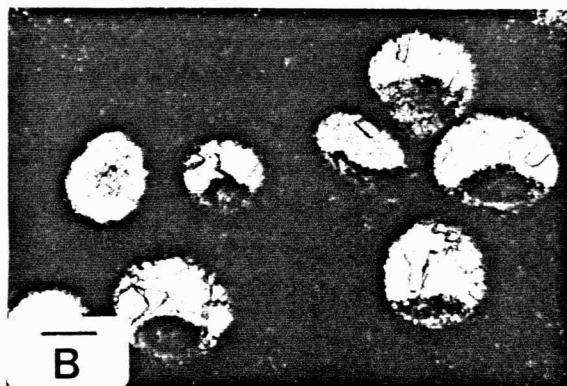
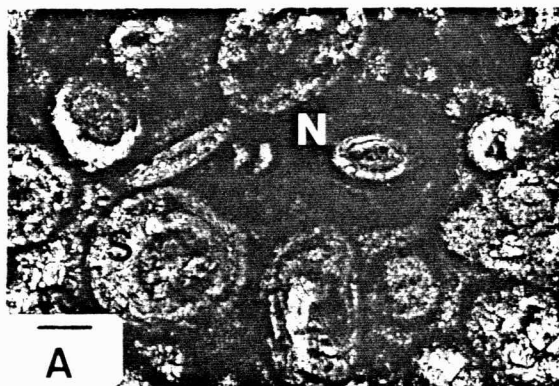
b) Pelletal nuclei in geopetal positions within ooids of structureless blocky calcite indicate a history of leaching of original aragonitic cortex, dropping of nuclei, and later filling of the oomolds by clear blocky calcite. (Plane-polarized light; IND 3-b; Scale bar = 0.20 mm.)

c) Only the outer cortical layers are preserved in the ooid at the center of the photo. The inner cortex has been leached and void-filled by syntaxial overgrowth of dropped echinoderm nucleus. (Cross-polarized light; FVN 2-4, Scale bar = 0.20 mm.)

d) Centrally located nuclei within open oomolds are supported by "bridges" of preserved cortex material (dark arrows). Note that nuclei lacking support is in a geopetal position (open arrow). (Plane-polarized light; B 2-3.5; Scale bar = 0.20 mm.)

e) Heterogeneity of ooid preservation is demonstrated by an ooid with well preserved concentric layering (W), an ooid with only its outer layers preserved (P), and several ooids that have no preserved structure or are now open oomolds (N), all occurring within several millimeters of one another. (Cross-polarized light; SCQ 2-3; Scale bar = 0.50 mm.)

f) Ooids sheltered within a bivalve, with neomorphosed upper valve (off photo) and leached lower valve (arrow), retain relict concentric layering, or, when oomoldic, remain open (upper 2 thirds). Ooids outside the bivalve have been entirely leached and filled by ferroan dolomite (lower third). (Cross-polarized light; CVC 1; Scale bar = 0.50 mm.)



subequal with approximately even amounts of preservation and leaching (often with neomorphosed outer rims and leached centers of ooids). Using this classification, a trend in the occurrence of dominantly neomorphosed ooids appears. At Tr, the northernmost outcrop of the oolitic grainstone facies, significant neomorphism of ooids occurs only near the base of the section, with structureless ooids occurring at the base of the facies and dominating the upper portion of the facies. This zone of significant neomorphism appears increasingly higher in the facies to the south, occurring at the top of the facies at XNW and SCQ (Fig. 10a).

#### Oomoldic Fabrics

Oomoldic porosity is common within the oolitic grainstone facies, and a gradational sequence of different oomoldic fabrics is evident from the top of the facies to the base. Near the top of the oolitic grainstone facies, vugs and enlarged oomolds are common. Vugs are usually irregularly shaped, but their outlines often consist of a number of small curved surfaces suggesting the original presence of a number of oomolds (Fig. 11a) and less commonly bivalve molds.

Lower in the facies the amount of vuggy porosity decreases, and oomolds are typically individual spherical voids within a matrix of intergranular clear blocky calcite (Fig. 11b).

Figure 10. Trends in the oolitic grainstone facies of Bethany Falls Member.

a) Cross section of oolitic grainstone facies. Zone of dominant neomorphism of ooids (oblique lines) occurs increasingly higher within the facies from north to south. Ooids are dominantly leached in blank zones both above and below the neomorphosed zone.

b) Cross section of oolitic grainstone facies showing distribution of zones of crushed oomolds containing collapsed ooids or cement shard fabrics (horizontally lined). Zones of crushing are concentrated near base of facies, with small zones occurring above a lense of wackestone and below the neomorphosed zone at CVC.

c) Zone within oolitic grainstone that retains much oomoldic porosity (stippled area) along the center of facies and generally excludes zones of preservation (oblique lines), zones of crushing (horizontal lines), and top of facies where mold-filling cementation is extensive.

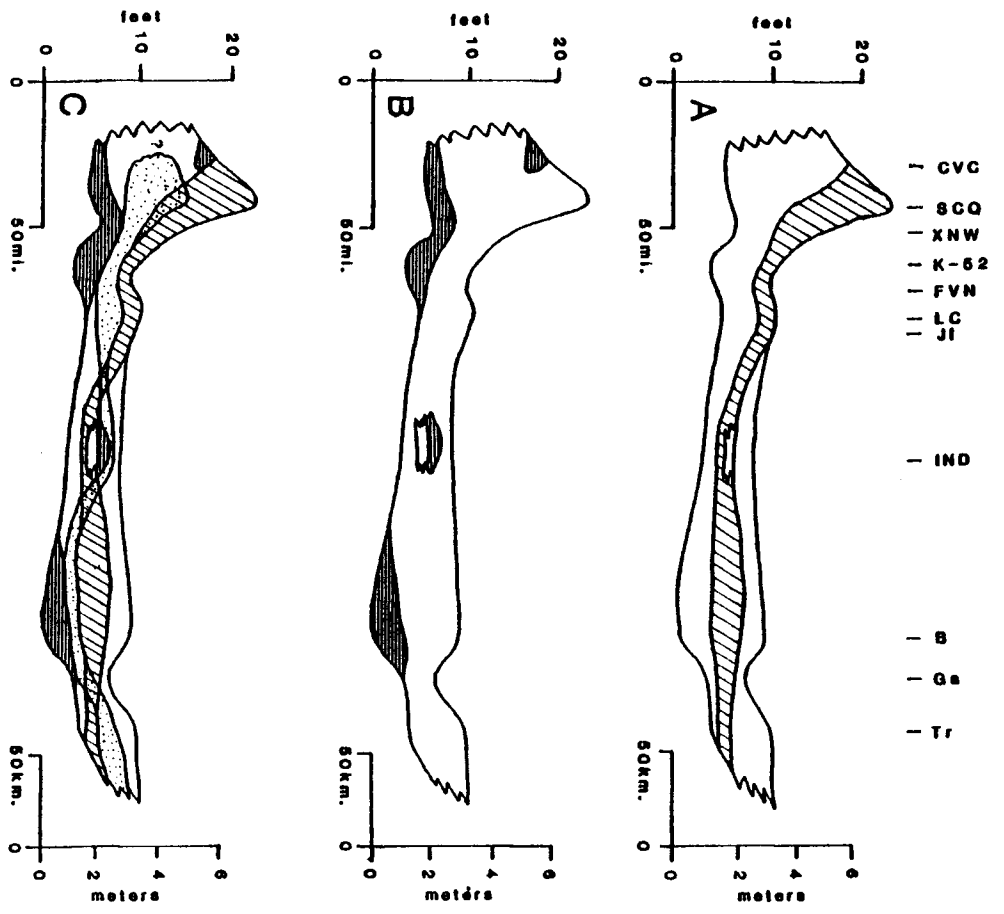
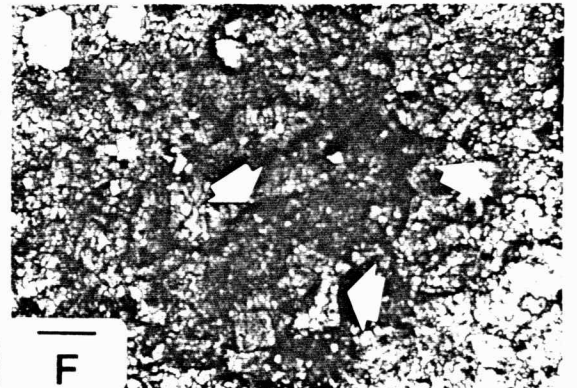
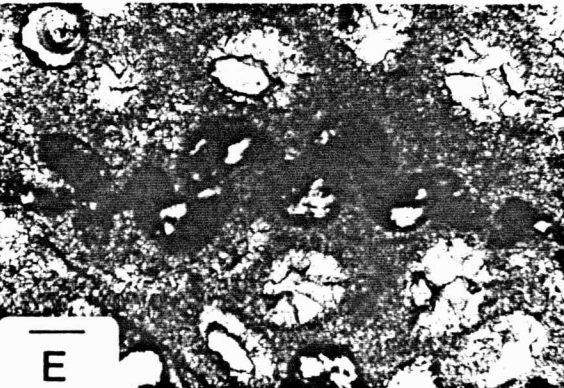
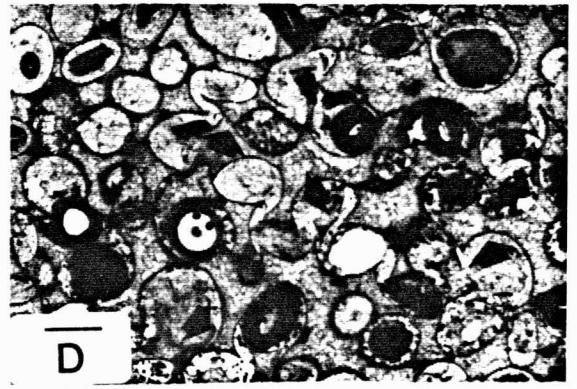
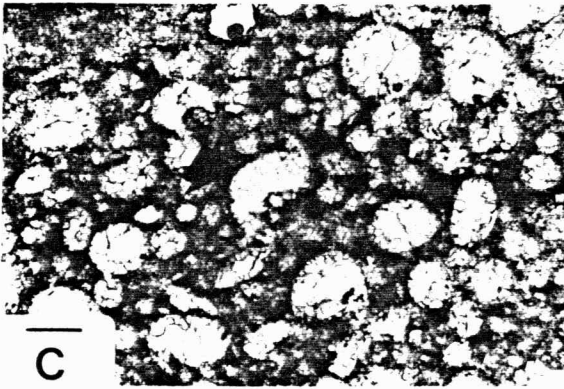
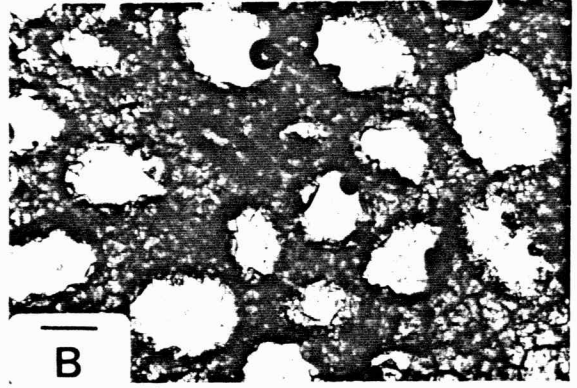


Figure 11. Oomoldic fabrics within oolitic grainstones.

- a) Near top of facies vuggy porosity is common. Large vug shows partial outline of several oomolds. This suggests enhancement of oomolds by minor leaching of relatively stable intergranular cement. (Plane-polarized light; XNW 5-t; Scale bar = 0.50 mm.)
- b) Lower in facies vuggy porosity decreases, leaving a typically oomoldic rock. (Plane-polarized light; SCQ 2-9; Scale bar = 0.20 mm.)
- c) Near base of facies many oomolds have collapsed (arrow), displacing semicircular rims of intergranular cement. (Plane-polarized light; XNW 5-2; Scale bar = 0.50 mm.)
- d) With increased collapse with depth, prongs of intergranular cement (arrows) protrude into collapsed oomolds further reducing porosity. (Plane-polarized light; CVC; Scale bar = 0.50 mm.)
- e) Chains of interlocking collapsed oomolds are common near base of facies. Collapsed oomolds are filled by ferroan dolomite and hematite in contrast to uncrushed oomolds filled by clear blocky calcite. (Plane-polarized light; IND 3-1.5; Scale bar = 0.20 mm.)
- f) At base of facies oomoldic fabrics locally have completely collapsed, destroying oomoldic porosity and producing a cement-shard fabric. Semicircular edges on cement shards (arrows) and open oomolds (upper left) are the only remaining evidence of earlier oomoldic fabric. (Plane polarized light; SCQ 2b/1t; Scale bar = 0.50 mm.)



Near the base of the facies displaced circular (in thin section) rims of intergranular cement indicate the collapse of certain oomolds (Fig. 11c and d). Although collapsed oomolds may have several outer preserved concentric layers, the inner cortex is always absent. Chains of interlocking collapsed ooids, outlined by intergranular cement or by thin rims of preserved outer cortex, often are filled by undisturbed ferroan cements suggesting that oomolds or central structureless zones were empty at the time of collapse (Fig. 11e).

Zones of crushing commonly occur near the base of the facies (Fig. 10b). These zones consist of shards of blocky calcite with small smooth-edged pores between shards. Close examination reveals semicircular edges on shards of cement, which are concave outward suggesting that cement shards were originally intergranular cement between ooids that have since been dissolved (Fig. 11f). Cement-shard fabrics are not present 1) where intergranular cements separating oomolds are unusually thick, 2) where many ooids demonstrate preservation of concentric layering in cortices, or 3) where oomolds are filled by nonferroan blocky calcite. At locality B, zones of cement-shard fabric occur in horizontal layers between layers where both ooids and intergranular cement have been wholly or partially silicified. Conley (1977) described similar cement-shard fabrics near the base of the Plattsburg Formation.

### Carbonate Cements

Original void space within the oolitic grainstone facies consisted of intergranular voids and minor intragranular voids. Intergranular voids throughout the facies are now completely filled by clear blocky cements consisting of either a thin peripheral rim of ferroan calcite followed by a central nonferroan calcite fill, or an entire filling of nonferroan calcite. Locally within the oolitic grainstone facies, point contacts between grains are absent and ooids are apparently "floating" within intergranular cements. In such cases relict fibrous rims around ooids are often preserved in blocky calcite cements. Relict fibrous rims are thin, extending only a small distance into intergranular pores, and are in contact with the relict fibrous rims surrounding neighboring ooids at points where the ooids are nearest each other. Original intragranular porosity is scarce in the oolitic grainstone facies, due to the abrasion and fragmentation of skeletal grains, and it occurred mostly within bryozoans where it is now filled by calcite.

Moldic porosity may be filled by nonferroan or ferroan calcite, ferroan dolomite, or a combination of these cements. A sequence of void-filling from void edge to void center of nonferroan calcite, followed by ferroan calcite, and finally ferroan dolomite exists where molds are filled

by multiple cements. Oomolds containing dropped echinoderm nuclei are filled by single-crystal syntaxial overgrowths of echinoderms (Fig. 9c). Void-filling of molds is variable even on a small scale, and adjacent oomolds may be filled to varying degrees by different cements. Near the base of the oolitic grainstone facies, collapsed oomolds and chains of collapsed oomolds remain open or are filled by ferroan calcite or dolomite, whereas uncrushed or round oomolds are generally filled entirely or partially by nonferroan calcite (Fig. 11e). At locality CVC, ooids within or sheltered by large bivalves are neomorphosed or, where oomoldic, remain open, while unsheltered ooids were leached and oomolds filled by ferroan dolomite (Fig. 9f).

Fractures throughout the oolitic grainstone facies are filled by either ferroan calcite or ferroan dolomite. Ferroan dolomite locally replaces intergranular cements within the facies, and locally fine rhombs of ferroan dolomite replace both clear blocky calcite and pelletal nuclei within ooids (Fig. 9a).

Unlike other depositional facies, the oolitic grainstone facies contains a significant amount of preserved porosity in the form of oomolds. Remaining oomoldic porosity has an inverse relationship with neomorphosed ooids and with cement-filled oomolds, both of which limit the amount of oomoldic porosity. Near the top of the facies,

the occurrence of both neomorphosed ooids and cement-filled oomolds is high, limiting the amount of remaining oomoldic porosity there. Furthermore, at the base of the facies, the abundance of neomorphosed ooids and the destruction of oomolds by compaction combine to reduce remaining porosity. Thus, the highest abundance of preserved oomoldic porosity occurs in a zone through the center of the facies where neomorphism of ooids and collapse or void-filling of oomolds is less common than elsewhere in the oolitic grainstone facies (Fig. 10c).

#### Caliche and Solution Channels.

A thin caliche crust covers the top of the oolitic grainstone facies at LC, and small patches of caliche are found at the top of the facies at FVN. The rubbly mudstone facies is absent at both localities where caliche marks the top of the Swope.

The caliche crust at LC ranges in thickness from several millimeters to tens of centimeters, thickening in topographic lows on the surface of the oolitic grainstone. The caliche is thinly laminated, commonly with interbedded laminae or lenses of chalcedony and chert (Fig. 12a). Local patches of nonlaminated caliche, containing some ooids, fill in some depressions overlying laminated caliche. Intergranular cement, and less commonly ooids, within the

oolitic grainstone have been silicified in a zone directly underlying the caliche. The degree of silicification in this zone appears to be roughly related to thickness of the overlying caliche. Ooids commonly have preserved concentric layering in the silicified zone.

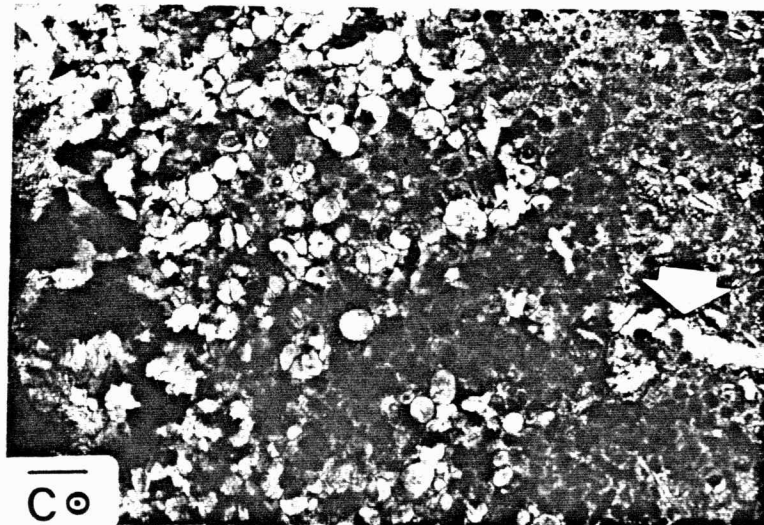
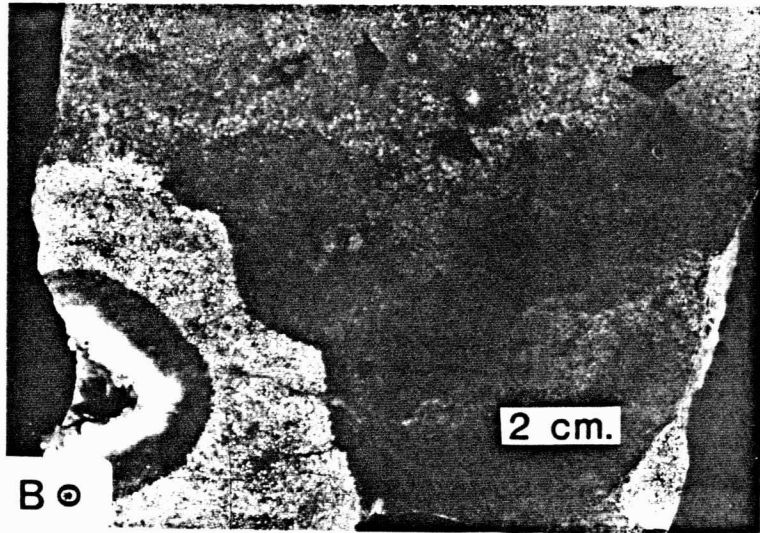
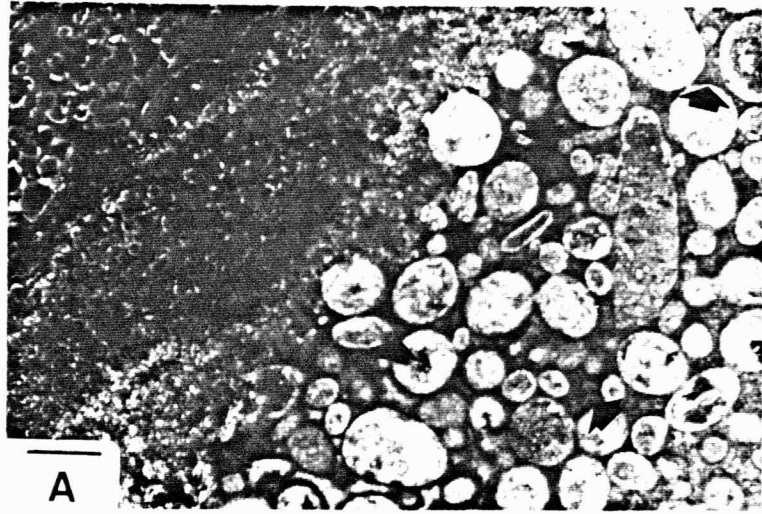
Vertical solution channels up to 3 cm. in diameter and over 20 cm. in length are abundant in the upper third of the oolitic grainstone facies at localities LC and JI. Channels range from large open cavities to thin rust-colored vertical strands through the rock. The polished surface in figure 12b (cut parallel to bedding) displays cross sections of one large channel and numerous smaller channels. Three zones are obvious around the large channel, from the center of the channel outward: 1) ferroan dolomite crystals growing toward the center of the channel, 2) ferroan dolomite-filled oomolds with partially silicified intergranular blocky calcite, 3) calichified and silicified zone with preserved concentric layering in many silicified ooids (Fig. 12c). The third zone appears similar to the silicified zone directly beneath the caliche at the top of the facies, and fractures within this zone are filled by ferroan dolomite. Less conspicuous channels show a similar zonation, although they often lack the inner zone of ferroan dolomite crystals, and silicification and calichification in the outer zone is less distinct.

Figure 12. Caliche and solution channels.

a) Irregularly laminated caliche (upper left) overlies oolitic grainstone at LC. Chert and chalcedony associated with caliche occur between laminae in caliche crust and replacing intergranular cement (arrows) and some ooids directly beneath caliche. (Plane-polarized light; LC 3-t; Scale bar = 0.50 mm.)

b) View looking down a large vertical solution channel (left), polished surface is parallel to bedding. Note cross sections of numerous smaller channels (arrows), and three distinct zones (light-dark-light) around larger channel.

c) Thin section showing zonation around large solution channel in b. Section is parallel to bedding with center of channel off left side of photo. Three zones are 1) ferroan dolomite crystals (left fifth) growing toward center of void, 2) ferroan dolomite-filled oomolds (center 2 fifths) with partially silicified intergranular cement, 3) silicified and calichified zone (right 2 fifths) with concentric structure preserved in silicified ooids. Ferroan dolomite-filled fracture (arrow) through third zone suggests that silicification occurred before precipitation of dolomite. (Cross-polarized light; LC 3-2.5; Scale bar = 1.00 mm.)



## Skeletal Wackestone Facies

### Bethany Falls Member

#### Grain Preservation

Grains within the skeletal wackestone facies of the Bethany Falls commonly have thin micrite envelopes, partial osagia coatings, or encrustations of bryozoans or foraminifers. Complete micritization of grains occurs locally within the wackestone facies at localities IJCL and ISC, where grains with thin micrite envelopes often contain sponge borings.

Unstable grains within this facies consist almost entirely of phylloid algae and molluscs. Ooids are present locally at the top of the facies in Missouri and Kansas, where the wackestone grades upward into an oolitic packstone commonly occurring at the base of the oolitic grainstone facies. Preservation of the internal structure in unstable grains is generally poor throughout the facies. Structureless grains were identified by their external shape outlined by encrusting organisms, micrite envelopes, or lime mud matrix. Typically, molluscan grains consist of structureless clear blocky calcite, within some of which collapsed micritic envelopes and encrustations, and slumping of rare preserved layers indicate the existence of earlier void space at one time (Fig. 13a). A small percentage of molluscan grains contain relict structure. Even within

these grains, preservation is usually limited to individual layers or patches of cloudy irregular calcite within which structure is well preserved, whereas the rest of the grains consist of structureless clear blocky calcite (Fig. 13b).

Preservation of relict structure in phylloid algae is even less common than in molluscs. Phylloid algal grains consist of structureless clear blocky calcite (Fig. 13c), and the occurrence of what appear to be preserved utricles within algal blades is very rare. Preservation of utricles is not clear enough to eliminate the possibility that these structures may actually be preserved micrite-filled borings (which would be in contact with the micrite matrix making their preservation less significant), or possibly small fragments of micrite collapsed into an algal mold. Hematite-rimmed molds of large phylloid algal blades remain open at locality Tr (Fig. 13d). Distribution of algal and molluscan grains with some relict internal structure is relatively even throughout the skeletal wackestone facies both vertically in measured sections and laterally along the outcrop belt.

Sheltered voids filled with clear bladed to blocky calcite are common beneath phylloid algal blades, and are distinguished from the clear blocky calcite filling algal molds only by micritic envelopes and encrustations outlining the blades (Fig. 13e) as described by Heckel and Cocke

Figure 13. Grain preservation in skeletal wackestones.

a) Gastropod (left) and bivalve (right) have been leached and molds filled by the same blocky calcite that fills intragranular voids. Geopetal fill in gastropod has slumped (arrow) while geopetal fill in bivalve remains in original position. (Plane-polarized light; XNW 2-m; Scale bar = 1.50 mm.)

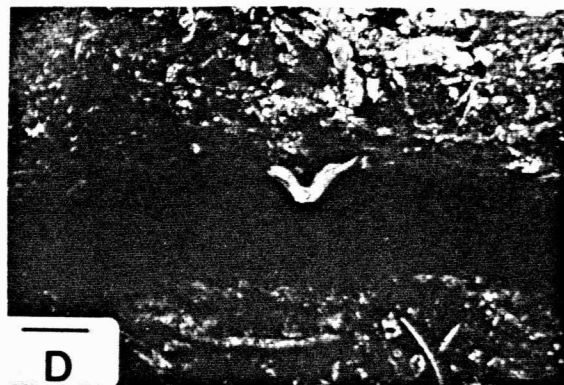
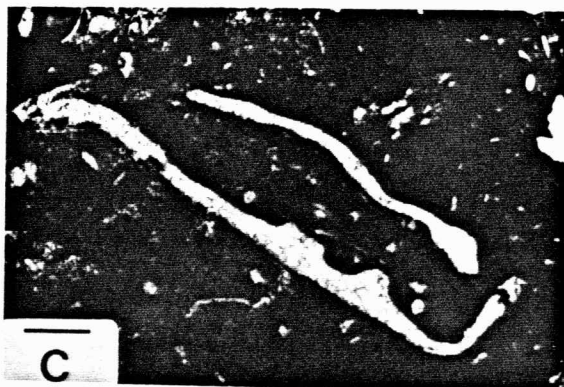
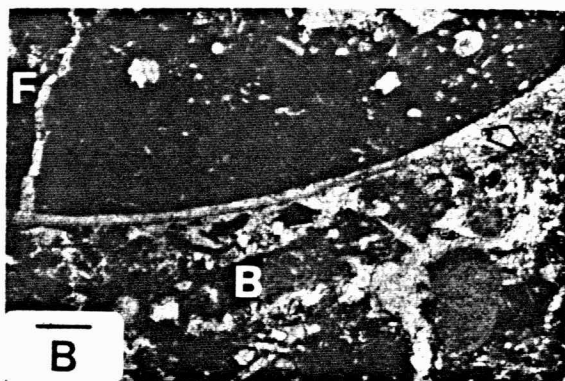
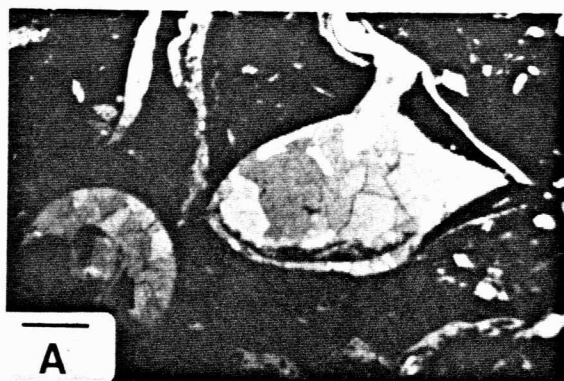
b) One thin layer is preserved (dark arrow) in a bivalve otherwise consisting of structureless blocky spar. Leaching and later mold-filling is suggested by fracture and collapse of the preserved layer (open arrow), the collapsed encrusting bryozoan (B) beneath the grain, and by adjoining fracture (F) filled by the same blocky calcite as the mold. (Plane-polarized light; LC 1-b; Scale bar = 0.50 mm.)

c) Phylloid algal blades consisting of structureless clear blocky calcite. Calcite is probably mold-filling. (Plane-polarized light; IND 1-5; Scale bar = 1.50 mm.)

d) Hematite-rimmed mold (black) of a large phylloid algal blade in the skeletal wackestone facies at Tr. Warping of algal mold around small brachiopod suggests early compaction before leaching of blade. (Cross-polarized light; Tr 2-t; Scale bar = 1.50 mm.)

e) Blocky calcite-filled algal mold (A) is separated from blocky calcite-filled shelter void (S) by an encrusting bryozoan outlining the blade. (Plane-polarized light; PLO 1.6; Scale bar = 0.50 mm.)

f) Large patch of spar with smooth upper edge may be combined void-filling of algal mold and underlying shelter void. (Plane-polarized light; FVN 1-5; Scale bar = 1.50 mm.)



(1969). Large patches of spar with smooth edges are common and often contain collapsed micrite envelopes or encrusting bryozoans suggesting that these patches of spar may be the combined filling of both molds of algal blades and the sheltered voids beneath (Fig. 13f). Similarly, large patches of spar with an elliptical shape and smooth edges may be the combined filling of molds of whole bivalves and their interior void space. Geopetal filling at the bottom of several of these patches of spar support this hypothesis. Spar-filled molds and the patches of spar described above are commonly interconnected by spar-filled fractures (Fig. 13a, b) throughout the facies suggesting that the fractures formed while the molds were open, and that the fractures resulted from the stress pattern set up in the matrix by gravity acting on the open voids.

#### Carbonate Cements

The following sequence of cements, from void edge to void center, fills original intragranular and shelter porosity within the skeletal wackestone facies: 1) a thin drusy rim of blocky calcite or ferroan calcite containing relict fibrous structure, 2) a thin irregular rim of fine dolomite rhombs, 3) a rim of bladed calcite or ferroan calcite, 4) blocky calcite, or less commonly ferroan to nonferroan blocky calcite, 5) blocky ferroan calcite, 6)

ferroan dolomite. This entire sequence of cements was not observed in any individual intragranular void, but was derived from the concurrence of various portions of the sequence in various intragranular voids throughout the facies. Crushed brachiopods contain displaced drusy rims and undisturbed central blocky filling (Fig. 14a). The thin irregular rim of dolomite rhombs was observed only at locality IND (Fig. 14b). Thin brownish films, which may be minor iron oxide staining, in some places occurs between layers of cement, marking boundaries between cement generations (Fig. 14c).

In contrast, molds of originally aragonitic grains, large patches of spar, and interconnecting fractures between molds are filled by blocky calcite or ferroan calcite, with ferroan dolomite commonly in the center of the void. When nonferroan and ferroan calcite occur within the same mold, ferroan calcite occurs closer to the void center.

#### Matrix

A pelleted or grumous texture occurs locally within the matrix, and pellets are commonly preserved within geopetal fillings of brachiopods in the skeletal wackestone facies of the Bethany Falls (Fig. 14d, e). Stylolites (except those associated with mottling) and crushed grains are rare at the top of the facies but are more common near its base.

Figure 14. Cements and matrix of skeletal wackestones.

a) Crushed brachiopod with shell and thin drusy rim displaced (arrow), while central blocky calcite fill is undisturbed. (Plane-polarized light; ICQ 1-6, s; Scale bar = 0.50 mm.)

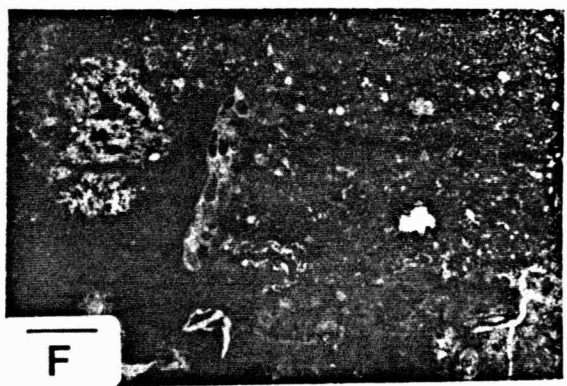
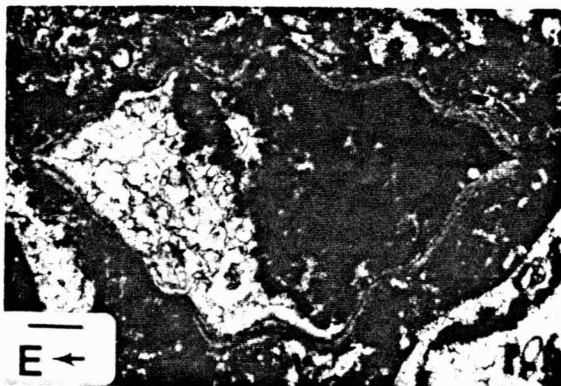
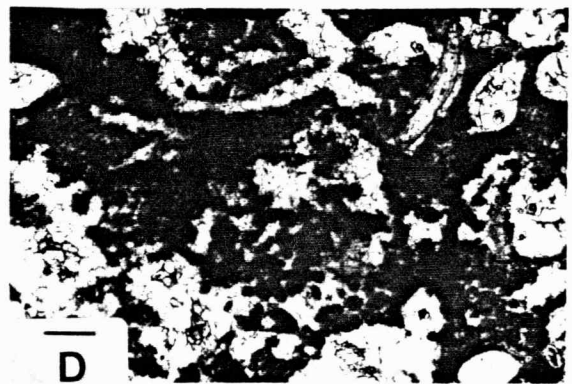
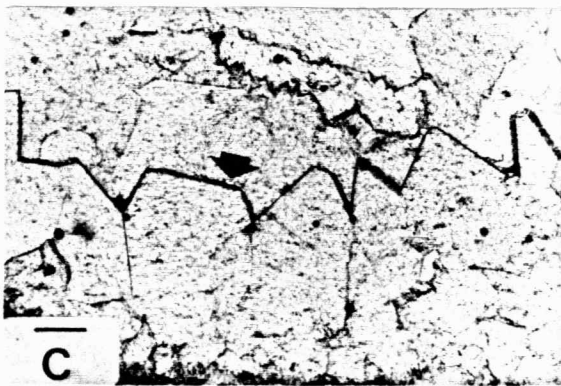
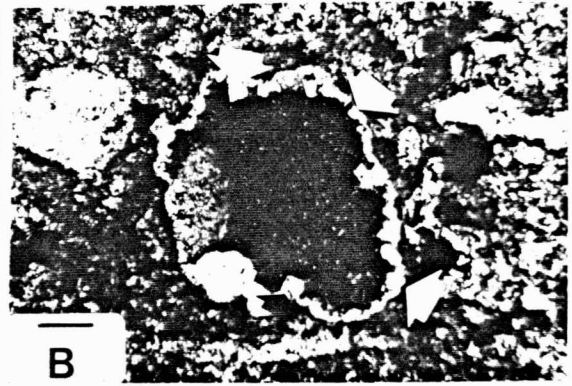
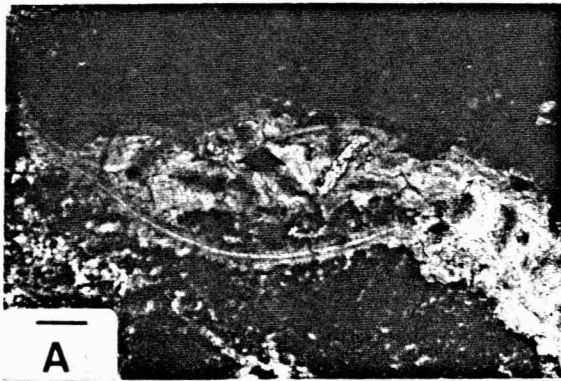
b) Irregular rim of nonferroan dolomite rhombs (arrows) around outer edge of interior void within a brachiopod precedes blocky calcite (black and gray) central fill. (Cross-polarized light; IND 1-1, s; Scale bar = 0.20 mm.)

c) Thin brownish film (arrow), possibly iron oxide, coats outer rim of drusy dogtooth calcite, within intragranular void of brachiopod, separating it from a later central fill of blocky calcite. (Plane-polarized light; ICQ 1-8; Scale bar = 0.20 mm.)

d) Preserved pellets grading into grumous fabric within matrix of skeletal wackestone facies of Bethany Falls. (Plane-polarized light; Tr 2-m; Scale bar = 0.50 mm.)

e) Pellets are commonly preserved in geopetal fillings of intragranular voids in brachiopods. (Plane-polarized light; IND 1-t; Scale bar = 0.50 mm.)

f) Ferroan dolomite (upper right) replaces patches of micrite in skeletal wackestone facies near base of Bethany Falls and in Middle Creek. (Cross-polarized light; K mc-2; Scale bar = 1.50 mm.)



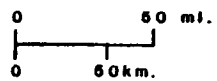
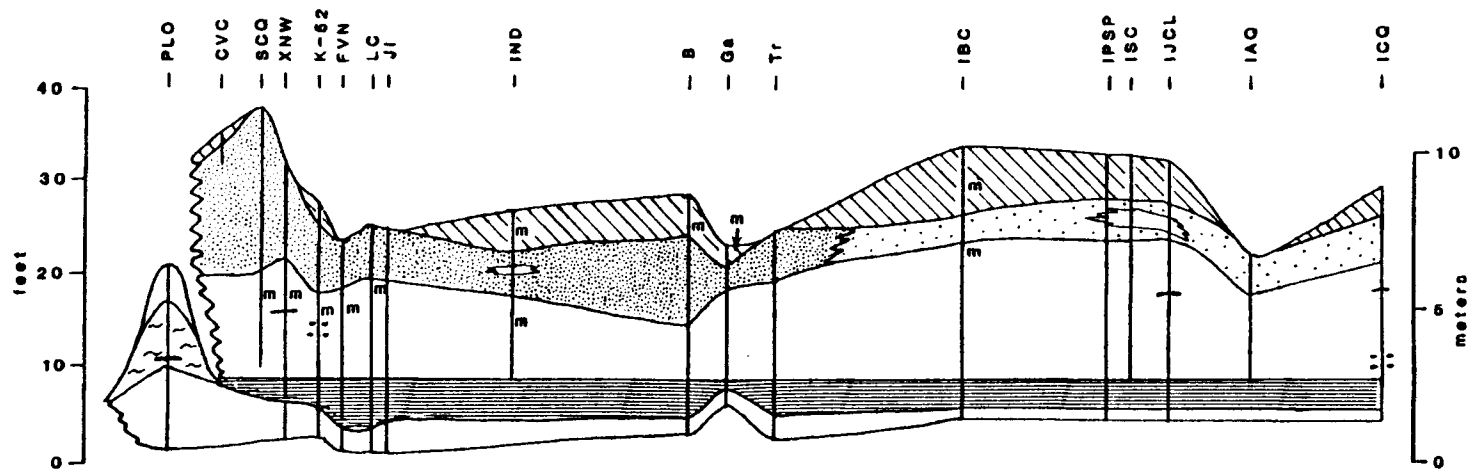
Syntaxial overgrowths on echinoderm fragments incorporate micrite and are generally thin, as their growth apparently was limited by the surrounding micrite. Patches of ferroan dolomite replace micrite in the lower third of the facies and locally ferroan dolomite completely replaces the matrix near the base of the Bethany Falls (Fig. 14f).





### Mottling

The upper third of the skeletal wackestone facies in Kansas, the top of the skeletal wackestone facies at locality IBC, and the entire rubbly mudstone facies in Kansas and Missouri display a distinctive color mottling. This mottling often occurs in portions of the skeletal wackestone facies directly overlying beds of chert or horizons containing nodular chert (Fig. 15). In outcrop or hand specimen, mottles are dark gray against a light gray matrix (Fig. 16a). As noted by Mossler (1970) mottles may occur as discrete patches, anastomosing networks, or in extreme cases (such as the rubbly mudstone facies at locality B), mottles may dominate the rock leaving only fingers of matrix among mottles. ✓

Petrographic study demonstrates that mottles are typically microspar (5-40 microns), although the size range of calcite crystals within mottles (5-250 microns) includes some coarser spar. The matrix typically consists of micrite

Figure 15. Distribution of mottling and chert. Microspar mottling (m) occurs in upper portion of skeletal wackestone facies in Kansas, at top of skeletal wackestone facies at IBC, and in rubbly mudstone facies in Kansas, Missouri, and IBC. Chert beds (dark horizontal lines) and nodular chert (dots) generally occur near center of skeletal wackestone facies, and mottling is limited to the portion of that facies directly overlying chert when they occur together.



-  Rubbly Mudstone
-  Osagia Grainstone
-  Oolitic Grainstone
-  Skeletal Wackestone
-  Gray to Black Shale
-  Algal Boundstone

- m* Mottling
- Chert Bed
- ∴ Nodular Chert

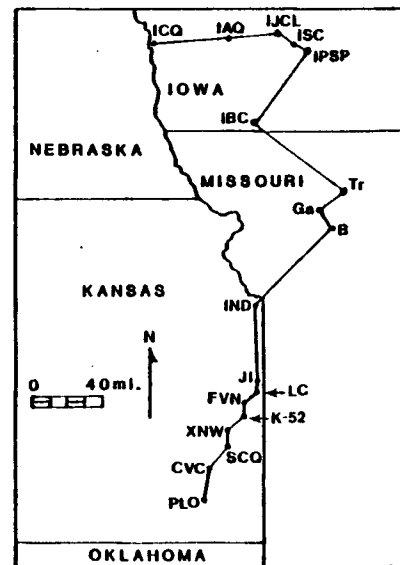


Figure 16. Color mottling in the Bethany Falls.

a) Polished slab showing dark mottles in a light matrix as is characteristic of the Bethany Falls in Kansas and Missouri.

b) Microscopic study reveals that mottles (M) are microspar whereas matrix (X) is micrite. Mottles appear lighter in thin section than does matrix (reverse of hand specimen appearance) due to greater translucence of larger microspar crystals. Microspar mottles may include grains such as pellets shown here. (Plane-polarized light; IND 6-3; Scale bar = 1.00 mm.)

c) SEM photo showing area of micritic matrix, with average crystal diameter of approximately 25 microns. (KV = 15; 0001; Scale bar = 100.0 microns.)

d) SEM photo showing area within microspar mottle from same sample shown in c. Mottles consist of tightly interlocking calcite crystals with average diameter of 200 microns. (KV = 15; 0001; Scale bar = 100.0 microns)

e) SEM photo showing a small microspar mottle (center) within micritic matrix (lower and upper left). (KV = 15; 0002; Scale bar = 100.0 microns)

f) SEM photo showing detail of lower boundary between microspar mottle and micritic matrix. Contact is relatively sharp, but crystal size does increase toward mottle center. (KV = 15; 0002; Scale bar = 50.0 microns)

g) SEM photo shows patches of small crystals (arrow) within micritic matrix. (KV = 15; 0001; Scale bar = 10.0 microns)

h) Patch of crystals enlarged from g are visible as rhombic dolomite. Dolomite and clay are common in minor amounts in micritic matrix, whereas microspar mottles are generally pure calcite. (KV = 15; 0001; Scale bar = 5.0 microns)

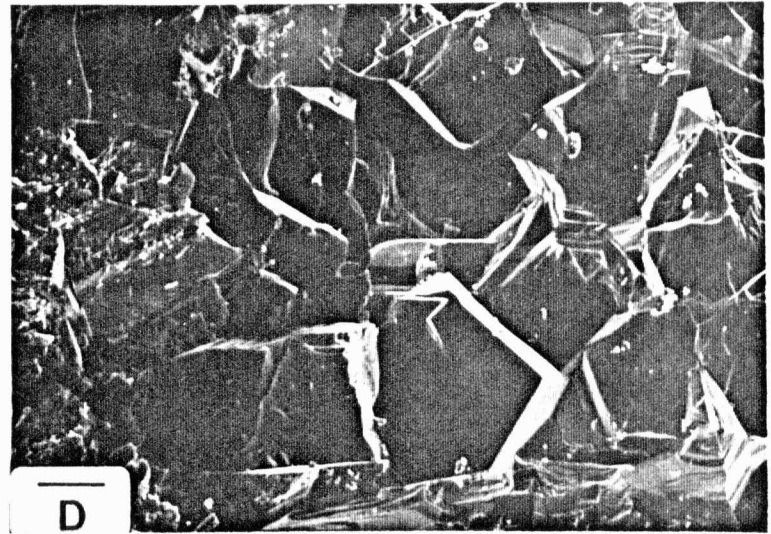
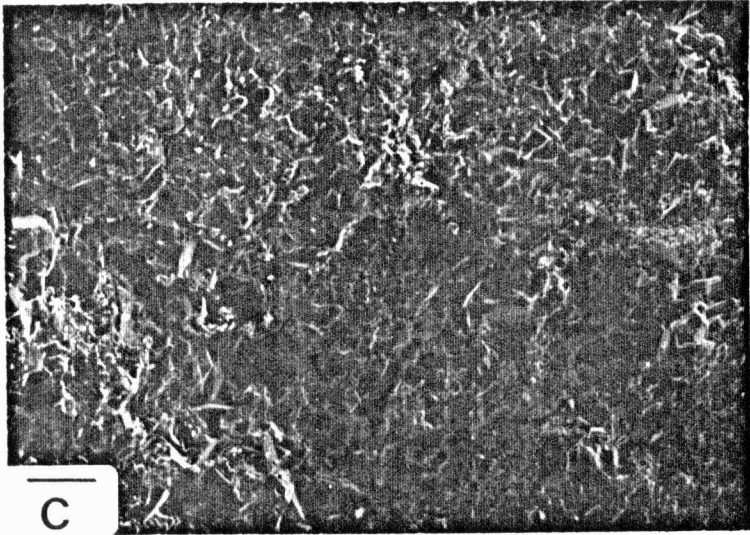
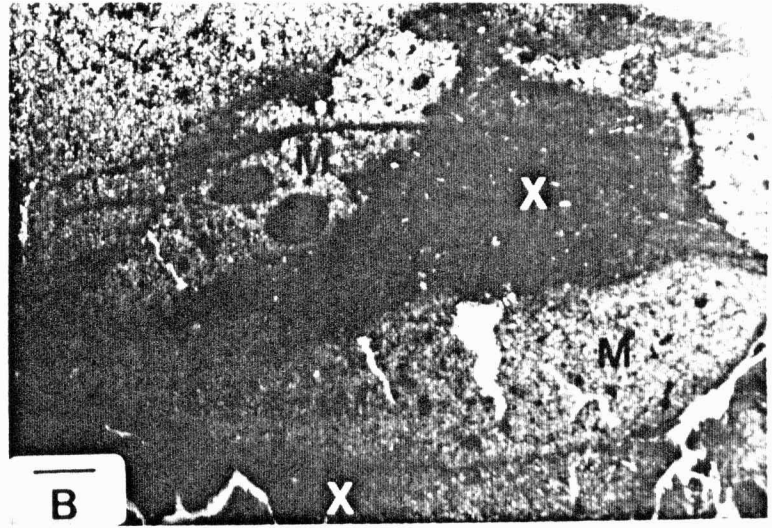
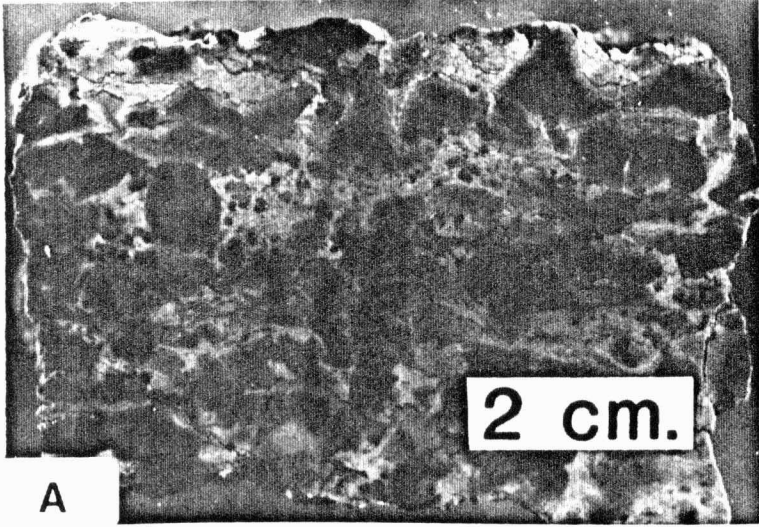
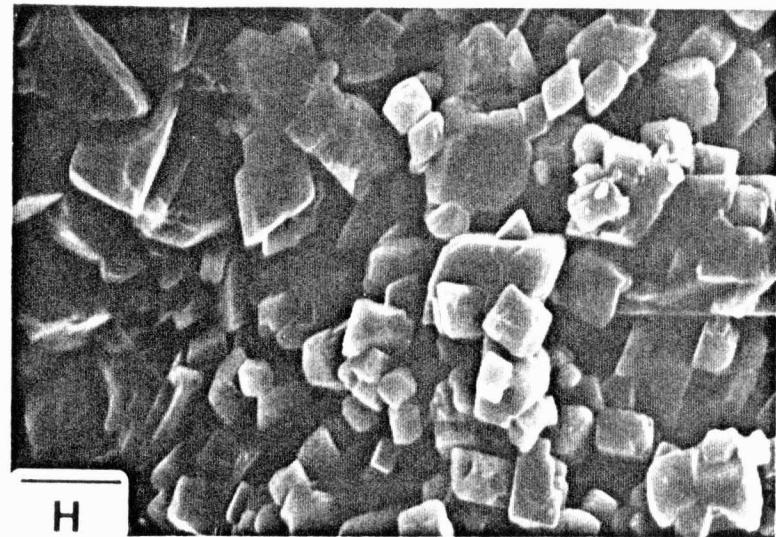
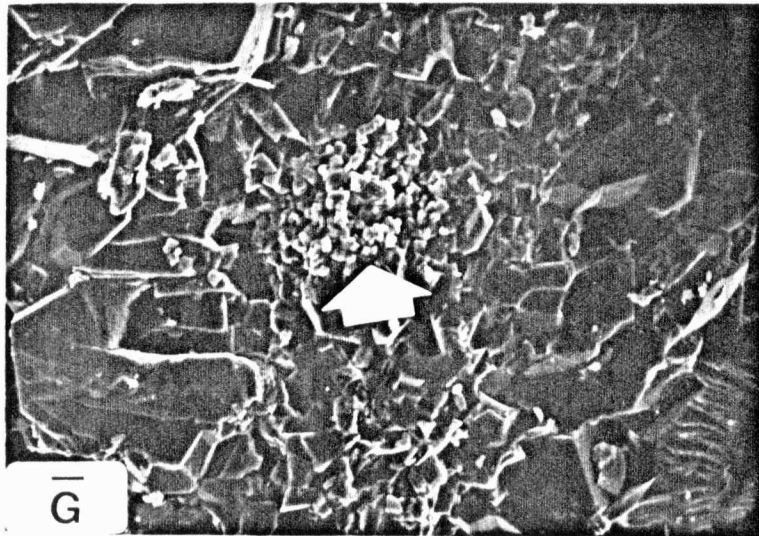
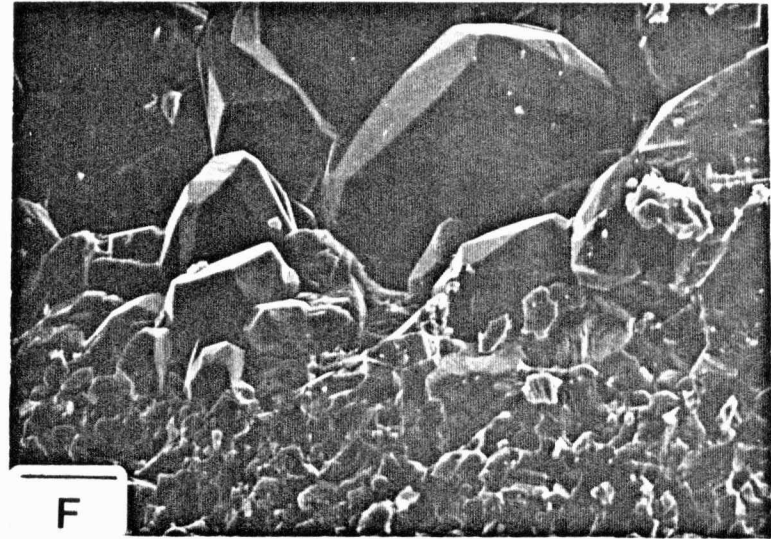
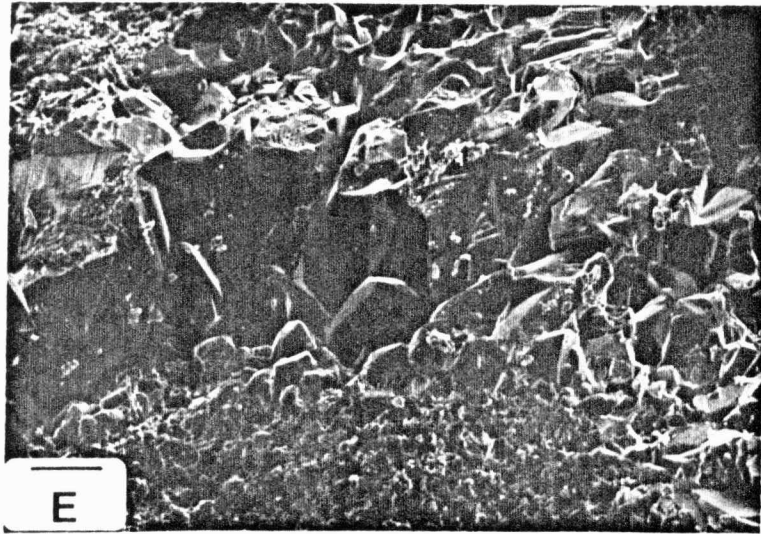


Figure 16 cont.



(1-5 microns), although the size range of calcite crystals in the matrix (1-30 microns) includes some microspar. In thin section, mottles appear lighter than the matrix (the reverse of their outcrop appearance) due to the greater translucence of the coarser microspar (Fig. 16b).

Microspar mottles contain very few depositional grains, compared to the abundance of grains in the micritic matrix, although pellets and skeletal grains do occur within mottles. Mossler (1970) noted that a difference in crystal size between mottles and matrix was not always distinguishable in thin section, but study with a Scanning Electron Microscope demonstrates clearly a significant difference in crystal size even when it is not apparent in thin section (Fig. 16c, d). Boundaries between mottles and matrix are typically sharp, although boundaries gradational over several millimeters are not uncommon, with microspar becoming coarser toward the center of mottles (Fig. 16e, f).

Stylolites or microstylolites (Wanless, 1979) are often associated with mottling, running through the matrix material and around the outer edges of mottles. Spar-filled cracks often occur at the upper and lower edges of mottles with a slight warping of matrix into the cracks as described by Mossler (1970).

Oxygen and Carbon Isotopes of Mottles vs. Matrix

Samples for carbon and oxygen stable-isotope analysis were taken from the centers of mottles and from adjacent matrix three or four millimeters from the outer edge of sampled mottles. Four mottle/adjacent matrix sample pairs were prepared, two from different levels in the skeletal wackestone facies at XNW, one from the skeletal wackestone facies at locality LC, and one from the rubbly mudstone facies at locality IND.  $\Delta O^{18}$  and  $dC^{13}$  were determined using a NBS 20 standard and then normalized to the PDB scale (K. Egan, pers. comm.). Figure 17 plots both  $dO^{18}$  and  $dC^{13}$  for the eight analyzed samples. Both the mottle and adjacent matrix samples from a particular locality are represented by the same geometric form, with mottles shaded and matrix unshaded (data shown in Fig. 17 is provided in Appendix B).

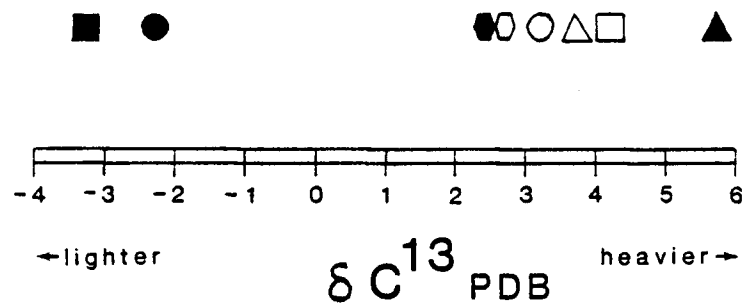
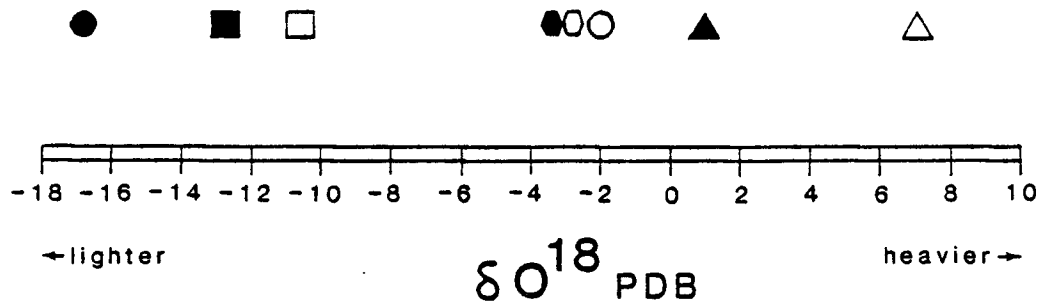
Comparison of  $dO^{18}$  values for mottles and matrix at individual localities shows that the mottles have lighter  $dO^{18}$  values than their paired matrix samples at each of the four localities, and that the mottles are significantly lighter (difference in  $dO^{18} > 2$  PDB units) than the matrix at three of the four localities (Fig. 17).  $\Delta O^{18}$  values for each mottle/matrix pair show much variation between different localities.

Comparison of  $dC^{13}$  values for mottles and matrix samples at individual localities shows that mottles have

Figure 17. Mottles vs. Matrix: O and C stable isotopes. Localities are represented by geometric forms, mottles are shaded, matrix samples are unshaded. Delta O<sup>18</sup> values are lighter for mottles than for matrix at each individual locality. Mottles have a wide range of dC<sup>13</sup> values while dC<sup>13</sup> values for matrix show little variation.

# MOTTLES VS. MATRIX

## Oxygen & Carbon Stable Isotopes



△ IND	○ XNW 4-b
◻ LC	◻ XNW 4-3

lighter  $\delta C^{13}$  values than matrix samples, except for the mottle/matrix pair from locality IND. Delta  $C^{13}$  values for matrix samples show little variation between different localities, all samples lying in a narrow range from 2.70 to 4.19 PDB. In contrast,  $\delta C^{13}$  values for mottles show a wide variation between different localities ranging from -3.15 to 5.79 PDB.

#### Chemical Composition of Mottles vs. Matrix

Eight mottle/matrix pairs were probed using Wave Length Dispersive Spectroscopy (WDS) and analyzed for  $CaCO_3$ ,  $MnCO_3$ ,  $FeCO_3$ , and  $MgCO_3$  (microprobe data is provided in Appendix B). These carbonates are the dominant constituents in both the microspar mottles and the micritic matrix, but no significant difference in any of them was noted between mottles and matrix. Although mottles and matrix have similar chemical compositions, the mottles contain a higher percentage of total carbonate (ranging from 92 to 100 oxide weight percent) than does the matrix (ranging from 86 to 99 oxide weight percent total carbonate). Although the quantitative analysis of probed samples was limited to the carbonates mentioned, analysis of x-ray spectrums of probed samples showed that matrix samples generally had a slightly higher clay content, as well as a trace of organic material not present in mottles.

Three mottle/matrix pairs were studied utilizing Electron Dispersive Spectroscopy (EDS) with the SEM (SEM x-ray data is provided in Appendix B). EDS analysis is less precise than WDS and provides only semi-quantitative data on SEM samples with irregular surfaces. These SEM x-ray analyses show that the micritic matrix contains a larger amount of  $\text{SiO}_2$  than microspar mottles. The silica probably occurs primarily in clays where aluminum is present, or replacing calcite where aluminum is absent. Other impurities occur within the matrix in amounts too small to be detected by EDS analysis. Patches of minute crystals (Fig. 16g) were observed with the SEM in matrix samples from several localities. Higher magnification revealed that these patches consisted of rhombic microdolomite crystals (Fig. 16h). In contrast, microspar mottles appeared to be clean calcite crystals.

#### Middle Creek Member

The skeletal wackestone facies in the Middle Creek Member is similar to the facies at the base of the Bethany Falls. As in the Bethany Falls, originally aragonitic molluscs and phylloid algae typically consist of structureless clear blocky calcite, which meets Bathurst's (1975) criteria for void-filling spar (Fig. 18a). Relict structures are rarely preserved and are limited to the outer

layers in molluscs and micrite-filled utricles in a small percentage of phylloid algal grains.

Brachiopods and ostracodes are more commonly crushed or flattened in the Middle Creek than in the Bethany Falls, and stylolites and microstylolites are abundant. Pelleted or grumous textures were not observed in the Middle Creek, where pellets are preserved only in geopetal fillings of intragranular voids or rarely in sheltered voids beneath encrusted phylloid algal blades.

Ferroan dolomite occurs as the central filling of many intragranular voids, fracture fillings, and (as at the base of the Bethany Falls) within the matrix of the skeletal wackestone. Ferroan dolomite that replaces micritic matrix is finely rhombic, commonly zoned, includes micrite, and surrounds unreplaced skeletal grains.

Burrows backfilled with swirled sediment give a mottled appearance to the Middle Creek at IJCL, but there was no microspar mottling (as described for the Bethany Falls) detected in the Middle Creek.

### Algal Boundstone Facies

#### Grain Preservation

Unstable grains within this facies include phylloid algal blades and molluscs, both of which are generally poorly preserved. Phylloid algal blades are usually

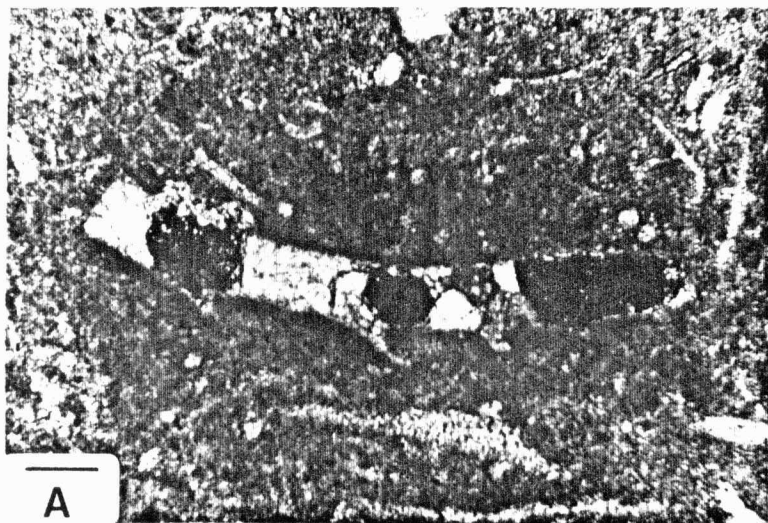
Figure 18. Diagenesis in Middle Creek Member.

a) Bivalve fragment leached and filled with structureless clear blocky calcite in skeletal wackestone facies of Middle Creek. (Cross-polarized light; LC mc-m, s; Scale bar = 0.20 mm.)

b) Typical poorly preserved phylloid algal blade consisting of blocky calcite. Small micrite inclusions within calcite (arrows) may be remnants of utricles. (Plane-polarized light; PLO 3.0; Scale bar = 0.20 mm.)

c) Encrusters have collapsed into blocky calcite-filled algal mold within algal boundstone facies at PLO. (Plane-polarized light; PLO 1.6; Scale bar = 0.50 mm.)

d) Preservation of mollusc grains is generally poor in algal boundstone facies. This bivalve consists of structureless clear blocky calcite. (Plane-polarized light; PLO 1.1; Scale bar = 0.50 mm.)



structureless blocky calcite (Fig. 18b) and were identified by their external shape outlined by micrite or encrusting organisms. Micrite-filled utricles are preserved within the blocky calcite of some blades and aid in distinguishing algal blades from underlying blocky spar-filled sheltered voids (Mossler, 1970). Large elongate sparry areas are common within this facies. These sparry areas often have smooth wavy upper boundaries and contain collapsed encrusting bryozoans (Fig. 18c), suggesting that the areas of spar are spar-filled algal molds or combined algal molds and underlying sheltered voids.

Molluscs are typically structureless blocky calcite (Fig. 18d) increasing in crystal size toward grain centers, and often contain collapsed encrusters indicating solution of mollusc grains and later void-filling of molds. A small percentage of mollusc grains have some preservation of layered internal structure within finely crystalline cloudy calcite.

#### Carbonate Cements

Original porosity, consisting of intragranular pores and sheltered voids beneath algae, is dominantly filled by blocky calcite, although thin zones of ferroan calcite may occur peripherally, and some voids contain a final central filling of ferroan dolomite.

Secondary porosity, consisting of algal and mollusc molds, is dominantly filled by peripheral blocky calcite with minor central filling of ferroan calcite and dolomite.

## CHAPTER III

## NONCARBONATE MINERALS AND HYDROCARBON

Silica

Silica within the Swope Formation occurs as grain replacement, as distinct chert beds or in horizons containing chert nodules, associated with local occurrences of caliche, as void filling, and at locality PLO as clusters of radiating chert-like fibers replacing calcite.

Brachiopods, echinoderms, and bryozoans are preferentially replaced by chert and/or chalcedony throughout the Swope Formation. Silicification by chert generally disrupts original structure within grains, while replacement by chalcedony often follows and preserves detailed internal structure within grains (Fig. 19a). Replacement is limited to grain interiors, except in chert beds, and the degree of replacement ranges from small patches in otherwise unaltered grains to complete silicification of grains. Both cortices and nuclei of ooids may be silicified, usually with concentric layering preserved. Rarely, chalcedony replaces molluscs and phylloid algal blades, preserving internal structures within neomorphosed segments of these grains.

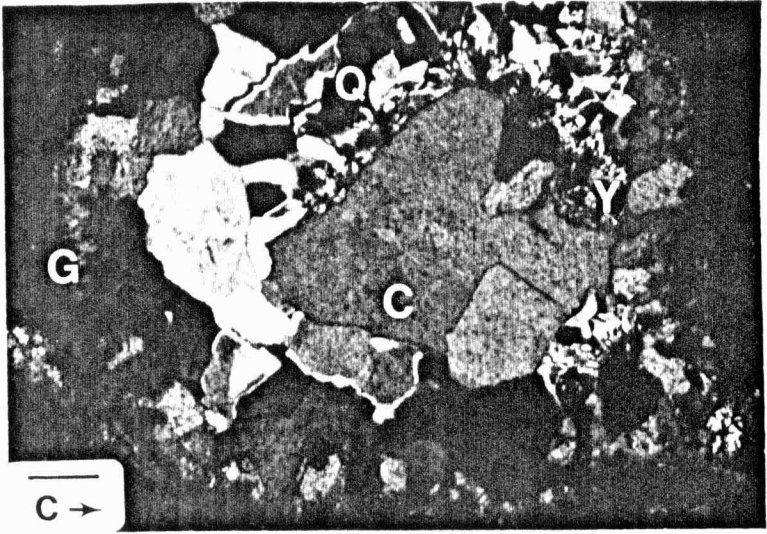
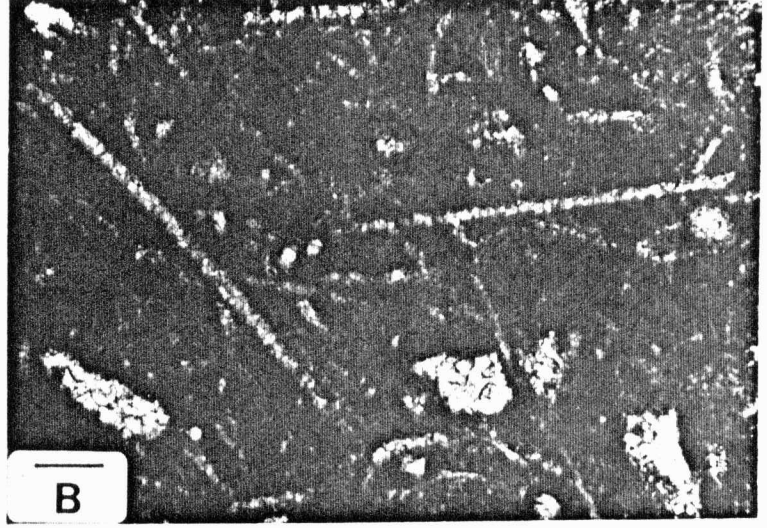
Figure 19. Occurrence of silica within the Swope.

a) Chalcedony replacement (arrow) follows and preserves detailed internal structure within a brachiopod. (Cross-polarized light; IJCL 67.8; Scale bar = 0.20 mm.)

b) Monaxon sponge spicules, abundant throughout skeletal wackestone and grainstone facies of Swope, have typically been replaced by fine blocky calcite as shown here. Only spicules within chert beds and nodules remain siliceous. (Plane-polarized light; IJCL 76.7; Scale bar = 0.20 mm.)

c) Interior void within brachiopod shows sequence of void-filling beginning with 1) thin geopetal layer (G), followed by 2) blocky calcite (C), 3) botryoidal chalcedony (Y), and 4) final filling of megaquartz (Q). (Cross-polarized light; IND 1-5; Scale bar = 0.50 mm.)

d) Some oomolds contain relict blocky mosaics within fibrous chalcedony, suggesting that chalcedony has replaced void-filling blocky calcite (arrows). Chalcedony in other oomolds lacking relict blocky mosaics is probably the original void-filling cement. Darker oomolds (D) are filled by ferroan dolomite with intercrystalline hematite. (Plane-polarized light; JI 3frt; Scale bar = 0.20 mm.)



Distinct beds of chert and horizons of nodular chert occur in the lower two thirds of the skeletal wackestone facies of the Bethany Falls in southeastern Kansas and southwestern Iowa (Fig. 15). The beds of chert are generally between 5 and 20 cm. thick, and nodular chert occurs in horizons generally less than a meter thick. At locality ICQ, chert preferentially replaces a thin grainstone within the skeletal wackestone facies, but chert nodules are found in wackestones as well, and the distribution of chert seems unrelated to original lithology. Within nodules and beds, chert has replaced both grains and matrix, preserving the fabric of the original limestone. The chert contains abundant inclusions of calcite, and voids are partially or completely filled by chalcedony. Monaxon sponge spicules, abundant throughout the Swope Formation, remain siliceous within chert beds and nodules, although spicules have been replaced by calcite in the rest of the formation (Fig. 19b).

Minor amounts of chert and chalcedony are associated with caliche crusts at localities LC and FVN, and occur within calichified oolitic grainstones beneath caliche crusts or in zones around solution channels at localities LC and JI. Chert and chalcedony occur in thin layers between irregular laminae in caliche crusts and replace intergranular cements as well as some ooids in calichified oolitic grainstones.

A small percentage of intragranular voids and molds contain final fillings of megaquartz or less commonly botryoidal chalcedony. Inclusions of megaquartz within void-filling blocky calcite are rare, but a sequence of void-filling first by geopetal mud, followed by blocky calcite, botryoidal chalcedony, and finally megaquartz has been observed in several brachiopods (Fig. 19c). Megaquartz and ferroan dolomite have not been observed together in the same void, making it difficult to determine their paragenetic relationship. However, SEM analysis has revealed minute euhedral quartz crystals appearing through a rim of ferroan dolomite and iron oxide toward the center of the oomold (Fig. 20). Apparently the quartz nucleated from the wall of the oomold before ferroan dolomite rimmed the mold and surrounded the base of the quartz crystals. Relict blocky mosaics within some oomolds filled by botryoidal chalcedony demonstrate that chalcedony does not always occur as an original void-filling cement, but in certain instances chalcedony may replace original blocky calcite cements (Fig. 19d).

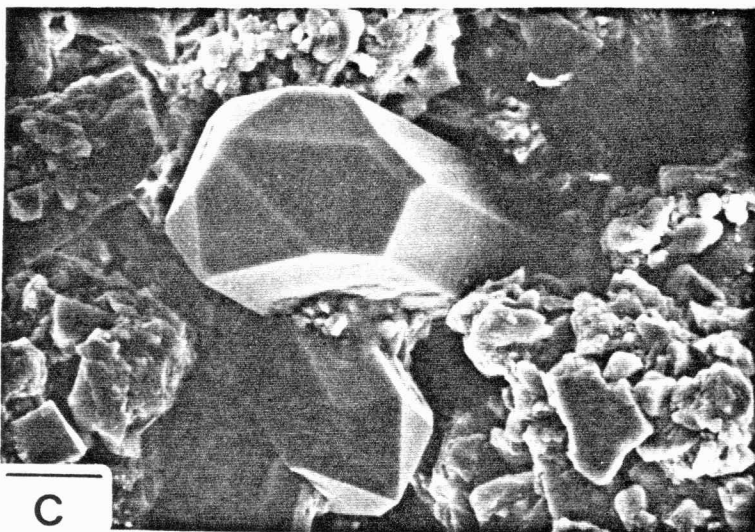
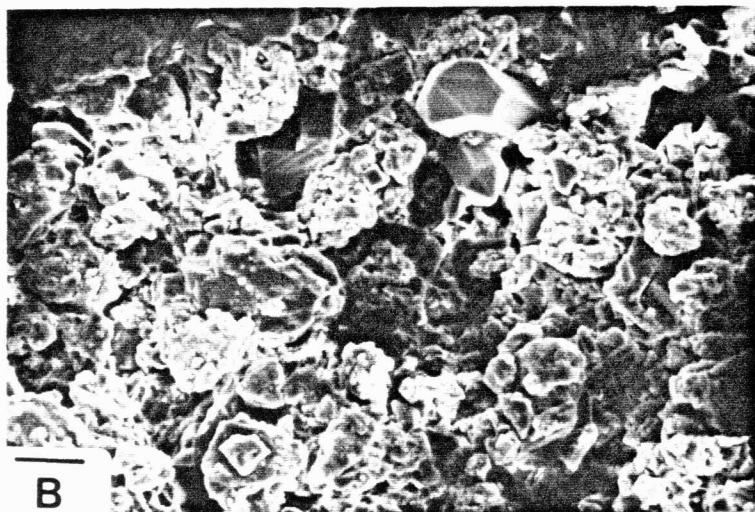
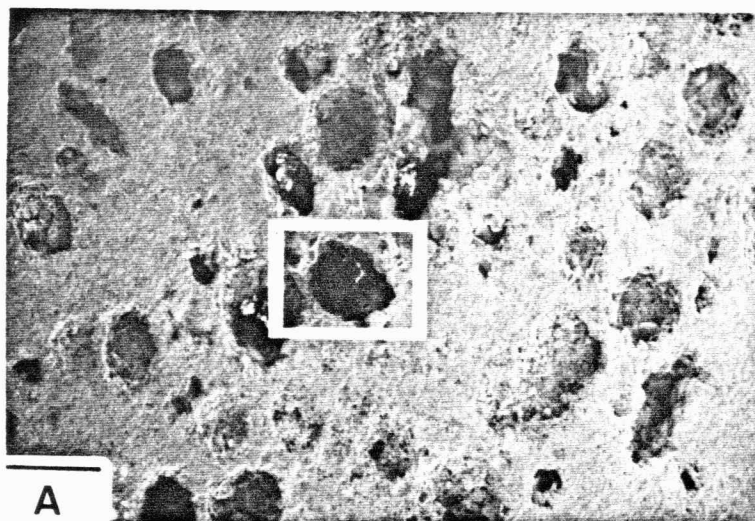
Chert often replaces micrite along stylolites in wackestones, and replaces intergranular cements and grains near clay seams, and also replaces lenses of packstone or wackestones in the oolitic grainstone facies.

Figure 20. SEM analysis shows euhedral quartz in oomold.

a) Oomoldic porosity, with box enclosing oomold whose wall is shown in greater detail in b and c. (KV = 13; 0005; Scale bar = 500.0 microns)

b) Wall of oomold is rimmed by ferroan dolomite (clean rhombs) which is generally coated by iron oxides (irregular aggregates). Two small quartz crystals are present toward upper right. (KV = 13; 0005; Scale bar = 10.0 microns)

c) Two euhedral quartz crystals appear through rim of ferroan dolomite and iron oxide, suggesting that quartz nucleated from the mold wall before ferroan dolomite coated the mold. (KV = 13; 0005; Scale bar = 5.0 microns)



A two-meter-thick horizon near the base of the algal boundstone facies at locality PLO is heavily silicified and displays clusters of fibrous silica unique within the Swope Formation. Fibrous silica occurs in semispherical clusters several millimeters to a centimeter in diameter (Fig. 21a). The fibrous clusters, which Mossler (1970) termed "spherulites", are chert-like and appear very similar to chert when cut perpendicular to the long axis of the fibers. Siliceous spherulites contain abundant calcite inclusions and replace both micrite and some calcite spar. Large voids, possibly algal molds and/or sheltered voids, within the heavily silicified horizon are typically filled by some portion of the following sequence: 1) first a clear bladed or blocky calcite, followed by 2) chert, 3) chalcedony, and finally 4) megaquartz or ferroan dolomite (Fig. 21b). As in the rest of the formation, ferroan dolomite and megaquartz do not occur together within the same voids at PLO. Voids bounded by silicified matrix or spherulites are entirely filled by chert, chalcedony, and megaquartz (Fig. 21c), whereas voids bounded by micrite have initial bladed or blocky calcite filling and are often entirely filled by carbonate cements (Fig. 21d). These relationships suggest that the carbonate cements required carbonate substrates as nucleation sites.

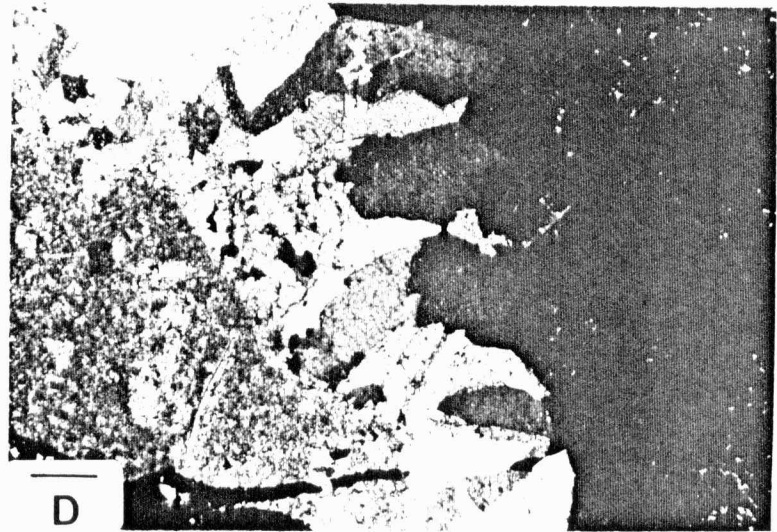
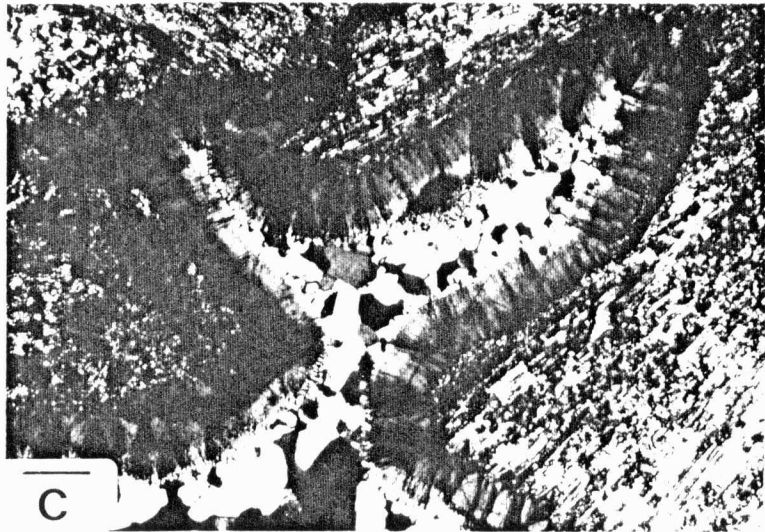
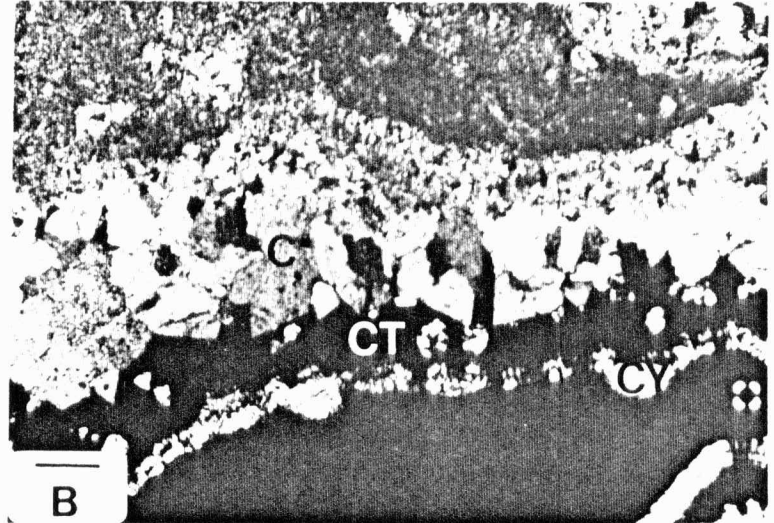
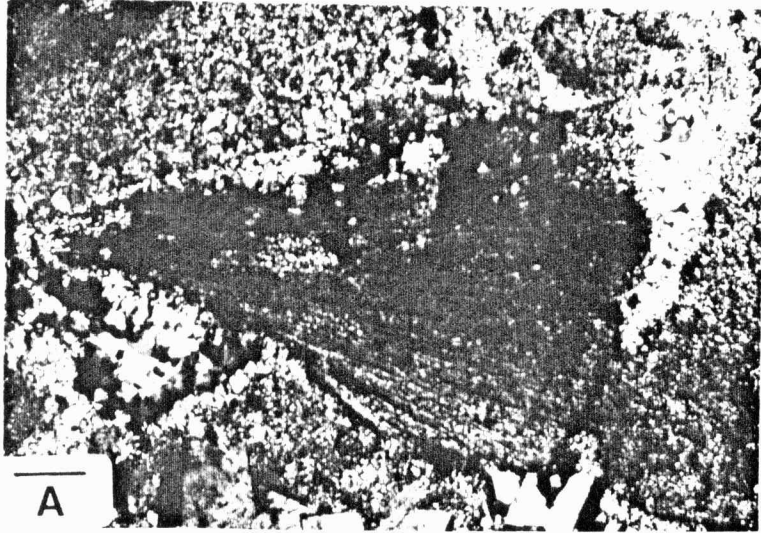
Figure 21. Fibrous silica and void-filling at PLO.

a) Semispherical clusters of fibrous silica, termed "spherulites" by Mossler (1970), are unique to the heavily silicified zone at PLO. Spherulites contain abundant inclusions of calcite (light areas within spherulite) and appear to be very similar to chert. (Cross-polarized light; PLO 3.0; Scale bar = 0.50 mm.)

b) Large void (black at base) partially filled by an initial rim of drusy calcite (C), followed by chert (CT), and finally by a layer of chalcedony (CY). (Cross-polarized light; PLO 3.0; Scale bar = 0.50 mm.)

c) Voids bounded by siliceous matrix are entirely filled with silica. Here a void bounded by spherulites is filled by several layers of chalcedony with a central filling of megaquartz. (Cross-polarized light; PLO 2-4; Scale bar = 0.50 mm.)

d) Voids bounded by carbonate have initial bladed or blocky calcite cements. here a void bounded by micrite (lower left) is rimmed by bladed calcite (center) followed by ferroan dolomite with associated hematite (dark area on the right). (Cross-polarized light; PLO 3.3; Scale bar = 0.50 mm.)



### Pyrite, Hematite, and Limonite

Minor amounts of subhedral pyrite replace brachiopod, echinoderm, bryozoan, and less commonly mollusc and phylloid algal grains throughout the Middle Creek and Bethany Falls limestones (Fig. 22a). Commonly pyrite replacement is associated with silicification in grains, and pyrite occurs only in neomorphosed sections of molluscs and phylloid algal blades. Pyrite is concentrated in the coating around grains in both osagia grainstone and skeletal wackestone facies.

Pyrite also occurs scattered throughout the micritic matrix of the skeletal wackestone facies, increasing in abundance toward the Hushpuckney Shale in both the Middle Creek and Bethany Falls. Pyrite also occurs concentrated within the lower outside edge of some blocky calcite void-fillings, and along stylolites and clay seams within the rock.

Hematite and limonite commonly occur as pseudomorphs of, or as alteration products around pyrite. In addition, iron oxides commonly line cleavage planes and coat ferroan dolomite crystals. Hematite rims are usually found around the outside edge of remaining oomolds (Fig. 22b). Close petrographic observation reveals fine rhombs of ferroan dolomite within the hematite rims, suggesting that the hematite is an alteration of the void-lining ferroan dolomite. Alteration of ferroan dolomite to hematite may

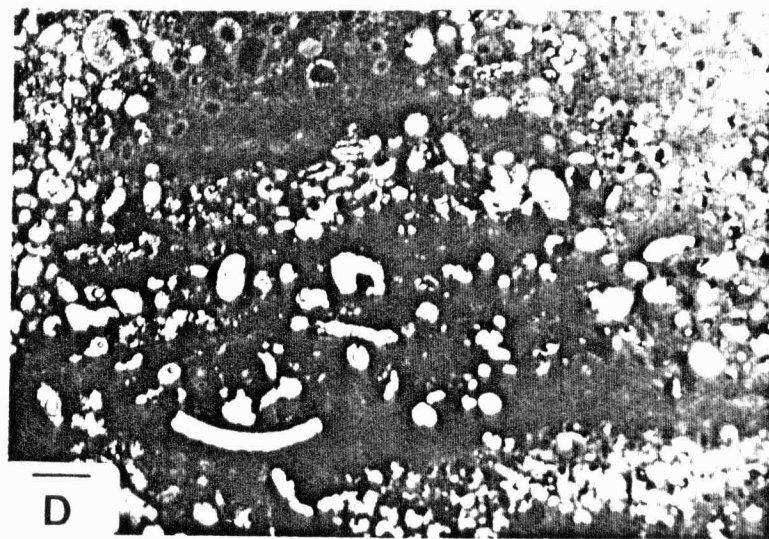
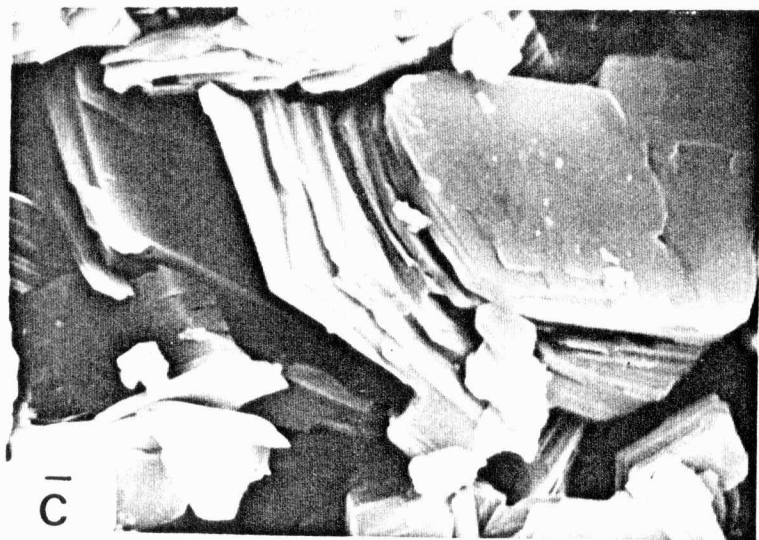
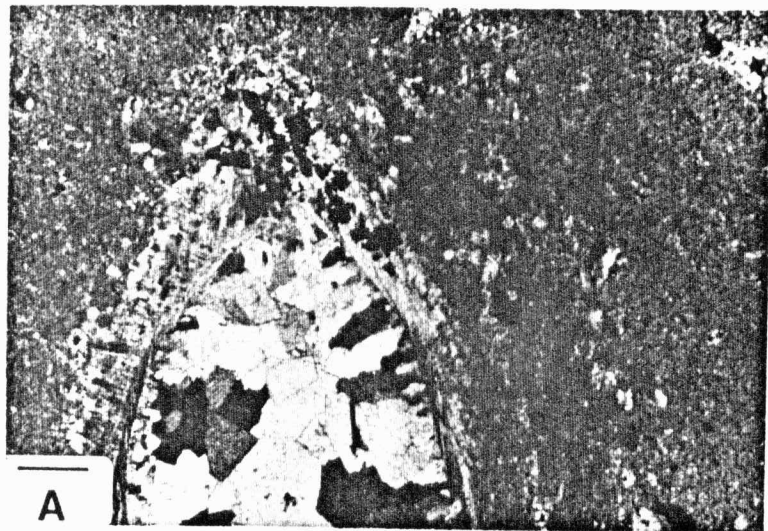
Figure 22. Occurrence of other noncarbonate minerals and hydrocarbon.

a) Subhedral pyrite (black) replacing shell material within brachiopod in skeletal wackestone facies. (Cross-polarized light; ICQ 1-8; Scale bar = 0.50 mm.)

b) Hematite (black) occurs as rim around remaining void of collapsed ooid. Close petrographic observation reveals that hematite is altering from and coating fine rhombic void-filling ferroan dolomite. (Plane-polarized light; SCQr 2b/1t; Scale bar = 0.50 mm.)

c) Kaolinitic clay fills bivalve molds at CVC. This SEM photo clearly shows hexagonal plates stacked in "booklets". The field of view shown here was X-rayed, confirming that clay is kaolinite or possibly its polytype dickite. (KV = 20; 0077; Scale bar = 1.0 microns)

d) Some oomolds are rimmed or filled by tar (black) in horizontal oomoldic layers in an oolitic packstone near center of oolitic grainstone facies at JI. (Plane-polarized light; JI 4frt; Scale bar = 1.00 mm.)



have begun as oxidizing meteoric water returned to the formation with recent uplift. The preservation of oomoldic porosity in hematite-rimmed oomolds suggests that iron oxide coatings provide poor nucleation sites for calcite cements, and that initial formation of hematite occurred prior to the introduction of cement-forming active-saturated meteoric waters. The alteration of ferroan dolomite to hematite has continued under recent oxidizing conditions.

#### Kaolinite and Dickite

Oomolds near the base of the oolitic grainstone facies at locality SCQ and bivalve molds at locality CVC are filled by kaolinitic clays. Mossler (1970) reported that these void-filling clays were dickite, but, SEM X-ray analysis has proved unable to distinguish dickite from kaolinite (see Appendix B for X-ray data). The two minerals are polytypes of one another, differing only in the stacking of chemically identical tetrahedral and octahedral sheets (Hurlbut and Klein, 1977). The kaolinitic void-filling consists of euhedral hexagonal plates or "booklets" of plates (Fig. 22c). Molds filled by kaolinite lack carbonate cements, making it difficult to establish the relationship of the clay with other void-filling minerals. Several oomolds at SCQ do show geopetal fillings of kaolinite and final void-filling by megaquartz. This relationship suggests that

kaolinitic clays formed before precipitation of megaquartz, and that the clay crystals probably precipitated out of pore fluids, slowly settling out of solution, rather than nucleating from pore walls.

### Hydrocarbons

Hydrocarbons are rare within the study area, occurring only in the middle of the oolitic grainstone facies at locality JI in southern Miami County, Kansas, where tar lines or fills oomolds in thin horizontal oomoldic layers within an oolitic packstone (Fig. 22d). Ferroan dolomite and associated hematite rim or partially fill much of this moldic porosity in oomoldic layers, but, tar and ferroan dolomite were not found together in oomolds, and the tar rimmed oomolds otherwise remain open. These observations, although inconclusive, suggest the migration of hydrocarbons occurred after solution of ooids and before precipitation of ferroan dolomite. Hydrocarbon rims in oomolds preserved oomoldic porosity by coating possible nucleation sites, and preventing later precipitation of ferroan dolomite. Had ferroan dolomite precipitated before hydrocarbon migration, tar should rim the central voids of those oomolds partially filled by ferroan dolomite.

CHAPTER IV  
REGIONAL DIAGENETIC TRENDS

Although original lithology may influence the development of particular fabrics, many diagenetic characteristics, such as degree of preservation in originally unstable grains, are not directly related to lithology, and trends in these characteristics cut across depositional facies boundaries.

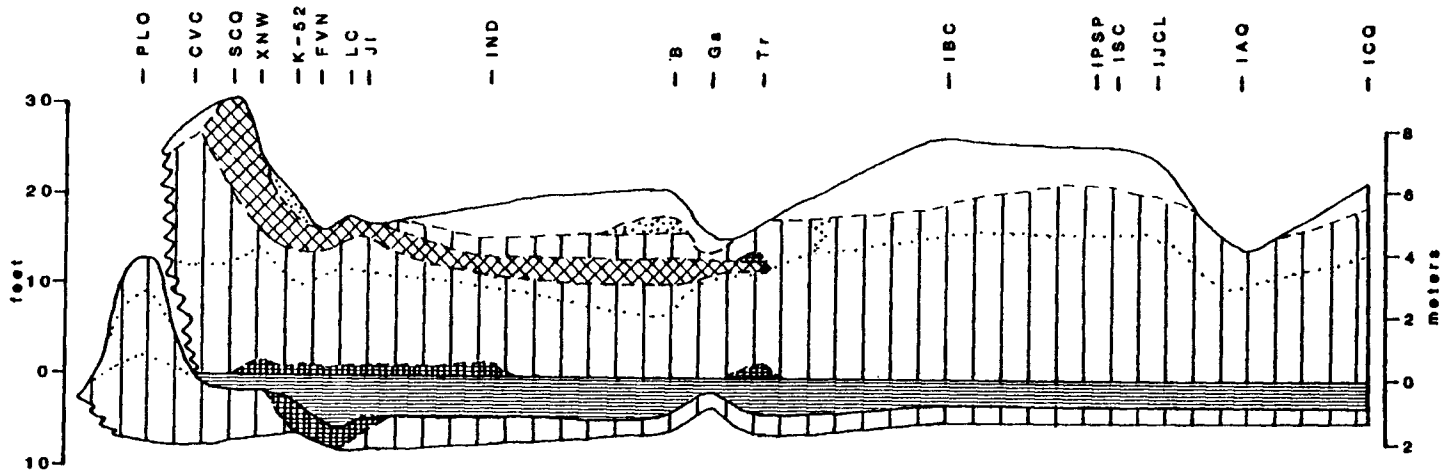
Preservation of Unstable Grains






Unstable grains within the Swope Formation include originally aragonitic bivalves, gastropods, dasycladacean and phylloid algae, and ooids. Preservation of original structure in unstable grains is generally poor within the Swope Formation. The zone of significant preservation of concentric structure in the oolitic grainstone facies (Fig. 10) is the only portion of the Swope where structure is preserved in the majority of unstable grains.

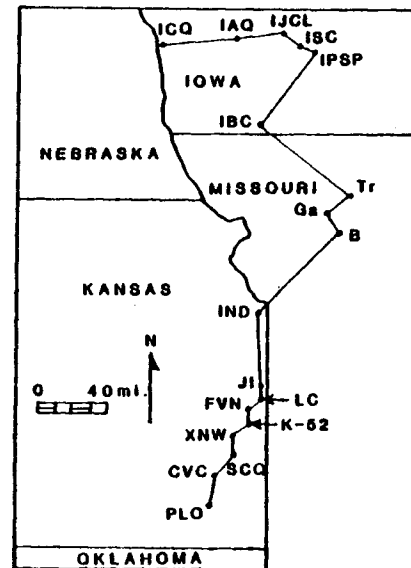
Railsback (1983) delineated five diagenetic facies within carbonate members of the overlying Dennis Formation on the basis of varying degrees of preservation in originally unstable grains. Railsback's diagenetic facies

include: Facies A, in which originally unstable grains contain no trace of original structure; Facies B, in which originally unstable grains contain little or no trace of original structure; Facies C, in which originally unstable grains commonly contain preserved structure but some grains do not; Facies D, in which all originally unstable grains contain preserved structure; and Facies E, which is devoid of unstable grains and has a dolomitic microspar matrix. Distribution of these facies demonstrates an increase of structure preservation in originally unstable grains downward and southward (paleogeographically seaward) within the Dennis Formation (Railsback, 1983 fig. 7). Application of Railsback's descriptive diagenetic facies to the carbonate members of the Swope Formation (Fig. 23) does not reveal a similar trend. Diagenetic Facies A occurs only locally at the base of the rubbly mudstone depositional facies, of which most is devoid of originally unstable grains. Facies B dominates both the Bethany Falls and Middle Creek limestones, cutting across all lithologic boundaries. Facies C occurs only in a band within the oolitic grainstone in Missouri and Kansas. Facies D was not detected in the Swope, and Facies E overlaps Facies B locally near the base of the Bethany Falls and in the Middle Creek Member.

Figure 23. Distribution of diagenetic facies in Swope Formation. Railsback's (1983) descriptive diagenetic facies based on amount of preservation of originally unstable grains, were applied to the Swope Formation. Facies A has no preserved original structure in unstable grains. Facies B has little or no preserved structure in unstable grains. Facies C commonly has preserved structure, but some unstable grains show no preservation. Facies E contains dolomitic microspar in matrix, and overlaps Facies B in the Swope. Dotted lines show depositional facies boundaries.



-  Facies A
-  Facies B
-  Facies C
-  Facies E
-  No Originally Unstable Grains



### Porosity

Primary porosity within the Swope Formation is closely linked to depositional facies, with intergranular voids in both oolitic and osagia grainstones forming most of the primary porosity (Fig. 24a). Minor primary porosity occurred as intragranular or sheltered voids within wackestones, and birdseye voids and mudcracks constituted traces of primary porosity in mudstones (Fig. 24a).

Secondary porosity is not directly related to depositional facies, although the occurrence of moldic porosity is related to the abundance of originally unstable carbonate grains. Because of the abundance of originally aragonitic ooids in the oolitic grainstone, this facies has had the most significant development of moldic porosity in the Swope (Fig. 24b). Minor amounts of moldic porosity occur in the osagia grainstone, skeletal wackestone, and algal boundstone facies, where its development is limited by the low abundance of originally unstable grains. Trace amounts of fracture porosity developed throughout the mudstone and wackestone facies, often connecting molds within wackestones.

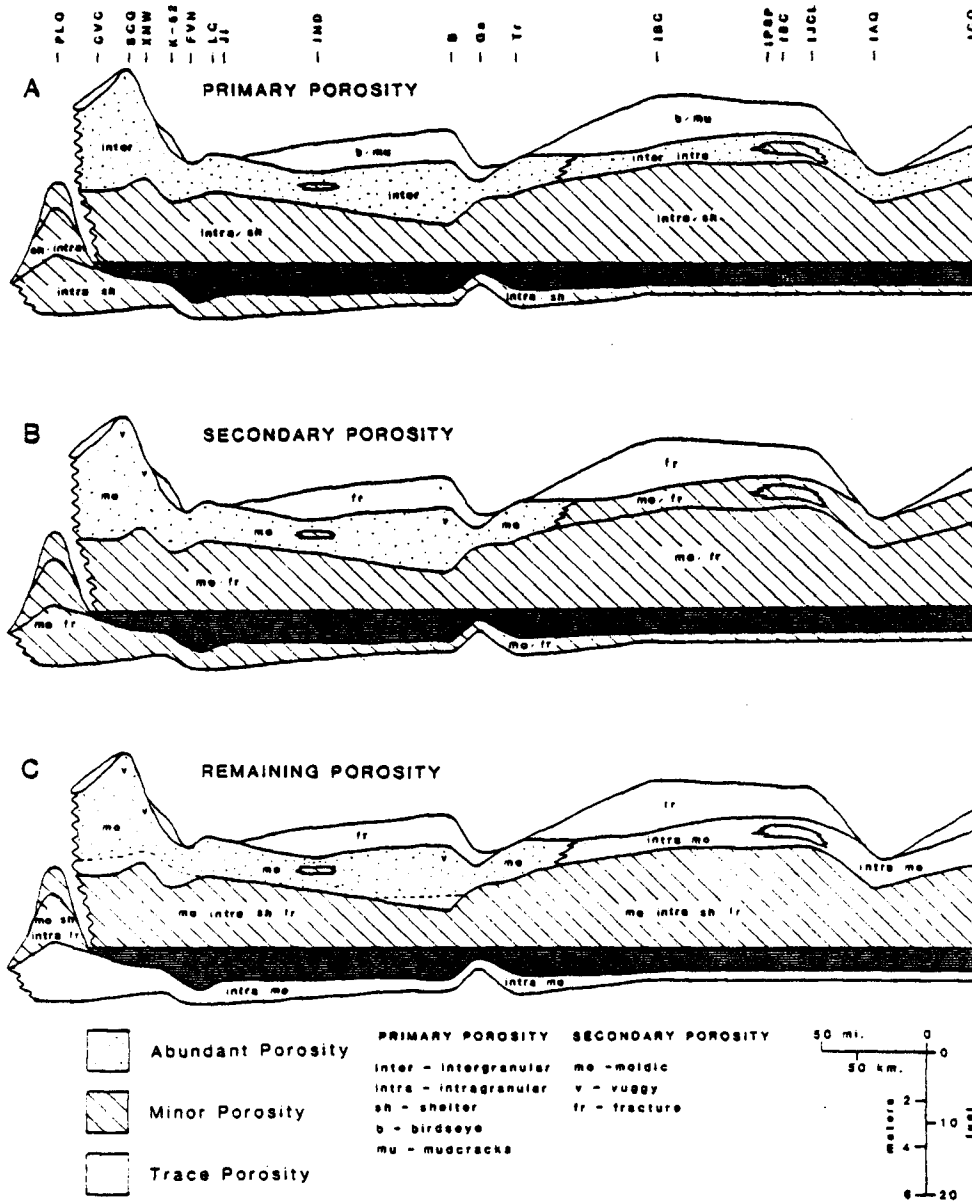
Remaining porosity in the Swope is dominantly secondary, occurring as open or partially open molds and in smaller amount as open fractures. Remaining primary porosity is scarce, consisting of some partially open

Figure 24. Porosity in depositional facies of Swope Formation.

a) Primary porosity in Swope consisted of abundant intergranular porosity in grainstones, lesser intragranular and shelter porosity in skeletal wackestones and algal boundstones, and a trace amount of birdseye and mudcracks in rubbly mudstones.

b) Secondary porosity developed dominantly as oomoldic and vuggy porosity in oolitic grainstones, with lesser amounts of moldic and fracture porosity developing elsewhere within Swope.

c) Although oomoldic porosity has been largely destroyed in crushed zones near base of oolitic grainstone, and partially filled by carbonate cements throughout, remaining porosity in Swope is most abundant as oomoldic and vuggy porosity in upper portion of oolitic grainstone facies. Mudstones and wackestones show little change in overall porosity with creation of minor moldic and fracture porosity compensating loss of minor primary intragranular and shelter porosity. Osagia grainstones with high primary porosity have virtually no remaining porosity due to cement filling of abundant intergranular porosity and limited development of secondary porosity.



intragranular and sheltered voids. Primary intergranular pores in both the oolitic and osagia grainstones have been almost entirely filled by carbonate cements.

Diagenesis has had less effect on the amount of porosity in the rubbly mudstone facies or in the skeletal wackestones of the Middle Creek. Both units had little original porosity and contained few originally unstable grains, thus limiting the development of later moldic porosity. Scarce intragranular pores were filled by carbonate cement. Secondary fractures and vugs near the top of the rubbly mudstone facies were filled by shale, and little moldic porosity developed. Skeletal wackestones of the Bethany Falls and the algal boundstone facies in the Middle Creek contained a fair amount of originally unstable grains, and even though cementation has filled most intragranular and sheltered voids, the creation of secondary molds and fractures has slightly increased the amount of porosity present in these units (Fig. 24c).

The oolitic and osagia grainstones contained abundant primary porosity. Although much porosity remains in the oolitic grainstone facies, primary intergranular porosity has been virtually obliterated in both grainstone facies. The significant amount of remaining porosity in the oolitic grainstone facies consists of oomoldic porosity, occurring above crushed zones, where many oomolds remain at least

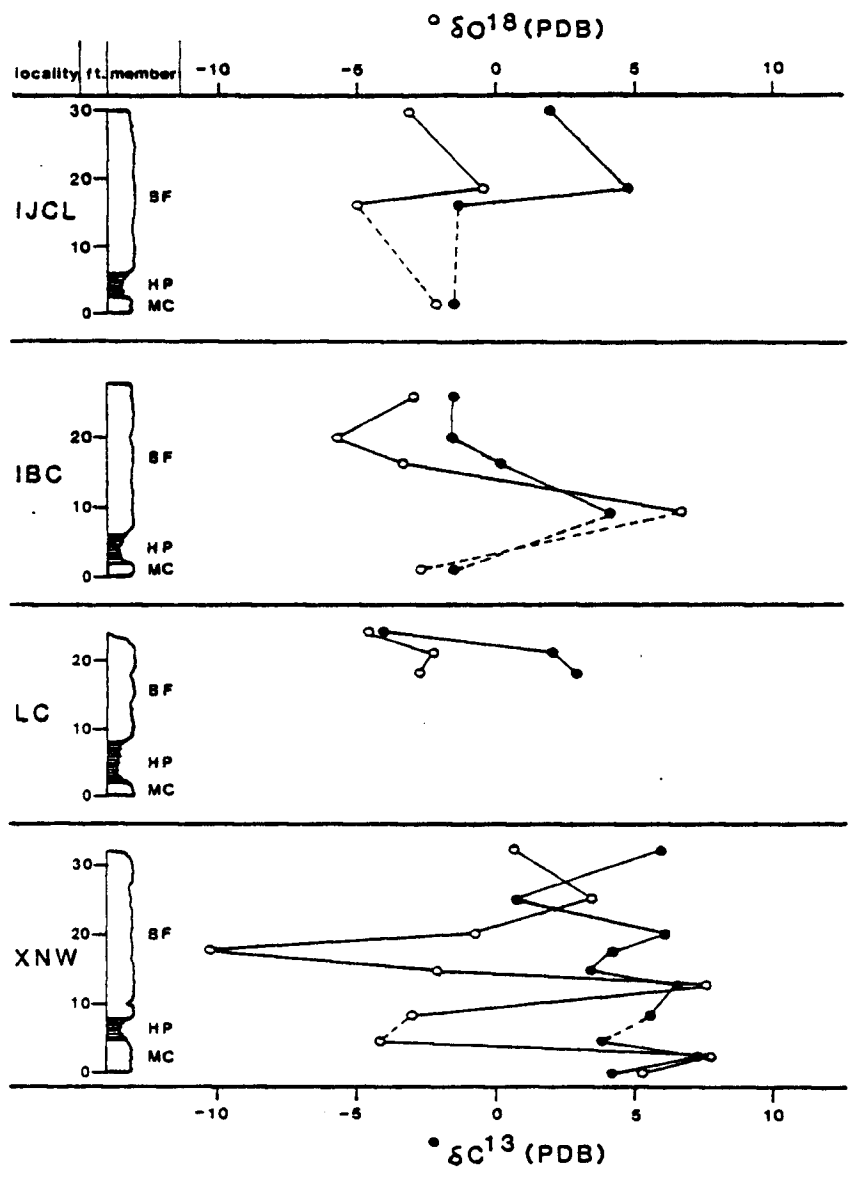
partially open even though neomorphosed ooids are common (Fig. 24c). Although creation of molds allowed oolitic grainstones to remain porous even though intergranular voids were filled, the scarcity of originally unstable grains in the osagia grainstone resulted in a drastic reduction in porosity, as primary pores were filled and few secondary pores were created. Only a trace of porosity remains in the osagia grainstone facies (Fig. 24c).

#### Stable Isotopes

Oxygen and carbon stable isotope analyses were made on bulk samples of the carbonate members of the Swope Formation at four localities. Bethany Falls samples have a mean  $\delta O^{18}$  value of -1.65 PDB (standard deviation = 7.38) and a mean  $\delta C^{13}$  value of 1.97 PDB (standard deviation = 8.81), while mean  $\delta O^{18}$  and  $\delta C^{13}$  values for Middle Creek samples are 0.69 PDB (standard deviation = 1.50) and 2.29 PDB (standard deviation = 5.12) respectively.

Except for its irregular distribution at locality XNW,  $\delta O^{18}$  generally lightens upsection within the Bethany Falls member (Fig. 25; data provided in Appendix B). This lightening-upward trend is displayed best at locality IBC and near the top of the Bethany Falls at LC where the top sample is caliche.  $\Delta C^{13}$  values show similar patterns as  $\delta O^{18}$  values.

Figure 25. Vertical trends in oxygen and carbon stable isotopes. Delta O<sup>18</sup> values (open dots) and  $\delta^{13}$ C values (shaded dots) of samples from Middle Creek (MC) and Bethany Falls (BF) members generally lighten upward, except for XNW where values are irregular. Top of Middle Creek is isotopically lighter than base of Bethany Falls. All isotopic values are relative to PDB standard.



Samples from the top of the Middle Creek member are isotopically lighter than samples from the base of the Bethany Falls (Fig. 25; localities IBC and XNW), and the Middle Creek member shows a distinct lightening upward  $dO^{18}$  trend at XNW.

### Cathodoluminescence

Study of cathodoluminescence within the Swope was originally undertaken as a means of determining the origin of spar in questionable cases. Luminescent zonation within spar suggests distinct episodes of void-filling cementation, whereas lack of zonation suggests 1) a single episode of void-filling cementation, 2) no change in Fe/Mn ratios throughout cementation, or 3) a neomorphic origin. Although luminescent zones were apparent in some voids, often the luminescence was patchy or gradational, and smaller molds typically showed no zonation, which limited the application of luminescence as an indicator of spar origin. Cathodoluminescence did, however, show thin dull or dead zones around the initial rims of some intragranular and intergranular voids. This observation led to the discovery of early ferroan blocky calcite cement rims when thin sections displaying the dull rims were stained.

CHAPTER V  
INTERPRETATION OF DIAGENESIS

Rubbly Mudstone Facies

Grain Preservation and Cements

Dropped nuclei in ooids near the base of the facies, and complete lack of preserved internal structure throughout the facies in sparse molluscs suggest that unstable grains were leached by undersaturated meteoric water. Complete lack of preserved structure within unstable grains also suggests that no saturated meteoric water had been introduced prior to leaching, or that exposure of the facies to saturated meteoric water prior to leaching was short-lived, thus preventing preservation by neomorphic processes.

Small original pores are filled by nonferroan blocky calcite, which most likely precipitated in the active-saturated zone of the meteoric phreatic environment (Longman, 1980; Folk, 1974). Secondary molds and fractures are typically filled by ferroan dolomite or less commonly nonferroan and ferroan calcite. Nonferroan calcite probably precipitated in the active-saturated meteoric phreatic, whereas the ferroan cements probably precipitated near the

base of the meteoric phreatic or in the deeper-burial connate environment, where reducing conditions prevailed. Some fractures are partially filled by possible pendent cements, although these cements often have crystal terminations rather than smooth edges expressing the air water interface around grains (Longman, 1980). If indeed they are pendent cements, they would have formed in the zone of precipitation in the meteoric vadose environment.

Microspar mottles in the rubbly mudstone in Kansas and Missouri are chemically similar to surrounding micrite suggesting that mottling is not due to concentration of impurities or organic matter, as was considered a possible cause by Mossler (1971). Mottles are isotopically lighter in  $\delta O^{18}$  and lighter and more variable in  $\delta C^{13}$  than surrounding matrix suggesting that microspar mottles formed in the presence of meteoric waters (Hoefs, 1980; Keith and Weber, 1964). This interpretation is supported by Steinen's (1982) discovery of microspar aggrading from micrite in recent Bahamian lime muds. (Interpretation of mottling will be discussed in greater detail in a later section).

The rubbly nature of the mudstone in outcrop through Kansas and Missouri is the result of differential weathering of resistant microspar mottles and less resistant micritic matrix. Therefore this weathering likely occurred after mottle formation. Near the top of the facies at locality

IBC the micritic matrix has been extensively leached and shale from the overlying Galesburg Formation has filtered downward, filling solution vugs and cracks or fractures around mottles. Schutter (1983) described the upper surface of the Bethany Falls as extensively solution pitted and suggested that much of the overlying Galesburg shale originated from subaerial weathering of the Bethany Falls Limestone.

Fine crystal size and occurrence of nonferroan dolomite in laminae interbedded with micrite at locality ICQ suggest that laminated nonferroan dolomite was syndepositional, probably forming on supratidal flats analogous to recent dolomitization in the Bahamas (Shinn et. al., 1965).

#### Summary

Diagenesis of the rubbly mudstone facies is best explained by early diagenesis in a supratidal setting followed by the introduction of undersaturated meteoric phreatic and vadose environments as regression continued, ending Bethany Falls deposition. Laminae of nonferroan dolomite formed as crusts replacing lime mud on supratidal flats at locality ICQ, and non-marine Galesburg shale filled mudcracks, fractures, and solution pits and vugs, probably as they developed at the top of the rubbly mudstone facies throughout its extent. Undersaturated meteoric phreatic,

and vadose water leached originally aragonitic grains within the facies, destroying all original structure and forming molds. Possible pendent cements suggest development of local zones of precipitation within the meteoric vadose environment as  $\text{CaCO}_3$  was transferred downward. Later as sea-level rose with the onset of the transgression that began deposition of the overlying Dennis cyclothem, the undersaturated meteoric zones were replaced by the active-saturated and then stagnant-saturated zones of the meteoric phreatic environment, and finally by the deeper-burial connate environment. With the introduction of saturated meteoric water, nonferroan blocky calcite filled small original pores and filled or rimmed larger molds. Microspar formed in the active-saturated zone in equilibrium with meteoric waters, where it aggraded from micrite in slightly more permeable zones within the mudstone, resulting in microspar mottling. As transgression continued, diagenetic environments continued to migrate upward through the facies introducing the base of the meteoric phreatic environment and deeper-burial connate environment where reducing conditions prevailed, allowing ferroan calcite and dolomite to fill remaining void space. Fractures, typically filled by ferroan calcite, probably formed near the base of the meteoric phreatic environment or within the deeper-burial connate environment. With recent uplift and

resumed exposure to unsaturated meteoric water, micritic matrix has been preferentially weathered and leached, allowing further infiltration of overlying shale into solution vugs and cracks around resistant microspar mottles, and enhancing the rubbly outcrop appearance of the facies in Kansas and Missouri.

#### Osagia Grainstone Facies

##### Grain Preservation and Cements

Algal and sponge borings and micritization of grains within the osagia grainstone facies must have formed while these organisms remained active, at or near the sediment-water interface in the stagnant zone of the marine phreatic environment.

Originally unstable grains within the facies, including fragments of phylloid algae, dasyclads, and molluscs, are generally poorly preserved suggesting that they were leached by undersaturated meteoric water. Phylloid algae show no preservation of structure, and dasyclads show no preservation of internal structure other than external pores preserved by micrite or finely crystalline cements. Preservation of some internal structure within a small portion of molluscan grains, however, suggests that some neomorphism of molluscan grains occurred prior to leaching. Neomorphism would require saturated meteoric water and

probably occurred in the stagnant-saturated zone of the meteoric phreatic environment (Folk, 1965; Longman, 1980).

Original pores within the osagia grainstone facies include intergranular and intragranular voids.

Intergranular voids filled with syntaxial overgrowths of echinoderms near the base of the facies and with blocky calcite upsection become less ferroan toward void centers, which suggests a change from reducing to oxidizing conditions during void-filling. Blocky calcite cements probably formed rapidly without echinoderm nucleation higher in the saturated meteoric phreatic environment where there was active circulation of pore waters, whereas syntaxial cements may have formed preferentially as circulation decreased lower in the saturated meteoric phreatic environment.

Intragranular cements display a sequence of early ferroan calcite, followed by nonferroan calcite, and final fill of ferroan dolomite or calcite. This sequence indicates the development of oxidizing conditions between early and late periods in reducing environments. The early ferroan calcite may have formed near the base of the meteoric phreatic environment where oxygen had been depleted. The nonferroan calcite probably formed higher in the active-saturated zone of the meteoric phreatic environment, during greatest penetration of the oxygenated

meteoric environment at maximum regression, and later ferroan cements probably formed in the deeper-burial connate environment.

Both intergranular and intragranular voids at locality IND often contain sparse early rims of scattered nonferroan dolomite rhombs. The peripheral location of these rims indicates that dolomite formed before precipitation of meteoric cements, and probably represents dolomitization within the initial passage of the mixing zone where waters may be saturated with respect to dolomite while undersaturated with respect to calcite (Badiozamani, 1973).

In contrast, grain molds are filled by early rims of nonferroan calcite and later inner fillings of ferroan dolomite or less commonly ferroan calcite. This sequence is identical to the final two stages of intragranular void filling, but the earlier rims of dolomite and ferroan calcite seen in primary pores were never seen in molds. These observations suggest that unstable grains were leached by undersaturated meteoric water after the rims of dolomite and early ferroan calcite had already formed in primary voids. The preservation of large gastropod molds at ICQ within the grainstone also suggests that dissolution of originally aragonitic grains must have occurred after intergranular cements had lithified the sediment.

Crushed brachiopods suggest that some compaction took place before lithification, and stylolites concentrated near the base of the facies indicate that compaction continued after lithification by pressure solution.

#### Summary

Diagenesis in the osagia grainstone facies is best explained by the progression of diagenetic environments from the marine phreatic through the mixing zone, saturated meteoric phreatic, and undersaturated meteoric phreatic and possibly vadose environments with regression, followed by the reversal of this progression culminating in the introduction of a deeper-burial connate environment with the transgression that began deposition of the overlying cycle.

Micritization and boring of grains occurred in the marine phreatic, and early nonferroan dolomite rims around original voids probably formed as the mixing zone passed through during early regression. As regression continued, the osagia grainstone facies was introduced to the meteoric phreatic environment, base first. The meteoric phreatic lense was thick enough to allow reducing conditions to develop near its base, where early ferroan calcite precipitation and minor neomorphism of unstable grains occurred. As the meteoric phreatic environment migrated downward through the osagia grainstone facies, syntaxial overgrowths and blocky calcite cements continued to

precipitate, becoming less ferroan as the upper, more oxidizing portion of the saturated meteoric phreatic reached the sediment. At maximum regression, introduction of undersaturated meteoric water leached those unstable grains that had not been neomorphosed. With renewed transgression, migration of diagenetic environments reversed, reintroducing the saturated meteoric phreatic where further growth of nonferroan blocky calcite partially filled molds of unstable grains and remaining portions of intragranular voids. Finally with the introduction of reducing conditions in the deeper-burial connate environment, ferroan dolomite filled remaining interiors of molds and intragranular voids.

#### Oolitic Grainstone Facies

##### Grain Preservation

Preservation of molluscan grains in the oolitic grainstone facies is very similar to that within the osagia grainstone facies, with relict structure persisting in a small percentage of molluscan grains. The general lack of preservation suggests solution of molluscs by undersaturated meteoric water. The preservation of some relict structure in molluscs suggests that minor neomorphism of some molluscs occurred in saturated meteoric water prior to solution.

Preservation of concentric structure in originally aragonitic ooid cortices is extremely variable, ranging from

structureless to well preserved. Structureless ooids often contain dropped nuclei and thus resulted from the leaching of the entire cortex by undersaturated meteoric water. Solution of the cortices formed oomolds and allowed insoluble nuclei to settle into geopetal positions within oomolds. Oomolds then may persist as voids if not filled by cement.

Many ooids show preservation of some original structure. Ooids with well preserved concentric cortical layering have been entirely neomorphosed. Neomorphism preserved the outer concentric layering in many ooids with structureless, leached, inner cortices. Preservation of cortical material may cut across concentric layering, and neomorphosed bridges of cortical material support centrally located nuclei in some otherwise leached ooids. In bipartite ooids at CVC, preserved inner cortices around nuclei have settled to the bottom of the void created by solution of the outer cortical layering. Preservation in all cases can be related to neomorphism of unstable material in the first passage of the saturated meteoric phreatic environment. Because pore waters would have affected the outer portion of grains first, preservation of outer cortical layering and leaching of inner cortical layering throughout the facies suggests early exposure to saturated meteoric phreatic water followed by later exposure to

undersaturated meteoric water. The preservation of the inner cortex and not the outer cortex in bipartite ooids suggests early exposure of the facies to undersaturated meteoric water followed by later exposure to saturated meteoric water.

The variability of preservation in ooids compared to the consistently poor preservation of molluscs in the facies suggests that the heterogeneity of ooid preservation may be a result of an original heterogeneity of ooid composition or microstructure. Although inorganic precipitation may play the dominant role in ooid genesis, even minor biologic influence by algae, bacteria, and fungi in some ooids could affect their susceptibility to the processes of neomorphism or dissolution (Bathurst, 1975; Newell et. al., 1960).

#### Oomoldic Fabrics

From the top of the facies downward, oomoldic fabrics range from vuggy, to oomoldic, to collapsed oomoldic, to crushed oomoldic in zones at the base. Vugs at the top of the facies often show outlines of numerous oomolds and resulted from enhancement of oomoldic porosity by local solution of relatively stable intergranular cement. The development of vugs began with prolonged exposure to the undersaturated meteoric vadose environment during maximum regression, and may have been enhanced by recent exposure to

undersaturated water in the modern meteoric vadose environment.

Lower in the facies oomolds remain as individual spherical voids, suggesting that ooids were leached by undersaturated meteoric water, but were not exposed to the undersaturated meteoric water long enough to produce vugs.

Collapsed oomolds and chains of collapsed oomolds suggest differential compaction of the oolitic grainstone in zones weakened by solution. Conley (1977) interpreted similar fabrics in the Plattsburg Limestone as resulting from solution of most or all of the ooid cortices and subsequent displacement of intergranular cements, often with several neomorphosed outer cortical layers, distorting the oomolds and reducing porosity. Wilkinson and Landing (1978) also have interpreted similar distortion of ooids in the Twin Creek Limestone to be the result of solution-enhanced compaction. The occurrence of nonferroan blocky calcite fillings in spherical oomolds, in contrast to ferroan dolomite or lack of filling in collapsed oomolds suggests that compactional collapse took place after precipitation of mold-filling nonferroan blocky calcite in the active-saturated zone of the meteoric phreatic environment but before precipitation of ferroan dolomite in the deeper-burial connate environment.

Zones of crushing at the base of the facies suggest the complete collapse of original oomoldic fabric, resulting in packing of intergranular cement shards. Conley (1977) emphasizes that cement-shard fabrics indicate a reversal of grains and pores. Original intergranular pores were filled by cement whereas ooids were leached, becoming pores. With compaction, oomolds were crushed destroying all obvious evidence of the original ooid grains, and intergranular cement shards became the actual grains of the rock. Cement-shard fabrics developed near the base of the facies, where lithostatic pressure was greatest, in structurally weak zones with a high abundance of open oomolds, thin intergranular cements, and where there was little preservation of outer cortical layering. At locality B, cement-shard fabric developed in weaker zones between rigid silicified layers, suggesting that silicification predated leaching of ooids.

#### Carbonate Cements

Original pores within the oolitic grainstone facies are dominantly filled by nonferroan blocky calcite, which probably formed in the active-saturated zone of the meteoric phreatic environment. Some intergranular pores, especially near the base of the facies, contain thin peripheral rims of ferroan blocky calcite, which may have formed under reducing

conditions near the base of the saturated meteoric phreatic environment. Relict fibrous rims often occur around grains within intergranular blocky calcite in areas lacking point contacts between ooids. Relict fibrous rims are interpreted to be early marine cements, which probably precipitated in the active zone of the marine phreatic environment before meteoric penetration. The lack of microdolomite inclusions in the relict fibrous rims suggests that they were originally aragonite rather than high magnesium calcite (Lohmann and Meyers, 1977).

Moldic porosity is generally filled to some degree by either nonferroan blocky calcite, ferroan calcite or dolomite, or by the combination of early nonferroan blocky calcite and later ferroan calcite or dolomite. Nonferroan blocky calcite probably formed in the active-saturated zone of the meteoric phreatic environment, whereas ferroan void-filling cements and minor replacement ferroan dolomite formed in the deeper-burial connate environment. The diversity of mold-filling within a small area suggests that microenvironments and local hydrologic controls played a major role in determining which oomolds remained open, which were filled, and what type of cements filled them. The sheltering of ooids within large bivalves at CVC (Fig. 9f) is an example of local hydrologic control. Sheltering of ooids within bivalves inhibited them from being leached and

eventually filled by ferroan dolomite (as were ooids outside the bivalves) and allowed them to be neomorphosed in the microenvironment within the bivalves.

#### Caliche and Solution Channels

The caliche crust capping the Bethany Falls at locality LC has been interpreted by Heckel (1983) to represent paleocaliche, formed near the surface of subaerial exposure in the saturated zone of the meteoric vadose environment during extreme regression. This interpretation is supported by Watney's (1980) discovery of similar caliche crusts capping regressive limestones in Missourian cores from western Kansas, and by Schutter's (1983) determination of a well developed soil profile in the overlying Galesburg Shale. Petrographic study of solution channels below the crust at localities LC and JI reveals direct evidence that the crust is indeed paleocaliche.

Large vertical channels at locality LC and JI are interpreted as solution channels formed by undersaturated meteoric water, which moved downward through the oolitic grainstone selectively dissolving unstable ooids in more permeable downward pathways. Solution of ooids made downward movement of water even easier in these zones, and continued flushing by undersaturated meteoric water eventually dissolved the relatively stable intergranular

cements from the centers of larger pathways, creating channels. Mossler's (1970) interpretation of a burrowing origin for these channels seems doubtful because the smaller channels actually contain no open channel, but rather consist of a vertical zone of oomoldic porosity with intergranular cement intact.

The large vertical pathways consist of a central channel and a zone of oomolds grading into a host rock of unleached oolitic grainstone. Finely crystalline (thermodynamically less stable) caliche has replaced coarser (thermodynamically more stable) intergranular cements in a zone of unleached oolitic grainstone around solution channels. This suggests that boring by soil-forming microorganisms may have aided calichification (Klappa, 1979), and that waters moving downward through channels became saturated in the meteoric vadose environment. Later, ferroan dolomite precipitated in the deeper-burial connate environment and filled central channels, oomolds, and fractures within the calichified zone. The ferroan dolomite-filled fractures cutting the calichified oolitic grainstone are petrographic evidence in favor of Heckel's interpretation of the crusts as paleocaliche rather than modern caliche.

### Summary

The diagenetic features present in the oolitic grainstone facies are best explained by the progression of marine phreatic, meteoric phreatic and meteoric vadose environments through the facies during regression, and the progression of meteoric vadose, meteoric phreatic, and deeper-burial connate environments with succeeding transgression. Fibrous rims of aragonite cement precipitated around ooids in local active zones of the marine phreatic environment shortly after deposition. As regression began, marine phreatic water was replaced by saturated meteoric phreatic water. Thin early rims of blocky ferroan calcite formed under reducing conditions brought about by early organic decay near the base of the facies. Reducing conditions were probably limited to the base of the saturated meteoric phreatic environment, and the highest occurrence of these early ferroan rims in any one section may mark the top of the reducing or stagnant portion of the meteoric phreatic environment before the higher diagenetic environments migrated downward with regression. Nonferroan blocky calcite then precipitated in intergranular voids above the base of the active oxidizing portion of the saturated meteoric phreatic, and followed the early ferroan calcite as the base of the active environment migrated downward through the rock. Fibrous marine cements, ooids,

and molluscs were neomorphosed to varying degrees, from the outer edge to the grain center, while the facies was permeated with saturated meteoric phreatic water. Unneomorphosed portions of unstable grains were later leached by unsaturated meteoric waters, producing moldic and vuggy porosity. With extreme regression the oolitic grainstone was locally subaerially exposed, and solution channels developed within the solution zone of the meteoric vadose environment. Continued solution and local accumulation of calcium carbonate formed saturated zones at and near the surface of the meteoric vadose environment, where caliche precipitated.

With the onset of transgression which began deposition of the overlying cyclothem, migration of diagenetic environments reversed, reintroducing saturated meteoric phreatic water. In the active-saturated meteoric phreatic zone, nonferroan blocky calcite began to fill oomolds. With deposition of more of the overlying cyclothem, lithostatic pressure increased, and open oomolds collapsed near the base of the facies; oomoldic fabrics were completely crushed in zones at the base of the facies, producing cement-shard fabrics. This compaction occurred between the precipitation of nonferroan calcite in the active-saturated zone of the meteoric phreatic and the precipitation of mold- and fracture-filling ferroan dolomite and calcite in the

deeper-burial connate environment. Minor replacement of preserved nuclei and mold-filling cements in ooids, and of intergranular cement by rhombs of ferroan dolomite also probably occurred in the deeper-burial connate environment.

### Skeletal Wackestone Facies

#### Bethany Falls Member

#### Grain Preservation, Cements, and Matrix

Boring by sponges, encrustation by algae, bryozoans, and foraminifers, and micritization of grains are all the result of biologic agents at or near the sediment/water interface within the stagnant zone of the marine phreatic environment.

The general lack of preserved original structure in unstable grains, including molluscs and phylloid algae suggests that unstable grains were leached by undersaturated meteoric water. As grains were dissolved, micrite envelopes and encrustations often collapsed into the molds of grains that formerly supported them. Large patches of spar, often with smooth upper edges, probably represent combined algal molds and sheltered voids or combined bivalve molds and interior voids. The collapse or absence of original encrustations or micrite envelopes makes it impossible to distinguish the original mold from the rest of the void. Fractures connecting molds and patches of spar usually are

filled by cement similar to that filling the molds. This suggests that fractures probably formed while open molds existed as weak points in the rock.

Preservation of original layering in a small portion of mollusc grains, and the possible preservation of utricles in some phylloid algae suggest that minor neomorphism of some unstable grains occurred in saturated meteoric water before leaching.

Original voids within the facies are filled with some portion of a sequence that includes up to six zones or rims of cement (chapter 2). Thin rims of blocky calcite or ferroan calcite (1) that contain relict fibrous structure are interpreted as early aragonite rims, formed in the active marine phreatic and later neomorphosed to blocky calcite in saturated meteoric water. Thin irregular rims of fine nonferroan dolomite rhombs (2) occurring near the edges of voids, between fibrous marine cements (when present) and blocky meteoric phreatic cements, may have formed in the mixing zone, which separated marine from meteoric pore water. Considering Folk's (1974) concept of magnesium poisoning, the thin rims of bladed cement (3) may also represent precipitation in the mixing zone where salinities were too low for fibrous cements to develop but too high for equant cements to form. Early thin ferroan blocky calcite rims (4) probably formed under local reducing conditions in

the stagnant zone near the base of the saturated meteoric phreatic environment. The thick nonferroan blocky calcite (5) filling the dominant portion of original voids, probably precipitated in the subsequent active-saturated zone of the meteoric phreatic environment. Ferroan dolomite and calcite (6) that fill the central portions of original voids probably formed under reducing conditions in the deeper-burial connate environment.

Secondary porosity, including molds and interconnecting fractures between molds and large patches of spar, were filled by peripheral nonferroan blocky calcite of generation (5) in the active-saturated meteoric phreatic, followed by central ferroan cements (6) formed under reducing conditions in the deeper-burial connate environment.

The local occurrence of pelleted or grumous textures and the lack of crushed grains in the upper portion of the wackestone facies suggests that little compaction took place before cementation in the active-saturated meteoric phreatic. However, crushed brachiopods with displaced rims containing relict fibrous structure and undisturbed central blocky fills, abundant stylolites, and lack of grumous textures in the lower part of the facies suggest that significant compaction occurred there before cementation in the active-saturated meteoric phreatic.

Ferroan dolomite replaces micrite locally near the base of the Bethany Falls in areas adjacent to the Hushpuckney Shale Member. McHargue and Price (1982) recognized that ferroan dolomite replaces micritic zones adjacent to shales in a number of Pennsylvanian cyclothems, including the Swope, and proposed that magnesium is released during shale diagenesis in the deeper-burial connate environment as temperature and duration of burial increase.

### Mottling

Color mottling in the Bethany Falls is due to the crystal size difference between mottles and matrix. The more coarsely crystalline microspar mottles absorb more light than the micritic matrix and therefore appear darker than the matrix in reflected light in hand samples. In thin section, the mottles appear lighter than matrix because microspar is much more translucent than the micrite. The reversal of color from hand sample to thin section is analogous to that of a spar-filled intragranular void. ✓

The stratigraphic distribution of microspar mottling in the rubbly mudstone facies, and above chert horizons interpreted as originating in the mixing zone (see later section on silica) in the upper skeletal wackestone facies, suggests that the microspar may have aggraded from micrite in the saturated meteoric phreatic environment while chert ✓

formed in the mixing zone beneath the meteoric wedge. The occurrence of mottles as discrete patches, or in anastomosing networks suggests that aggradation of microspar occurred in slightly more permeable zones, such as burrows or where pelletal textures remained, where a greater volume of meteoric water was flushed through the rock. ✓

Analyses of oxygen and carbon stable isotopes in microspar mottles and the adjacent micritic matrix samples from four localities provide further evidence that mottles had a meteoric origin. Mottles at each locality have lighter  $\delta O^{18}$  values than corresponding matrix samples at each locality suggesting that microspar formed in equilibrium with isotopically lighter meteoric waters. Fractionation of seawater by evaporation produces meteoric water deficient in  $O^{18}$ , compared to seawater (Hoefs, 1980). The variability of  $\delta C^{13}$  values in mottles suggests they formed in a meteoric system where  $C^{13}$  deficient carbon derived from land plants and humus would have been introduced in several stages (Keith and Weber, 1964; Allan and Matthews, 1977). Micritic matrix samples have a narrow range of  $\delta C^{13}$  values suggesting formation in a stable marine environment, unaffected by plant derived  $C^{12}$  enriched soil gas (Keith and Weber, 1964; Allan and Matthews, 1977). ✓

Microprobe and SEM x-ray analyses demonstrate that although mottles and matrix have very similar chemical

compositions, microspar mottles are slightly purer calcite than the micritic matrix, which often contains minor dolomite and has a slightly higher clay content. This suggests that impurities may have been expelled from the mottles during recrystallization to microspar. All probed mottles consisted of more than 95% pure calcite, with average calcite content of 97%. No evidence was found to support Mossler's (1970) speculation that concentrations of organic material and/or iron sulfides may have caused some of the mottling in the Bethany Falls.

Mottling occurs throughout the outcrop belt in Kansas and Missouri and was detected in core at locality IBC in southwest Iowa, but is not present at any other Iowa locality (Fig. 15). Accepting the idea that mottling probably resulted from exposure to saturated meteoric phreatic water, paleohydrologic and paleogeographic reconstruction may explain the lack of mottling in Iowa. Southwestern Iowa was paleoshoreward during the Upper Pennsylvanian and with regression the sea withdrew to the southwest, toward the Oklahoma border (Heckel, 1980a). As regression began in the Swope cycle the wedge of saturated meteoric phreatic water may have passed rapidly through the Iowa region, introducing undersaturated meteoric phreatic and then undersaturated meteoric vadose environments at a stage early enough to prevent aggradation of micrite to

microspar, which requires saturated meteoric water. In support of this model, Railsback (1983) concluded that calcium carbonate was transferred downward and southward in the Dennis Limestone under similar hydrologic conditions. He suggested that the saturated meteoric phreatic wedge would increase in thickness as it migrated downward and southward, and would have had little early influence on upper paleoshoreward deposits. ✓

Heckel's (1980a) paleogeographic reconstruction of the midcontinent during the Upper Pennsylvanian suggests that climatic variation along the outcrop belt may also have played a role in preventing mottling within the Bethany Falls in Iowa. In his reconstruction, the Midcontinent outcrop belt from southeast Kansas to the approximate location of core IBC runs subparallel to the equator between latitudes of 6° and 7° (Fig. 26). This portion of the outcrop belt would have been near the doldrums rain belt in a relatively humid climate. Rainfall would have frequently flushed meteoric water through the sequence, producing a thick meteoric phreatic wedge, which would favor the development of microspar mottling. The Iowa localities where mottling is absent are along a portion of the outcrop belt which runs directly westward from south-central Iowa. Paleogeographically this portion of the outcrop belt ran due north, directly away from the doldrums rain belt and into

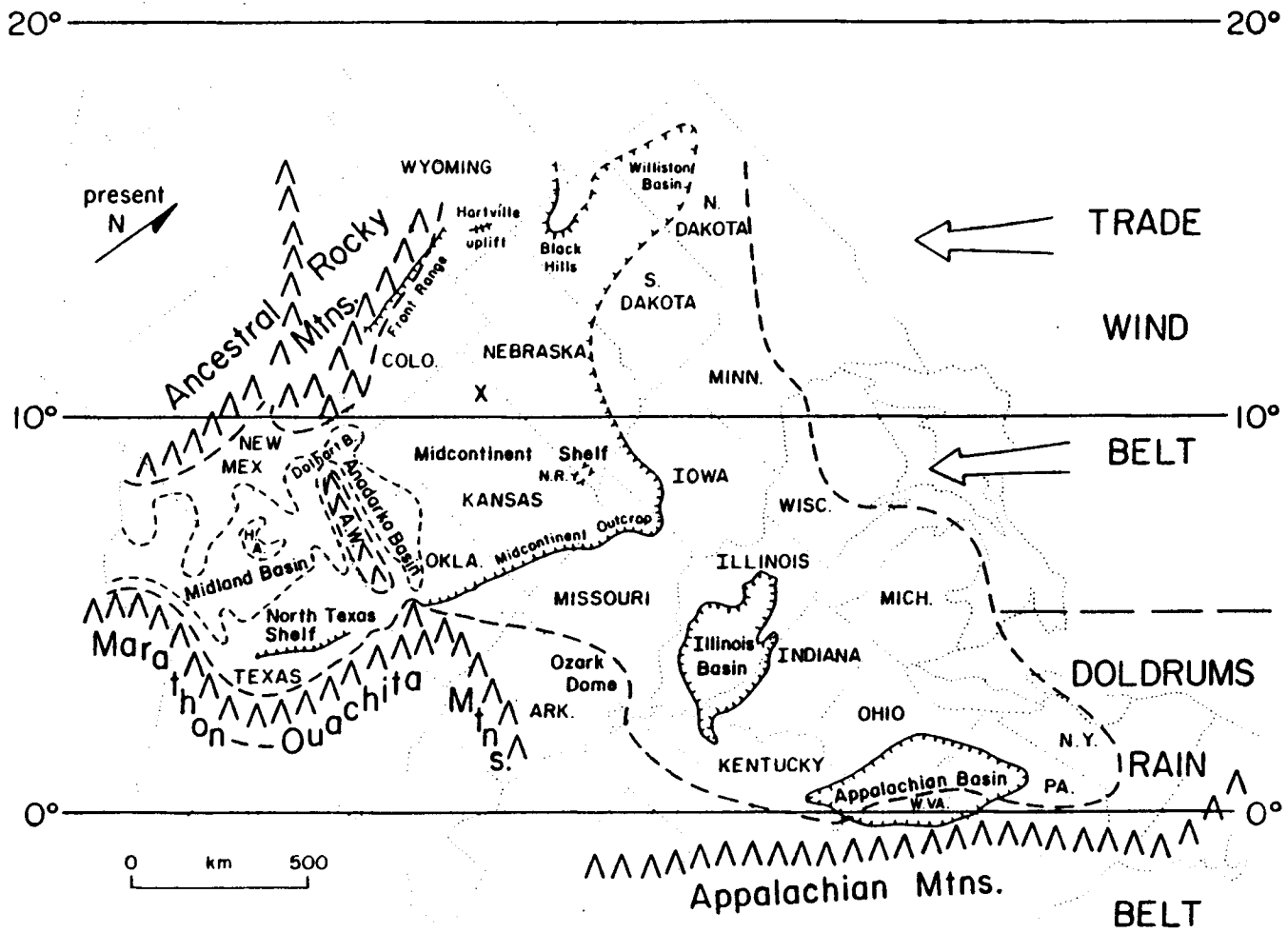
the arid trade wind belt (Fig. 26). The more arid climate would have resulted in a thinner meteoric phreatic wedge, thus reducing the opportunity for microspar mottling to develop as the thin wedge of meteoric water migrated downward with regression.

An excellent modern analogue for microspar mottling in the Bethany Falls is provided by Steinen's (1982) discovery of nodules of microspar aggrading from micrite in meteoric phreatic lenses within modern Bahamian lime muds. SEM study of these nodules shows solution molds of aragonite crystals, demonstrating the crystal by crystal solution of mud and growth of microspar (Steinen, 1982).

#### Summary

Diagenesis within the skeletal wackestone facies of the Bethany Falls Members may be explained by progression from marine phreatic to mixing zone, saturated meteoric phreatic, and undersaturated meteoric phreatic environments with regression, and reversal from the undersaturated meteoric phreatic to finally the deeper-burial connate environment with the following transgression. Fibrous rims of aragonite lined intragranular voids in active zones of the marine phreatic environment, while boring, encrustation, and micritization occurred in stagnant zones of the marine phreatic environment. As the mixing zone passed through,

Figure 26. Upper Pennsylvanian paleogeographic reconstruction of Midcontinent. Base of Midcontinent outcrop belt (solid hachured line) ran subparallel to equator from southeastern Kansas into south-central Iowa, where it turned sharply northward heading away from doldrums rain belt into more arid trade wind belt. Absence of microspar mottling in Iowa may be due to a drier paleoclimate limiting extent of meteoric phreatic wedge. (From Heckel, 1980a)



thin irregular rims of scattered dolomite rhombs formed within original voids as did rims of bladed calcite. Near the base of the facies, compaction destroyed pelletal textures and crushed some brachiopods before introduction of saturated meteoric water. With the introduction of saturated meteoric water, fibrous marine cements and some unstable grains were neomorphosed. Thin early rims of blocky ferroan calcite may have formed under local reducing conditions at the base of this environment. Blocky calcite cements then precipitated in remaining original pores, and micrite began to aggrade to microspar in patchy regions in the active-saturated zone of the meteoric phreatic environment. During maximum regression, unstable grains were leached in the undersaturated zone of the meteoric phreatic environment, producing moldic porosity. With the advent of later transgression, saturated meteoric water rose through the facies and precipitated nonferroan blocky calcite in the remainder of original pores, in some molds, and in fractures that connected structurally weak open molds in the rock. Formation of microspar mottles, which began in the saturated meteoric phreatic environment during regression, may have resumed with the return of the same environment during transgression. Finally the facies passed into the deeper-burial connate environment, where ferroan dolomite and calcite filled central portions of remaining

pores, and fine rhombic ferroan dolomite replaced micrite in zones adjacent to the core shale.

#### Middle Creek Member

Preservation of unstable grains in the Middle Creek ranges from generally the same as, to perhaps slightly better than preservation in the Bethany Falls. This suggests that following minor neomorphism of unstable grains in the saturated meteoric phreatic, undersaturated meteoric water from the Bethany Falls penetrated the Hushpuckney shale and leached unstable grains.

The skeletal wackestone facies in the Middle Creek contains crushed brachiopods and stylolites, and lacks recognizable pellets within the matrix, suggesting that it underwent similar or slightly more severe compaction than the base of the Bethany Falls prior to cementation.

Replacement of micrite by fine ferroan dolomite is locally more extreme in the Middle Creek than at the base of the Bethany Falls. This may be a result of magnesium expulsion, late in the deeper-burial connate environment, from the Ladore Shale underlying the Middle Creek as well as from the overlying Hushpuckney Shale.

#### Algal Boundstone Facies

### Grain Preservation and Carbonate Cements

Phylloid algae and molluscs within this facies show poor preservation of original structure, suggesting that most unstable grains were dissolved by undersaturated meteoric water. Preservation of some structure within a small percentage of originally unstable grains suggests that minor neomorphism occurred prior to solution. This neomorphism probably occurred within the saturated meteoric phreatic environment.

Original porosity is dominantly filled by blocky nonferroan calcite, which probably formed in the active-saturated zone of the meteoric phreatic environment as developed above. Thin peripheral rims of ferroan calcite occurring before nonferroan blocky calcite in some original voids may have formed where reducing conditions developed in the lower, stagnant zone of the saturated meteoric phreatic environment.

Secondary porosity is filled by peripheral nonferroan blocky calcite, which likely precipitated in the active-saturated meteoric phreatic environment as it passed back through after the leaching environments of maximum regression. Then it was filled by central ferroan calcite and dolomite, which formed later under reducing conditions from near the base of the saturated meteoric phreatic environment on into the deeper-burial connate environment.

### Summary

Diagenesis in the algal boundstone facies may be explained by progression from the marine phreatic through the saturated meteoric and undersaturated meteoric phreatic environments during regression, and from undersaturated meteoric phreatic through saturated meteoric phreatic and deeper-burial connate environments during transgression in the overlying cycle. Thin peripheral rims of ferroan calcite formed in original voids near the base of the saturated meteoric phreatic environment where reducing conditions had developed. Nonferroan blocky calcite filled or partially filled remaining original voids as the upper active portion of the saturated meteoric phreatic environment was introduced. Minor neomorphism of unstable grains occurred in the saturated meteoric phreatic before undersaturated meteoric water was introduced, dissolving unstable grains and portions of unstable grains that had not been neomorphosed, forming molds. Transgression, beginning deposition of the overlying cyclothem, reversed migration of diagenetic environments reintroducing saturated meteoric waters in which nonferroan blocky calcite filled or partially filled molds and remaining primary voids. Ferroan dolomite and calcite precipitated later under reducing conditions from near the base of the saturated meteoric phreatic into the deeper-burial connate environment.

Compaction in the algal boundstone facies is similar in degree to that in the skeletal wackestone facies in the Bethany Falls, and is less severe than compaction in the rest of the Middle Creek. The absence of overlying Hushpuckney and Bethany Falls members, at locality PLO, may explain the lesser compaction in the algal boundstone facies of the Middle Creek.

### Noncarbonate Minerals

#### Silica

Chert and chalcedony replacement of preferred carbonate grains, and the formation of chert beds and horizons of nodular chert probably occurred early in diagenesis within the mixing zone environment. The silicification of carbonate grains within blocky calcite-cemented grainstones suggests that water saturated with silica must have been introduced prior to cement formation in the active-saturated marine phreatic environment. This conclusion is supported by the fact that silicification of this type never extends into intergranular cements or matrix surrounding silicified grains. Krauskopf (1959) demonstrated that amorphous silica may dissolve readily in fresh or marine water at ordinary temperatures. Knauth (1979) proposed that dissolution of amorphous biogenic silica and mixing of marine and meteoric water, in a zone containing 35% to 75% marine water, would

result in mixing-zone waters saturated with silica and undersaturated with calcite. The occurrence of thin chert beds and horizons of chert nodules in the Swope Formation fit Knauth's (1979) model of silicification in a near-horizontal mixing zone that migrated upward or downward as a result of sea-level changes. Abundant originally siliceous sponge spicules, which are now leached and filled by calcite throughout the Swope Formation, provided the source of silica.

Chert and chalcedony layers within caliche crusts and silicification associated with caliche beneath crusts and around solution channels probably formed at the same time as caliche in the saturated meteoric vadose environment.

In contrast, botryoidal chalcedony in the Middle Creek algal mound at PLO formed after precipitation of blocky calcite in the active-saturated meteoric phreatic and before precipitation of megaquartz in intragranular voids. SEM observation of euhedral quartz crystals extending through a later rim of ferroan dolomite within an oomold, suggests that megaquartz precipitation may have begun during second passage of the mixing zone after calcite precipitation in saturated meteoric water but before ferroan dolomite precipitation in the deeper-burial connate environment. Because voids partially filled by megaquartz or ferroan dolomite are typically mutually exclusive, the

interpretation above is based upon SEM observation within a single oomold.

Spherulites of radial chert replace both micrite and calcite spar at PLO. Voids bounded by spherulites are filled by siliceous cements, whereas voids bounded by micrite have initial carbonate cements. This suggests that radial chert replaced micrite or fibrous marine cements during the first passage of the mixing-zone, before preferential precipitation of blocky calcite on carbonate substrates. Replacement of spar by radial chert suggests that replacement resumed after precipitation of blocky calcite, probably during the second passage of the mixing zone.

#### Pyrite, Hematite, and Limonite

Subhedral pyrite crystals replacing carbonate grains are often embayed by silica replacement. This suggests that pyrite replacement occurred early in local reducing microenvironments within the marine phreatic environment before silicification of grains in the mixing zone.

Geopetal pyrite included within the lower edges of blocky calcite void-filling suggests that pyrite precipitated out of a reducing solution within the void and settled to the bottom of the void. Inclusion of the pyrite within blocky calcite suggests this took place prior to

extensive cementation in the active-saturated meteoric phreatic environment.

Increased abundance of pyrite nearer the core shale in both the Bethany Falls and Middle Creek Members suggests the possibility of pyrite formation due to release of iron from the core shale. Petrographic observations provide no clues to the timing of such a process.

Hematite and limonite formed from pyrite and ferroan dolomite when oxidizing conditions were introduced to the rock, much of it probably in the modern meteoric environments.

#### Kaolinitic Clays

SEM study demonstrates that void-filling kaolinitic clays consist of euhedral crystals, which suggest an authigenic origin. Geopetal accumulations of kaolinitic clay in megaquartz-filled oomolds indicate that clays formed after mold formation in undersaturated meteoric water, and before megaquartz precipitation in connate water.

#### Hydrologic Implications of Unstable Grain Preservation

The generally poor preservation of unstable grains throughout the Bethany Falls and Middle Creek Limestones (both dominated by Railsback's diagenetic Facies B) suggest that undersaturated meteoric water migrated all the way

through the Swope Formation during regression, even penetrating the core shale (except at PLO) and affecting the transgressive Middle Creek Member much more than it did the homologous transgressive Canville Creek Member of the Dennis cycle studied by Railsback. The core shale is absent at PLO where the Middle Creek is overlain by fluvial Dodds Creek Sandstone, which apparently cut out the overlying Hushpuckney Shale (and possibly the Bethany Falls Limestone) and would have easily introduced meteoric water into the Middle Creek algal mound. The absence from the Swope of Railsback's (1983) diagenetic Facies D, in which all originally unstable grains are well preserved by neomorphic processes, supports the interpretation that undersaturated meteoric water flushed the entire formation.

Minor preservation of original structures occurred within some unstable grains throughout the Swope Formation (except in the rubbly mudstone facies). This suggests that marine phreatic water within the sequence was first replaced for a short time by saturated meteoric water, allowing for minor neomorphism, before being permeated for a long time by undersaturated meteoric water during most of the regression.

The band of well preserved structure (Railsback's Facies C) within the oolitic grainstone, which is generally horizontal throughout central and northern Kansas and becomes concave upward in southeastern Kansas, has a form similar to that of the hypothetical base of the meteoric

phreatic environment at a particular stage of development (Fig. 5). This band of preservation may possibly represent a portion of the sequence that remained in the saturated meteoric phreatic environment for a longer period of time than those zones above and below, allowing more neomorphism of grains before undersaturated meteoric water finally reached the rock. A slowdown or lag in the rate of regression would explain the extended residence time of this particular band of the sequence in saturated meteoric phreatic waters.

The lack of any preserved structure in unstable grains (Railsback's Facies A) within the rubbly mudstone suggests that these muddy shoreline deposits passed from the marine phreatic directly into the undersaturated meteoric phreatic environment before any of the zone had time to become saturated, thus preventing any neomorphism prior to solution.

#### Porosity

Figure 24 demonstrates that little primary porosity remains in the Swope Formation, whereas a significant amount of secondary porosity remains. The preferential preservation of secondary porosity relates to several factors. The scarcity of remaining primary porosity is not surprising considering the greater opportunity for

cementation of primary pores. Early marine cements, mixing-zone cements, and active-saturated meteoric phreatic cements all precipitate in primary pores during early regression before creation of moldic secondary porosity around the time of maximum regression when the most undersaturated water moved through the limestone. In addition, intergranular primary porosity in grainstones is generally interconnected allowing access to large volumes of saturated water. In contrast, secondary porosity, dominantly moldic in the Swope, typically occurs as more isolated pores, which would limit permeability and inhibit cement formation.

#### Stable Isotopes

The general lightening upward trend in  $dO^{18}$  values in the Bethany Falls and in the Middle Creek at XNW suggest that meteoric waters migrated downward through the sequence, exhibiting a greater influence higher in the section (Allan and Matthews, 1977). Meteoric water is derived by fractionation of marine water through evaporation, which enriches meteoric water in lighter  $O^{16}$  (Hoefs, 1980).

A slight lightening upward trend in  $dC^{13}$  values suggests the influence of isotopically light, plant derived carbon dioxide near the top of the section (Allan and Matthews, 1977).

Allan and Matthews (1982) demonstrate that surfaces of subaerial exposure are characterized by strongly  $C^{12}$  enriched limestones. The rapid and extreme lightening of  $dC^{13}$  values in the top of the Bethany Falls at LC suggests that it was subaerially exposed, as is compatible with the caliche crust there.

Delta  $O^{18}$  values are typically lighter in the Middle Creek than at the base of Bethany Falls, suggesting that once meteoric water penetrated the core shale, it flushed through the Middle Creek Limestone, which probably had a slightly higher permeability than the surrounding shales.

#### Paleotopography

Evidence for intense subaerial exposure or early introduction of undersaturated meteoric water at several localities suggest that they may have been topographic highs. The caliche crust, solution channels, and sharp lightening upward trend in  $dC^{13}$  at the top of the Bethany Falls at LC suggest that the locality may have been a subaerially exposed topographic high. The occurrence of Railsback's (1983) diagenetic Facies A in the rubbly mudstone facies at B and K-52 could indicate that these localities were topographic highs, causing early introduction of undersaturated water. The development of vuggy porosity at SCQ, XNW, B, and Tr may indicate that

these were topographic highs, with vugs forming in the meteoric vadose environment.

The interpretation of these localities as paleotopographic highs seems consistent with depositional and stratigraphic evidence. The greater thickness of the oolitic grainstone facies at these localities suggests that they may have been topographically high. The rubbly mudstone facies at these localities is either thin and heavily weathered or completely absent, suggesting subaerial exposure and erosion by leaching and soil formation as the Galesburg Shale formed (Schutter, 1983).

The effects of meteoric diagenesis are less severe at locality IND, which suggests that it may have been a topographic low between the topographic highs in southeastern Kansas (localities JI, LC, K-52, XNW, and SCQ) and those in northwestern Missouri (localities B, and Tr). This interpretation is supported by the occurrence of a layer of skeletal wackestone within the thin oolitic grainstone facies at this locality, and corresponds to a topographic low in the overlying Dennis Formation, as interpreted by Railsback (1983).

The topographic highs in southeastern Kansas and northwestern Missouri suggest that the influence of the Bourbon and Saline County Arches respectively reported for the Middle Pennsylvanian Pawnee Limestone by Price (1981) may have persisted into the Upper Pennsylvanian.

## CHAPTER VI

## CONCLUSIONS

The majority of diagenetic features in the Swope Formation were formed relatively early in its diagenetic history. These features trace the downward migration of diagenetic environments during regression, which deposited the Bethany Falls Member and formed the overlying soil of the Galesburg Shale, and the migration back upward of diagenetic environments during subsequent transgression, which deposited the transgressive limestone and core shale of the overlying Dennis cyclothem. The absence of original structure within unstable grains in the rubbly mudstone facies suggests that undersaturated meteoric water entered this facies with the onset of exposure. Minor preservation of structure within unstable grains lower in the formation suggests that some saturated meteoric water replaced marine water before the introduction of undersaturated meteoric water. Leaching of unstable grains at the base of the Bethany Falls and within the Middle Creek Member suggests that at maximum regression, undersaturated meteoric water reached not only the base of the regressive Bethany Falls but penetrated the Hushpuckney core shale and entered the

transgressive Middle Creek Limestone. With onset of transgression, diagenetic environments migrated back up through the sequence until the entire sequence was permeated by deeper-burial connate water. There is no evidence that later Pennsylvanian sea-level changes affected the Swope Formation, which probably remained in the deeper-burial connate environment until recent uplift and exposure.

The apparent leaching of unstable grains within the transgressive Middle Creek Limestone, the abundance of oomoldic porosity locally leading with collapse to cement-shard fabrics in the grainstone facies, and the extensive development of microspar mottling in both skeletal wackestone and rubbly mudstone facies in the regressive Bethany Falls Limestone, all reflect extensive meteoric diagenesis of the Swope Formation, inferring that the regression that closed the Swope cycle was extreme. The occurrence of local caliche and solution channels in grainstones and of extensive solution of muddy shoreline facies at the top of the Bethany Falls, along with the occurrence of well developed soil profiles within the overlying Galesburg shale support this conclusion. Further support for a major regression is found in the generic change in fusulinid faunas from the Swope to Dennis cycles reported by Thompson (1957) and reaffirmed by Heckel and Meacham (1981).

Diagenesis within the Bethany Falls Limestone is consistent with that predicted for regressive limestones by Heckel's (1983) model for diagenesis in Upper Pennsylvanian eustatic cyclothems. Although the Middle Creek displays the effects of early compaction predicted for transgressive limestones by Heckel's model, unstable grains show only minor neomorphism and seem dominantly leached within the Middle Creek in contrast to the discernable neomorphism of unstable grains in transgressive limestones suggested by Heckel, and seen throughout most of the transgressive Canville Limestone of the overlying Dennis cycle by Railsback (1983). Leaching of unstable grains in the Middle Creek suggests that regression in the Swope cyclothem may have been more extreme than that in most if not all other Upper Pennsylvanian cyclothems and that in such a case, core shales may not be effective impermeable "seals" as predicted by Heckel's model. Also the Middle Creek algal mound was affected by the overlying Dodds Creek Sandstone which removed the overlying Hushpuckney Shale and directly introduced meteoric water.

Microspar mottling in Bethany Falls skeletal wackestones and rubbly mudstones is the result of aggradation of microspar from micrite within the saturated meteoric phreatic environment, and provides an excellent ancient analogue to Steinen's (1982) discovery of microspar

aggrading from micrite in meteoric phreatic lenses in modern Bahamian lime muds.

Four types of dolomite, similar to those observed in the Iola Limestone by Mitchell (1981), occur in the Swope Formation: 1) thin laminae of nonferroan dolomite interbedded with micrite within the rubbly mudstone facies at ICQ are interpreted as syndepositional dolomite formed in a supratidal environment; 2) thin irregular rims of nonferroan dolomite rhombs around the outer edge of primary pores are interpreted as forming in the first, downward passage of the mixing-zone environment; 3) ferroan dolomite filling central portions of primary and secondary voids is interpreted as forming under reducing conditions in the deeper-burial connate environment and; 4) ferroan dolomite replacing micrite in zones adjacent to the core shale is interpreted as resulting from late-stage release of magnesium from the shale as suggested by McHargue and Price (1982).

APPENDIX A  
LOCATION OF OUTCROPS AND CORES

IOWA

Locality ICQ: Crescent Quarry 1.5 miles southwest of Crescent, Iowa. Border between sec. 27 & 34, T75N R44W, Pottawattamie County.

Locality IAQ: Atlantic Quarry northwest of Atlantic, Iowa. Center sec. 6., T76N R37W, Cass County.

Locality IJCL: Lower Jefferson Core taken near Jefferson Quarry, center sec. 17, T77N R31W, Adair County. (Core is in possession of the Iowa Geological Survey.)

Locality ISC: Stanzel Core taken near Stanzel Quarry, 3 miles east of Stanzel, Iowa. Center sec. 5, T75N R29W, Madison County. (Core is in possession of the Iowa Geological Survey.)

Locality IPSP: Streamcut cliff by county road, 0.5 mile southeast of Pammel State Park. SE1/4 NW1/4 sec. 22, T75N R29W, Madison County.

Locality IBC: Bedford Core taken near Bedford, Iowa. SE1/4 sec. 4, T67N R34W, Taylor County. (Core is in possession of the Iowa Geological Survey.)

## MISSOURI

Locality Tr: Roadcut on Highway 6, 1.5 miles southwest of Trenton, Missouri. NE1/4 NW1/4 sec. 13, T61N R25W, Grundy County.

Locality Ga: Roadcut on Highway 6, 2.5 miles northeast of Gallatin, Missouri. SE1/4 SE1/4 sec. 32, T60N R27W, Daviess County.

Locality B: Roadcut on Highway 36, 2 miles southwest of Breckenridge, Missouri, Caldwell County.

## KANSAS

Locality IND: Quarry and roadcut on southeast side of Inland Drive, Kansas City, Kansas. SE1/4 T11S R24E, Wyandotte County.

Locality JI: Roadcut on the north side of county road just east of Highway 69, 2 miles north of Jingo, Kansas. SW1/4 SE1/4 sec. 31, T18S R25E, Miami County.

Locality LC: Two consecutive roadcuts on Highway 69, 1 mile north of junction of Highways 69 & 135, 4 miles east of La Cygne, Kansas. Center sec. 31, T19S R25E, Linn County.

Locality FVN: Roadcut on west side of Highway 7, 1.25 miles north of Farlinville, Kansas. S1/2 NW1/4 sec. 2, T21S R23E, Linn County.

Locality K-52: Roadcut on northwest side of Highway 52, 2.5 miles southwest of Mound City, Kansas. Center sec. 23, T22S R23E, Linn County.

Locality XNW: Roadcut on county road, 2.5 miles northwest of Xenia, Kansas. Center south line sec. 20, T23S R22E, Bourbon County.

Locality SCQ: Schubert Creek Quarry and roadcut on county road by Schubert Creek, 4.5 miles west of Uniontown, Kansas. NE1/4 sec. 24, T25S R21E, Bourbon County.

Locality CVC: Stream bed exposure along Canville Creek, below Highway 59 bridge, 3 miles west of Stark, Kansas. NE1/4 NE1/4 sec. 22, T27S R20E, Neosho County.

Locality PLO: Roadcut on county road along southeast edge of Lake Parsons. NW1/4 sec. 33, T30S R19E, Neosho County.

APPENDIX B  
GEOCHEMICAL DATA

Table 1  
General Carbon and Oxygen Isotopes (PDB)

Sample	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
IJCL 61.5	1.63	-3.35
IJCL 74.2	4.37	-0.52
IJCL 75.2*	-1.39	-5.89
IJCL 87.1*	-1.78	-2.31
ISC 112.6	-2.83	-5.07
IBC 524.8*	-0.20	-2.91
IBC 530.0*	-1.70	-5.89
IBC 534.0	0.33	-3.44
IBC 541.1	3.81	6.48
IBC 549.4*	-1.73	-2.68
LC 3-ta	-0.63	-4.56
LC 3-tb	-4.14	-4.54
LC 3-2.5	1.96	-2.42
LC 2-t	2.70	-2.83
XNW 5-t	5.81	0.57
XNW 5-5	0.62	3.40
XNW 4-t	6.06	-0.78
XNW 4-3	4.19	-10.42
XNW 4-b	3.37	-2.32
XNW 3-4.5	6.47	7.51
XNW 1-b	5.21	-3.15
XNW mc-4	3.78	-4.36
XNW mc-3	7.11	7.52
XNW mc-b	4.05	5.26
IND 6-3	3.66	7.12

\* These samples run by Ken Schmitz, Northern Ill. Univ.; all others run by Keith Egan, Oklahoma University.

Table 2

Carbon and Oxygen Isotopes of  
Matrix and Mottles (PDB)

Sample	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
LC 2-t matrix	2.70	-2.83
LC 2-t mottle	2.40	-3.16
XNW 4-3 matrix	4.19	-10.42
XNW 4-3 mottle	-3.15	-12.39
XNW 4-b matrix	3.37	-2.32
XNW 4-b mottle	-2.26	-16.89
IND 6-3 matrix	3.66	7.12
IND 6-3 mottle	5.79	0.98

Table 3

Chemical Composition of Mottles  
and Matrix (WDS microprobe  
analyses)

Sample	Point	Unnormalized Oxide Weight Percent Total	Mole Percent			
			MnCO <sub>3</sub>	CaCO <sub>3</sub>	FeCO <sub>3</sub>	MgCO <sub>3</sub>
<b>Mottles:</b>						
IND 6-3	1	97.65	0.05	96.99	0.34	0.26
IND 6-3	2	92.45	0.03	91.50	0.47	0.45
IND 6-3	3	98.51	0.06	97.83	0.28	0.35
IND 6-3	4	98.73	0.06	97.91	0.35	0.41
XNW 4-b	1	100.23	0.05	99.13	0.56	0.49
XNW 4-b	2	99.45	0.05	98.76	0.16	0.50
XNW 4-b	3	99.38	0.05	98.71	0.18	0.46
XNW 4-b	4	99.06	0.05	98.36	0.22	0.42
<u>Mean Total</u>			<u>0.05</u>	<u>97.40</u>	<u>0.32</u>	<u>0.42</u>
<b>Matrix:</b>						
IND 6-3	1	97.54	0.10	96.58	0.39	0.48
IND 6-3	2	99.17	0.07	98.33	0.37	0.40
IND 6-3	3	98.20	0.08	97.33	0.33	0.46
IND 6-3	4	98.98	0.05	98.23	0.25	0.45
XNW 4-b	1	85.75	0.03	85.33	0.11	0.29
XNW 4-b	2	93.56	0.06	92.68	0.37	0.45
XNW 4-b	3	94.56	0.06	93.87	0.23	0.41
XNW 4-b	4	97.40	0.09	96.70	0.25	0.37
<u>Mean Total</u>			<u>0.07</u>	<u>94.88</u>	<u>0.29</u>	<u>0.41</u>

Table 4

Chemical Composition of Mottles,  
Matrix, and Clay (EDS SEM x-ray  
Analyses)

Sample	Normalized Oxide Percent			
	CaCO <sub>3</sub>	FeO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
Mottles:				
43A	68.42	0.00	18.16	13.42
632A	80.61	0.00	19.39	0.00
633A	84.86	0.00	15.14	0.00
Matrix:				
43B	69.61	0.00	30.39	0.00
632B	53.30	6.79	26.30	13.48
633B	85.08	0.00	14.92	0.00
Clay:				
77	6.56	0.00	59.12	34.32

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