DIAGENETIC AND SEA-LEVEL CONTROLS ON POROSITY EVOLUTION FOR OOLITIC AND CRINOIDAL CARBONATES OF THE MISSISSIPPIAN KEOKUK LIMESTONE AND WARSAW FORMATION

by

Matthew E. Ritter
B.S., Lake Superior State University, 2000

Submitted to the Department of Geology and the Faculty of the Graduate School of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Science

Redacted Signature
Professor in Charge

Redacted Signature
Committee Members

Redacted Signature

Date Submitted: _____________
ABSTRACT

Mississippian (Osagean-Meramecian) oolitic and crinoidal carbonates were deposited on a ramp in Kansas and Missouri. Textures, stratigraphic relationships and sedimentary structures indicate that: bioclastic packstone, grainstone, and graded-bed facies were deposited by storms in depths of 10-50 m; tabular cross-bedded oolitic facies was deposited in the foreshore; trough cross-bedded facies formed in depths of 0-5 m; and structureless oolite facies was deposited by storms, probably in depths of 2-10 m. Stratigraphic distribution and pendant and meniscus cements are used to quantify the history of relative sea-level change associated with oolite deposition. The history began with a fall of at least 10 m, was followed by a rise and fall of 7 m, progradation, and then another rise of at least 7 m. The oolite could be classified as a lowstand deposit, but minor relative sea-level fluctuations caused its wide distribution and complex internal architecture.

The early diagenetic stage comprises isopachous, bladed, meniscus, and pendant cements. Owing to the lowstand position, early-stage subaerial exposure had little effect on porosity creation or reduction.

Intermediate-stage cements consist of seven nonluminescent-to-luminescent syntaxial-overgrowth couplets traceable up to, but not above, the sub-Pennsylvanian unconformity. Tm ice measurements from primary, all-liquid fluid inclusion assemblages range from -3.0° to 0.0°C. δ18O values (V-PDB) are -8.20‰ to -4.55‰ and δ13C values are -0.15‰ to +3.44‰. 87Sr/86Sr values of 0.70805±2 to 0.70823±2 indicate Chesterian to Atokan ages. The data indicate cementation from meteoric, marine, mixed, and evaporated marine water. Crinoidal grainstone started with higher porosity than oolitic grainstone, but after intermediate-stage cementation the porosity for both was approximately equal because of preferential cementation around crinoidal nuclei.

During the late stage, grain-to-grain pressure solution in grainstones reduced porosity greatly and was not prevented by intermediate-stage cement. It appears that lowstand oolites may experience more grain-to-grain pressure solution than highstand oolites, and if original mineralogy is calcite rather than aragonite, the lowstand oolites are unlikely to make good hydrocarbon reservoirs. For the packstone facies, mechanical compaction squeezed un lithified lime mud into remaining pore space and largely occluded the porosity, indicating that packstone lithologies of original calcite mineralogy may make poor hydrocarbon reservoirs.
This work is dedicated to my parents, Steven and Helene Ritter who have always encouraged me to follow my dreams.
ACKNOWLEDGEMENTS

No thesis would be completed without help from many outside individuals. I would like to thank Bob Goldstein for his guidance and tutelage throughout the learning experience of this project. Many thanks also go out to my other thesis committee members Evan Franseen and Ross Black for all of their help. Paul Enos is also worthy of special recognition because of all things carbonate that I have learned during my tenure at KU. Luis Gonzalez supplied a low-light camera and a computer that made it possible for me to take digital pictures under cathodoluminescence and allow me to write my thesis without the distractions associated with a computer lab. The chairman of the KU Geology Department, Randy Van Schmus, was more than fair when I asked for support with research or a trip to the AAPG Student Expo to find employment in Houston, TX.

I would like to thank the KU Department of Geology and AAPG for partial financial support during my master’s research.

I also encountered a great group of friends while here at KU. Erik Hiemstra and Niall Toomey were especially helpful by imparting hard-learned graduate student wisdom when trying to complete a master’s thesis. They were also a great sounding board for many of the ideas present herein. I would also like to thank Alycia Rode, Ed Washburn, Steve Sellwood, Vionette DeChoudens, Govert Buijs, Juli Ruth-Emry, Tim Perkins, Amy Englebrecht, and Lisa Davis for all their support.

I would like to thank my family for all of the support and encouragement that you have imparted throughout my life. Lastly, I would like to thank my friends from home, Nick Marsack, Miguel Garrido, and Rachel Stafford for your moral support through the years.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION PAGE</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES AND FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>2</td>
</tr>
<tr>
<td>Study Area and Stratigraphy</td>
<td>2</td>
</tr>
<tr>
<td>Geologic Setting</td>
<td>5</td>
</tr>
<tr>
<td>Pertinent Previous Research</td>
<td>9</td>
</tr>
<tr>
<td>Methods</td>
<td>11</td>
</tr>
<tr>
<td>LITHOFACIES</td>
<td>14</td>
</tr>
<tr>
<td>Bioclastic Packstone Facies</td>
<td>14</td>
</tr>
<tr>
<td>Bioclastic Grainstone Facies</td>
<td>18</td>
</tr>
<tr>
<td>Graded Bed Facies</td>
<td>18</td>
</tr>
<tr>
<td>Cross-Bedded Facies</td>
<td>25</td>
</tr>
<tr>
<td>Structureless Oolite Facies</td>
<td>30</td>
</tr>
<tr>
<td>Structureless Oolite with Bioclastic Infill Facies</td>
<td>33</td>
</tr>
<tr>
<td>Mudstone/Silty-mudstone Facies</td>
<td>38</td>
</tr>
<tr>
<td>Bioclastic Wackestone Facies</td>
<td>41</td>
</tr>
<tr>
<td>STRATIGRAPHY</td>
<td>42</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>50</td>
</tr>
<tr>
<td>DIAGENESIS</td>
<td>52</td>
</tr>
<tr>
<td>Paragenetic Sequence</td>
<td>52</td>
</tr>
<tr>
<td>Porosity</td>
<td>77</td>
</tr>
<tr>
<td>Geochemistry and Origin of Isopachous, Bladed Cement</td>
<td>83</td>
</tr>
<tr>
<td>Geochemistry and Origin of Pendant Cement</td>
<td>83</td>
</tr>
</tbody>
</table>
LIST OF FIGURES AND TABLES

1. Location of the measured sections .......................................................... 3
2. Devonian and Mississippian stratigraphic column for southwestern Missouri 4
3. Middle Mississippian paleogeography .................................................... 6
4. Bioclastic packstone and bioclastic grainstone ........................................ 15
5. Paired transmitted-light and CL photomicrographs showing the Bioclastic facies 19
6. Outcrop photographs of bioclastic packstone, bioclastic grainstone, graded bed, and cross-bedded facies, and hummocky cross stratification ........................................ 20
7. Brachiopod orientations ...................................................................... 23
8. Outcrop photograph showing trough cross stratification and structureless oolite with bioclastic infill facies ................................................................. 26
9. Structureless oolite facies .................................................................... 31
10. Outcrop photograph of Chondrites and the structureless oolite with bioclastic infill facies ................................................................. 34
11. Cross section ................................................................................ 37
12. Karstic cavities with siliciclastic infill .................................................. 39
13. Relative sea-level curve ..................................................................... 45
14. Paragenetic sequence of events ............................................................ 53
15. Early-stage isopachous, bladed cements ................................................. 57
16. Early-stage pendant cements ............................................................... 59
17. CL photomicrograph showing cement stratigraphy employed for this study 60
18. CL photomicrograph showing cement stratigraphy employed for this study 62
19. Siliciclastic karst fill after intermediate-stage cement ............................... 66
20. Paired transmitted-light and CL photomicrographs showing recrystallization 67
21. Chert .................................................................................................. 70
22. Compaction ........................................................................................ 73
23. Paired transmitted-light and CL photomicrographs showing replacement dolomite ................................................................. 76
24. Porosity and compaction figures..........................................................78
25. Stable isotope data from all sampled diagenetic cement phases..............84
26. Summary figures to explain stable isotope data resulting from recrystallization,  
    meteoric-marine mixing zone cements, or physical mixtures of meteoric and  
    marine cements.............................................................................87
27. Overlain transmitted-light and CL photomicrographs showing fluid inclusions  
    and cathodoluminescence..................................................................88
28. Histogram of final melting temperatures of ice for primary fluid inclusions......89
29. Plot showing $^{87}$Sr/$^{86}$Sr versus total Sr (in ppm).................................92
30. Histogram of final melting temperatures of ice for primary fluid inclusions within  
    recrystallized cement.........................................................................95
31. $^{87}$Sr/$^{86}$Sr ratios for recrystallized cement samples with age correlations........98
Table 1. Grain percentages in major lithofacies............................................14
INTRODUCTION

Carbonate ramps (Ahr, 1973) are shallow-water depositional systems with low-gradient slopes (<1°) lacking a pronounced shelf margin (Wilson, 1975; Read, 1985; Burchette and Wright, 1992; Wright and Burchette, 1998). Many papers have described depositional aspects of ramp sequences (e.g. Wright, 1986; Faulkner, 1988; Burchette et al., 1990; Elrick and Read, 1991; Handford and Loucks, 1993; Smith and Read, 2001; Rankey, 2003). Because ramps have gentle slopes, sedimentary environments may shift radically in response to relative sea-level change. Relative rises in sea level may lead to shallow-water deposits directly overlying deeper-water deposits, with intermediate-water-depth deposits absent (e.g. Wright, 1986; Van Steenwinkel, 1990; Gomez-Perez et al., 1998; Rankey, 2003). Relative rises in sea level may produce a rock record with a basal surface of subaerial exposure overlain by a lag deposit and either carbonate sands, peritidal deposits, or deeper-water deposits (Wright, 1986; Burchette et al., 1990). Despite these models for sedimentary response to sea-level change, much remains to be learned about the sequence-stratigraphic response of ramp deposits to minor relative changes in sea level. Early field work by Goldstein (personal communication) and Thompson (1986) has shown that the upward transition from the upper Osagean Keokuk crinoidal carbonates to the Short Creek Oolite Member in southwestern Missouri and neighboring areas may have been in response to a relative sea-level fall. This study tests this hypothesis and, as a means of improving understanding of response of carbonate ramp depositional systems to minor relative changes in sea level, documents relative changes in sea level, geometries, and facies distributions in the Keokuk-Short Creek-Warsaw interval.

Diagenetic alteration of oolitic and crinoidal carbonates is known to have significant effects on porosity and permeability of petroleum reservoirs (Moore and Druckman, 1981; Humphrey et al., 1986; Swirydczuk, 1988; Sellwood et al., 1989; Manley et al., 1993; Moore and Heydari, 1993; Budd et al., 1995). In particular, meteoric diagenesis associated with relative sea-level fall commonly is assumed to
exert a major control on such alteration (Moore and Druckman, 1981; Craig, 1988; Nieman and Read, 1988; Swirydczuk, 1988; Budd et al., 1995; Frank and Lohmann, 1995). This research evaluates how diagenesis associated with subaerial exposure, during or just after oolite deposition and later in the Mississippian or Pennsylvanian, altered the reservoir characteristics of the oolitic and crinoidal carbonates of the Keokuk-Short Creek-Warsaw interval. Kaufman et al. (1988) conducted a study in Missouri and western Illinois and suggested that early crinoid syntaxial overgrowths precipitated from meteoric waters. This study adds a new dimension and evaluates the possibility that cement precipitation occurred within meteoric, marine, and mixing-zone systems.

The thesis evaluates the effect of original lithology on the preservation of porosity throughout diagenesis and compaction, and examines whether high percentages of echinoderm grains might act to preserve porosity. This is hypothesized because echinoderm grains may be overgrown with calcite cement preferentially over other bioclastic grains, possibly preventing later compaction.

It also evaluates the importance of depositional lime mud in enhancing compaction and destroying porosity. Lasemi et al. (1990) documented that originally aragonitic or high-magnesium calcite mud is more susceptible to early diagenesis than low-magnesium calcite mud. It is now well documented that middle Mississippian seas precipitated abundant calcite (Sandberg, 1983; Lohmann and Meyers, 1985; Stanley and Hardie, 1998). If so, the depositional lime mud of the studied interval may have remained unlithified for long periods of time, leading to reduction of porosity through physical compaction.

BACKGROUND

Study Area and Stratigraphy

Mississippian strata are exposed in and around Joplin, Missouri, and include Osagean and Meramecian carbonates (Figure 1). These units include the Pierson Limestone, Reeds Spring-Elsey Formations, Burlington and Keokuk Limestones,
Figure 1. Geographic setting of outcrops and cores for this study. See appendix I for details of each location.
Short Creek Oolite Member of the Keokuk Limestone, and the Warsaw Formation (Figure 2).

The focus of this study is on the Keokuk Limestone, Short Creek Oolite Member of the Keokuk Limestone, and the Warsaw Formation, rocks of late Osagean and early Meramecian age (Figure 2). Two major lithofacies, termed the bioclastic facies and oolitic facies, are further subdivided into 9 lithofacies to aid in the understanding of depositional environments. The lowermost stratigraphic unit is the bioclastic facies of the Keokuk Limestone. This is overlain by the ooid-rich Short Creek Oolite Member of the Keokuk Limestone. Above the oolite are more bioclastic facies of the Warsaw Formation.

Conodont biostratigraphy for the Short Creek Oolite points to an age within the late Osagean (Thompson and Fellows, 1969; Kammer et al., 1990). The Short Creek appears to be time-equivalent to the Peerless Park Member of the Keokuk Limestone of eastern Missouri and western Illinois (Kammer et al., 1990). In southwestern Missouri, the Keokuk Limestone and the overlying Warsaw Formation have a conodont fauna nearly indistinguishable from each other (Rexroad and Collinson, 1965; Thompson and Fellows, 1969). Because of this indistinguishable fauna, Sable (1979) suggested that the texturally distinct Short Creek Oolite be used as an arbitrary marker bed for the boundary between the Osagean and Meramecian (Figure 2).

**Geologic Setting**

The setting for deposition of these strata was originally described as a “shelf” (e.g. Lane, 1978), but the broad facies belts, subtle facies changes, absence of a well-defined shallow-water shelf margin, and presence of higher energy facies in the updip (Northern) areas suggest a gentle regional paleoslope (probably <0.01°; Rankey, 2003) characteristic of a ramp. The northward extent of this ramp was bounded by the Transcontinental arch, in present-day Iowa, and the ramp extended ~650 kilometers southward toward a basinal setting in northern Arkansas (Figure 3;
Figure 2. Columnar section of Mississippian formations recognized in southwestern Missouri. Adapted from Spreng (1961).
Figure 3. Map showing known distribution of 3 of the 4 late Tourmaisian (Osagean) depositional magnafacies discussed in Lane and De Keyser (1980). The 4th, the Clastic Magnafacies, is not illustrated because it is located far to the east and off the map. The Clastic Magnafacies prograded and smothered all other magnafacies during the Visean (approximately = Meramecian and early Chesterian). The Carbonate Magnafacies is subdivided into 3 Depofacies based on Lane and De Keyser’s (1980) depositional environment interpretations: Inner Shelf, Main Shelf, and Shelf Margin. Even though this was originally described as a shelf, it is best classified as a ramp. The equivalent ramp terminology in Missouri, Kansas, Oklahoma, and Arkansas would be that the inner shelf is equivalent to inner-ramp facies, main shelf is equivalent to mid-ramp facies, and shelf margin is equivalent to ramp-slope facies. Modified from Lane and De Keyser, 1980. Paleolatitude is inferred for Visean time (late Osagean through middle Chesterian) (Witzke et al., 1990).
Handford and Manger, 1993). From cross sections drawn by Lane and De Keyser (1980), the strike of this ramp system was generally east-west, with distal steepening approximately 40 km south of the Missouri-Arkansas border. Therefore the best description of this system is that of a distally steepened ramp (sensu Read, 1985). The ramp prevailed throughout most of the Mississippian, but the distal part was terminated during the Late Mississippian by the Ouachita Orogeny (Handford and Manger, 1993).

The North American continent has been hypothesized to have drifted north during the Mississippian Period from subtropical latitudes (~25-30° S) to tropical latitudes (equatorial) (Witzke, 1990). This migration from a subtropical to tropical climate may be reflected in the rock record; there is a transition from crinoid-bryozoan facies in the Lower Mississippian to oolitic and crinoidal-bryozoan facies in the Upper Mississippian. During the late Osagean and early Meramecian, the study area was between 15° and 25° S (Witzke, 1990; Figure 3), well within the range for tropical carbonate production.

Magnitudes of sea-level change are lowest during greenhouse conditions, greatest during icehouse conditions, and have moderate values during transitional times from greenhouse to icehouse worlds (Read, 1998). Rankey (2003) attributed the middle Mississippian to a transitional time of greenhouse to icehouse conditions. He showed the carbonate-filled channel complex (Peerless Park Member of the Keokuk Limestone) near St. Louis, Missouri to result from a relative sea-level fall of at least 5 meters. Even though sea level fell, no evidence for subaerial exposure exists beneath the Peerless Park Member. Because the Short Creek Oolite has been interpreted to be nearly time equivalent to the Peerless Park Member (Kammer et al., 1990), I propose to determine if the Short Creek is likewise related to this relative sea-level fall.

Other sea-level changes have been modeled or documented throughout the Mississippian by several workers (Ross and Ross, 1988; Elrick and Read, 1991; Witzke and Bunker, 1996; Smith and Read, 2001). Elrick and Read (1991) studied
Early Mississippian (Kinderhookian) rocks in Wyoming and Montana and modeled fifth-order sea-level fluctuations to be at least 20-25 m. Smith and Read (2001) documented fourth-order (= 400 ky) sea-level changes of 30-100 m for Late Mississippian (middle Chesterian) rocks on the ramp adjacent to the Illinois Basin. In a study of Mississippian rocks in Iowa, Witzke and Bunker (1996) documented third-order sea-level changes of 10-70 m. Near the end of the Mississippian and continuing through the Early Pennsylvanian, a worldwide sea-level fall produced an unconformity throughout most of the Southern North America that caused subaerial exposure of Mississippian strata that lasted for approximately 10 million years (Ross and Ross, 1988).

Pertinent Previous Research

Speer’s (1951) investigation documented the sedimentological transitions of facies in the Short Creek Oolite of Ottawa County, Oklahoma. He concluded that the vertical transition from oolite to bioclastic facies is conformable in the Miami (northeastern Oklahoma) area. Speer (1951) also concluded that the lower contact, from crinoidal packstones and grainstones to oolitic grainstone, is gradational at every outcrop. He found no evidence of an unconformity in southwestern Missouri and northeastern Oklahoma.

A later investigation of the Short Creek Oolite Member was by Greenberg (1981). He concentrated his efforts in the mid-ramp setting near Joplin, Missouri. The purpose was: 1) to delineate the sedimentologic development of the Short Creek Oolite; and 2) to interpret the diagenetic history of the Short Creek with emphasis on compaction, pressure solution, and cementation. Greenberg (1981) concluded that the ooids accumulated in a high-energy, shallow, shelf-margin environment (oolite shoals) during progradation of Burlington shelf deposits. Pressure solution was the most significant means of porosity reduction, and this pressure solution provided approximately 40% of the cement within the Short Creek. He identified marine phreatic and freshwater phreatic cementation in near-surface diagenetic environments, in addition to burial cementation.
The next contribution to the Short Creek Oolite literature was by Lisle (1983). She focused on one outcrop from the distally steepened portion of the ramp, in the War Eagle Quarry near Huntsville, Arkansas, 45 kilometers south of the Missouri border. The objective of her study was to determine the origin of the oolite in this distal setting. Modal analysis of thin sections and the position of the oolite within deep-water deposits suggested deposition in a deep-water setting, possibly by turbidity currents. Low ooid percentage, variation in ooid content, lack of cross stratification, lack of current structure, high percentage of mud, and deep-water strata bounding the oolite at this location all supported the deep-water hypothesis.

The most recent investigation of the Short Creek Oolite was by Vaden (1987). The purpose was to gain a more detailed understanding of the petrologic and depositional aspects of the Boone Formation in Ottawa County, Oklahoma. Ottawa county is the northeasternmost county in Oklahoma, and is ~20 km southwest of Joplin, Missouri. The Boone Formation is nomenclature used by the Oklahoma and Arkansas Geological Surveys. It is equivalent to the Fern Glen Formation, Reeds Spring Formation, Grand Falls Chert, Burlington Limestone, Keokuk Limestone, Short Creek Oolite Member of the Keokuk Limestone, and Warsaw Formation. Vaden interpreted the oolite to have been deposited as part of an oolitic shoal, in upper subtidal or lower intertidal conditions. Bedding was described as typically massive but with localized medium- to large-scale planar cross bedding. The contact between the underlying formations and the Short Creek Oolite is gradational, and therefore conformable. Vaden concluded that lagoonal deposits overlay the ooid shoal deposits. The overlying deposits were interpreted to represent lagoonal conditions because lithologies consist of bioturbated bioclastic wackestones with mudstone intraclasts. Vaden also concluded that several diagenetic environments were involved in cementation of these sediments: meteoric, marine, and burial.

Harris (1982) established a calcite cement and dolomite zonal stratigraphy for the Burlington and Keokuk Formations in southeastern Iowa and limited portions of western Illinois. Kaufman et al. (1988) conducted a field- and lab-based research
project of the calcite cement stratigraphy of the Burlington and Keokuk limestones in western Illinois and eastern and central Missouri using the nomenclature of Harris (1982). Six regionally correlative cement zones (II, III, IV, V, VI, and II') in the Burlington-Keokuk were distinguished by their luminescent intensity, relative Fe$^{2+}$ content, interzonal dissolution features, thickness, position within the zonal sequence, and the internal consistency of their timing relative to other diagenetic features, such as cement fracturing and calcite dissolution. Kaufman et al. (1988) suggested that these cements precipitated within meteoric-phreatic systems established during subaerial exposure associated with development of the sub-Pennsylvanian and earlier unconformities.

Contrasting this view, that meteoric-phreatic waters were those responsible for precipitation of early syntaxial cements in Mississippian limestones, is a study conducted by Frank and Lohmann (1995). They used detailed micron-scale sampling methods to analyze isotopic signatures of individual cement zones in the Lake Valley Formation (Osagean) in New Mexico. They suggested that regionally extensive mixing between marine and meteoric water was responsible for cementation of alternating luminescent and non-luminescent cements that are similar in luminescence to the cements found within this study and described by Kaufman et al. (1988). Based upon this information, I propose to evaluate the origin of the cements identified by Kaufman et al. (1988) in order to determine if the cements precipitated in an environment other than fresh water.

Even though three Masters theses and one undergraduate thesis have been dedicated to the study of the Short Creek Oolite Member, no study has documented or explained if a sequence boundary exists. I propose to document the transitions from crinoidal-rich packstone and grainstone to oolitic grainstone, determine if a sequence boundary exists, and what, if any, diagenetic effect the processes associated with its formation had on these sediments.
Methods

Ten stratigraphic sections and three cores were described in western Missouri and eastern Kansas (Figure 1, Appendix 1). Where outcrops were not available, cores were substituted so that a north-south-trending transect could be compiled down the approximate dip of the ramp.

The lithologies were described using Dunham's classification (1962). While measuring the stratigraphic sections, samples were taken at every geologically important surface, or at least one every meter of vertical section. Between 5 and 14 samples were collected from each outcrop or core, except core C3, with the greatest sampling density in the oolitic horizon. Selected samples were slabbled and polished, or prepared for thin-section analysis. One hundred and fifteen doubly polished thin sections were prepared for thin section petrography and fluid inclusion work using a low-speed saw and cold-curing epoxy to avoid heating or fracturing the sample prior to microthermometric measurements.

Carbonate cement types were characterized in thin section by petrographic examination under transmitted light and cathodoluminescence. Cathodoluminescence petrography was performed using a Cambridge Image Technology LTD Clmk4 mounted on a Leitz SM-LUX-POL microscope. Operating conditions for luminescence were 16kV acceleration potential and 0.5mA gun current. Standard petrography and some cathodoluminescence work were conducted before microthermometry to integrate fluid inclusion assemblages (FIAs) and cement stratigraphy, however, care was taken to avoid heating areas that would later be used for microthermometry.

Samples were selected for microthermometric analysis based upon the availability of primary all-liquid inclusions. Preparation of samples and fluid inclusion petrography was conducted using the methodology and terminology for fluid inclusion analysis proposed by Goldstein and Reynolds (1994). Thin sections were stored in a refrigerator for three months, prior to microthermometry, to facilitate nucleation of bubbles from all-liquid inclusions. After locating adequate samples,
inclusions were videotaped to document the phase ratios within the fluid inclusions. After documentation, the chips were heated to 150-200°C for 8-12 hours to stretch the all-liquid inclusions in order to nucleate bubbles subsequently upon cooling. The chips were then cooled within a refrigerator to help facilitate this process. If bubbles did not nucleate, the temperature was raised sufficiently until bubbles were generated. Once a bubble nucleated, it was possible to conduct freezing measurements.

Microthermometric analyses were performed using a Fluid Inc.-adapted U.S.G.S.-design gas-flow heating and freezing system. Temperature measurements were made to the nearest 0.1°C by standard cycling techniques described by Goldstein and Reynolds (1994). After microthermometric analysis, cathodoluminescence and transmitted-light photomicrographs were overlain in Adobe Photoshop to determine the luminescence of cement around each measured fluid inclusion.

Samples of cement were obtained for isotopic analyses using a Merchantek microdrill. All isotopic samples were drilled from thin sections due to the minute nature of the cements. Most isotopic sample masses were between 0.3 and 1.0 mg. Despite careful microsampling, some of the carbonate-cement samples were unavoidably contaminated by later cement.

Samples were sent to the University of Iowa and the University of Kansas for stable isotope analysis and strontium isotope analysis respectively. The calcium carbonate powders for stable isotopic analysis were roasted in vacuo at 380°C for one hour to remove volatile contaminants and then desiccated. Carbonates were reacted with two drops of anhydrous phosphoric acid at 75°C. These samples were analyzed using a Finnigan-MAT 252 IRMS with a Kiel III automated carbonate device. Daily analysis of NIST powdered carbonate standards (NBS-18, 19, 20) and several in-house standards was conducted, with analytical precision (1σ) on these standards better than 0.1‰ for both δ18O and δ13C. All results are reported relative to V-PDB. 87Sr/86Sr was measured on four calcite microsamples (approximately 500 µg) to attempt to date the timing of calcite cementation of the fluid inclusion-rich cement. Samples were dissolved in 0.5 ml of 3.5N HNO3 and spiked in total with 84Sr tracer.
Chemical separation was accomplished using Eichrom Sr-Spec resin. Strontium was loaded in TaCl and 0.25M H₃PO₄ on single Re filaments and analyzed on a VG Sector mass spectrometer in dynamic multi-collector mode. All results are normalized to an NBS 987 value of 0.710250 and fractionation corrections were accomplished using \(^{86}\text{Sr}/^{88}\text{Sr}\) of 0.1194. Internal and external precision is better than +/- 25 ppm. Repeats of the same sample were not analyzed.

**LITHOFACIES**

For this study, nine lithofacies were defined on the basis of grain composition, texture, and sedimentary structures. Porosity estimates (minus cement) were determined semi-quantitatively using the visual comparison chart of Terry and Chilingar (1955). Extant porosity for all lithofacies is less than 1%, and is not considered when listing bulk-rock percentages. Table 1 lists average bulk volumes of crinoids, cement, bryozoans, brachiopods, ooids, and micrite for each lithofacies.

*Bioclastic Packstone, Bioclastic Grainstone, and Graded Bed Facies - Descriptions*

Above and below the oolitic interval are lithofacies that were subdivided into graded bed, bioclastic packstone, and bioclastic grainstone. Bedding varies from 4 to 150 cm thick. The lithofacies are grouped together because they are dominated by crinoid fragments and are interpreted to originate from the same general process. The graded bed facies consists of beds composed of both bioclastic packstone and bioclastic grainstone facies; bioclastic grainstone is more common near the bases of graded beds and bioclastic packstone is more common near tops of the graded beds.

*Bioclastic Packstone Facies.* — This lithofacies is characterized by a dominance of crinoids, packstone lithology, lack of grading, and generally fine grain size. Beds are 1 to 150 cm thick, with most 2 to 60 cm thick. Mottled fabrics, indicative of bioturbation, are common within this facies. Physical sedimentary structures are not apparent.

Average bulk volumes are 59% crinoids, 18% micrite, 12% cement, 7% bryozoans, 4% brachiopods, and trace ooids (Table 1; Appendix 2; n = 7). Ooids are found only above the Short Creek Oolite. Less abundant carbonate grains (<1%)
Table 1 Average grain percentages for selected lithofacies

<table>
<thead>
<tr>
<th>Lithofacies Name</th>
<th>Crinoid %</th>
<th>Cement %</th>
<th>Bryozoan %</th>
<th>Brachiopod %</th>
<th>Ooid %</th>
<th>Micrite %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioclastic PS</td>
<td>59</td>
<td>12</td>
<td>7</td>
<td>4</td>
<td>tr</td>
<td>18</td>
</tr>
<tr>
<td>Bioclastic GS</td>
<td>57</td>
<td>22</td>
<td>12</td>
<td>2</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>CB Oolite</td>
<td>14</td>
<td>18</td>
<td>tr</td>
<td>2</td>
<td>66</td>
<td>0</td>
</tr>
<tr>
<td>St. Oolite with B.I.</td>
<td>20</td>
<td>19</td>
<td>tr</td>
<td>3</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>St. Oolite</td>
<td>3</td>
<td>15</td>
<td>tr</td>
<td>1</td>
<td>80</td>
<td>0</td>
</tr>
</tbody>
</table>

List of approximate volume percentages of major components in major lithofacies determined semi-quantitatively from petrographic and field observations. Due to rounding all values may not add up to 100%. Minor components such as rugose coral and foraminifera are not included, but total less than 1% of any facies. Current porosity of all facies is 1% or less and therefore ignored. Tr = trace.

Bioclastic PS = Bioclastic Packstone  
Bioclastic GS = Bioclastic Grainstone  
CB Oolite = Cross-Bedded Oolite  
St. Oolite with B.I. = Structureless Oolite with Bioclastic Infill  
St. Oolite = Structureless Oolite
consist of rugose corals and foraminifera. Grain size ranges from 0.08 to 0.75 mm in the long dimension, with 0.10 to 0.35 mm most common (Figure 4). Most grains appear slightly to moderately abraded, but highly abraded grains also occur rarely. Mud matrix appears to have intruded pore space during compaction (this will be discussed later in the Paragenesis section). Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Brachiopod orientations could not be discerned because of their scarcity and fragmentation.

**Bioclastic Grainstone Facies.** — This lithofacies is characterized by a dominance of crinoids, grainstone lithology, generally coarse grain size, and lack of grading. Beds are 2 to 80 cm thick, with most 3 to 40 cm thick. Mottled fabrics, indicative of bioturbation, are common within this facies. Physical sedimentary structures are typically not apparent, however, some beds may have symmetrical wave ripples with chevron structures in which foreset laminae have a preferred orientation, appear laminated, or show erosional truncation.

Average bulk volumes are 57% crinoids, 22% cement, 12% bryozoans, 6% ooids, 2% brachiopods, and 0% micrite (Table 1; Appendix 2; n = 11). Ooids are only found above the Short Creek Oolite. Less abundant carbonate grains (<1%) consist of rugose corals and foraminifera. Grain size ranges from 0.08 to 6.2 mm in the long dimension, with 0.25 to 2.0 mm most common (Figures 4, 5). Most grains appear slightly abraded, but non-, moderately, and highly abraded also occur locally. Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Brachiopods are scarce and commonly fragmented, but where preserved, they have no preferred orientation.

**Graded Bed Facies.** — This lithofacies is characterized by a dominance of crinoid grains and normal grading. On outcrop, graded beds are 1 to 75 cm thick (Figures 6A, B), with most beds 2 to 30 cm thick. Mottled fabrics are most common in the uppermost parts of graded beds. On outcrop, coarser-grained grainstone dominates at the bases of graded beds and typically grade upward into finer-grained packstone (in places wackestone) near the tops of graded beds. When samples are
Figure 4. (A) Polished hand sample of the bioclastic packstone (PS) and bioclastic grainstone (GS) lithofacies. Horizontal lines indicate the base of each bed. Sample 4.1. (B) Transmitted-light photomicrograph of the bioclastic packstone lithofacies. Note how early syntaxial cements (SO) formed around crinoids (CR) before compaction caused micrite to occlude remaining pore space. (C) CL photomicrograph showing the same field of view as in B. Scale for B and C is 400 µm. (D) CL photomicrograph of the same thin section, but at higher magnification. Scale for image is 200 µm.
Figure 5. (A) Transmitted-light photomicrograph showing syntaxial overgrowths (SO), late-stage cements (LC), and crinoids (CR) from the bioclastic grainstone facies. Note that syntaxial cements (intermediate-stage cements) are pronounced around non-micritized crinoids, and that late-stage cement NL8 predates chemical compaction (grain-to-grain pressure dissolution; lower left). Also note that compaction is pronounced. (B) CL photomicrograph showing the same field of view as in A. Note the patchy CL distribution within crinoid grains due to recrystallization and internal cementation. Scale for both images is 400 µm. Sample 4.8
Figure 6. (A) At the base of the photograph are normally graded beds of bioclastic packstone and grainstone (GB). At the pencil tip is an erosive surface (ES) at the base of the oolitic facies. In the middle of the photograph is trough cross-bedded oolite (TCB) of the cross-bedded lithofacies. Overlying the cross-bedded oolite is the structureless oolite with bioclastic infill lithofacies (SOBI). Mechanical pencil is 13 cm long. Location 7. (B) Hummocky cross stratification (HCS) within the graded bed facies. Note the coarse crinoids at the base of individual beds (CC). Location 7. Hammer is 28 cm long.
slabbed and polished, a graded bed (on outcrop) is shown to consist of separate thin beds of bioclastic packstone and bioclastic grainstone facies, with coarser-grained bioclastic grainstone more common near the base and finer-grained bioclastic packstone more common near the top. Beds from polished hand samples are typically thin, 1 to 4 cm thick is common, and lack grading. The overall succession from coarser-grained basal beds to finer-grained beds near the top makes a normally graded bed on outcrop. In addition to grading, common sedimentary structures include an erosive base and a coarse basal layer of crinoid fragments (Figure 6A). Swaley and hummocky cross stratification is present, but not common (Figure 6B).

Because the graded bed facies consists of bioclastic packstones and grainstones, average bulk volumes range between the values already reported for those lithofacies. Values are 57-59% crinoids, 12-22% cement, 7-12% bryozoans, 2-4% brachiopods, 0-6% ooids, and 0-18% micrite (Table 1; Appendix 2; n = 18). Less abundant carbonate grains (<1%) consist of rugose corals and foraminifera. Grain size ranges from 0.08 to 6.2 mm in long dimension, with 0.10 to 0.75 common for the packstone component, and 0.25 to 2.0 mm most common for the grainstone component (Figures 4 and 5). Most grains appear slightly abraded, but grains can be non-, slightly, moderately, and highly abraded locally. Mud matrix appears to have intruded pore space during compaction (this will be discussed later in the Paragenesis section). Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Brachiopod shells are typically consistent in orientation within individual beds, typically either concave or convex up, but some are resting edgewise. Brachiopod shells are dominantly oriented parallel to bedding (~75%) with an approximate ratio of 3:2 (convex up:convex down; Figure 7).

**Bioclastic Packstone, Bioclastic Grainstone, and Graded Bed Facies Interpretations**

The graded bed lithofacies consists of the bioclastic packstone and grainstone lithofacies, and therefore the origin of all three lithofacies is intimately related. Three hypotheses can be evaluated to explain the origin for these lithofacies. They include deposition of sediments by: (1) processes below storm wave base; (2) processes
Figure 7. Photograph of polished hand sample showing brachiopod orientations. Brachiopods are predominantly either concave down (CD) or concave up (CU). Sample 4.12.
above fair-weather wave base; or (3) storms above storm wave base, but below fair-weather wave base.

If deposition occurred below storm wave base one would expect thorough bioturbation, muddy fabrics and a lack of evidence for oscillatory currents. Data that contrast these expectations include grainstone fabrics, lack of bioturbation in some examples, hummocky or swaley cross stratification, and symmetrical wave ripples. These observations indicate that deposition did not occur below storm wave base.

Sediments deposited above fair-weather wave base should have diagnostic sedimentary structures that include wave-ripple cross lamination, and trough and tabular cross bedding (Burchette and Wright, 1992; Boggs, 1995; Wright and Burchette, 1996). Grains should be well abraded and sorted. Bioturbation would not be dominant because of the constant movement of particles on the bottom. Grainstone fabrics should dominate. Evidence against deposition above fair-weather wave base includes slight abrasion of most bioclasts, locally abundant bioturbation, packstone, and locally abundant wackestone, lithology. Based on these data, it is unlikely that deposition occurred above fair-weather wave base.

The final hypothesis is deposition by storms above storm wave base, but below fair-weather wave base. Features that could be formed during storms include sharp, erosive bases, coarse bioclastic lags, gutter casts, tool marks, grain-dominated normally graded beds, symmetrical wave ripples, and hummocky or swaley cross stratification (Kreisa, 1981; Tucker and Wright, 1990; Burchette and Wright, 1992). Bioturbation and deposition of muddier facies with poorer sorting would be expected between storm events. Graded beds, bioturbation at the tops of graded beds, erosive bases, coarse lags, symmetrical wave ripples, and hummocky and swaley cross stratification suggest that deposition was dominated by storms above storm wave base but below fair-weather wave base.

Hummocky cross stratification is especially useful in recognizing storm deposits (Harms et al., 1975; Kreisa, 1981; Duke, 1985; Handford, 1986). It is present in the studied lithofacies but it is not abundant. The coarseness of sediments is
the likely reason for its low abundance. Hummocky cross stratification is most common in coarse siltstone to fine sandstone (0.03 to 0.2 mm) (Dott and Bourgeois, 1982; Brenchley, 1985).

The orientation of brachiopod shells also may be diagnostic for identifying storm deposits. At the bases of storm beds, Kreisa (1981) reported random- or vertical-shell orientations, whereas throughout the rest of each storm bed the shells are dominantly parallel to bedding (75%), with the majority of shells convex up as opposed to convex down (2:1). Sixty percent of the brachiopods from the graded bed lithofacies are convex up, which is comparable to the results from Kreisa (1981), where 67% are convex up. This brachiopod shell data suggests that the graded beds were deposited by storms.

Fair-weather wave base is commonly at a water depth of approximately 10 meters (Boggs, 1995), and storm wave base usually extends to 30-50 meters (Tucker and Wright, 1990; Elrick and Read, 1991). However, values for fair-weather wave base and storm wave base are dependent upon geographic and geologic factors. Samthein (1970) found that storm wave base in the Persian Gulf, which appears to be an analog for this study, is reflected by a maximum concentration of echinoderm fragments at 15-50 m, depending on fetch and geography. Based on the Persian Gulf example, and other fair-weather wave base data, it is likely that these sediments were deposited in 10-50 m water depth.

Cross-Bedded Oolite Facies-Descriptions

This lithofacies is characterized by cross-bedded grainstone that is dominated by ooids. Bed sets are 12 to 67 cm thick, with most between 12 and 32 cm (Figures 6B, 8). This lithofacies consists of trough and tabular cross beds, and lacks mottled fabrics that would be indicative of bioturbation. There is a sharp basal contact with underlying bioclastic grainstone (location 4; unit 5; Figure 9) and graded beds (location 2, unit 8; location 3, unit 7; location 7, unit 6; Figure 9). The trough cross beds can consist of up to four sets to make up a coset (terminology after McKee and Weir, 1953). Each set of cross-bedded strata range from 0.4 to 3.6 cm thick, with
Figure 8. At the base of the photograph is trough cross-bedded oolite (TCB) from the cross-bedded facies. The dashed white line is the boundary between TCB and the structureless oolite with bioclastic infill lithofacies (SOBI) facies. Field notebook is 19 cm long. Location 7.
Figure 9. Cross section showing vertical and lateral variability of lithofacies and boundaries of genetic units 1-19. Scale of spacing of stratigraphic sections is variable. Distance between each stratigraphic section is marked. Cross section is generally oriented north-south. Variations in orientation of line of section are marked on the top of each stratigraphic section. The sections are hung on a southward slope of 3 cm/km, which is assumed to approximate depositional dip.
most 0.5 to 1.0 cm. These layers have bedding surfaces that are curved, parallel, and curved, nonparallel (terminology from Campbell, 1967). The tabular cross beds at location 4 (unit 13) and location 7 (unit 12; Figure 9) can consist of up to two sets to make up a coset. Each set consists of strata that range from 0.5 to 3.6 cm thick, with most ~2 cm. The bedding surfaces are even, nonparallel (terminology from Campbell, 1967), and dip only 7-8°.

The composition of the cross-bedded oolite facies varies from 57 to 77% ooids, 4 to 21% crinoids, 15 to 19% cement, 2 to 4% brachiopods, and trace bryozoans (Appendix 2; n = 4). This facies has foraminifera that constitute less than 1% of the average bulk volume. Ooid grain size varies from 0.14 to 0.75 mm, with 0.3 to 0.6 mm common. Ooids are predominantly micritized, but concentric laminae are observable around some nuclei. Bioclasts (typically 1 to 3 mm crinoids) are interspersed within this facies. The bioclasts either have poorly developed oolitic coatings or lack coatings altogether. Most crinoid grains are highly abraded. Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Oolitic intraclasts may be present, vary from 1.0 cm to approximately 10 cm, have isopachous, bladed cement around ooids, are typically well rounded, and lack the compaction features seen in the host sediment.

Cross-Bedded Bioclastic Facies – Descriptions

This lithofacies is characterized by trough cross-bedded grainstone that is dominated by crinoid fragments. Trough cross-bedded bioclastic grainstone overlies oolite at locations 1 (unit 14), 3 (unit 15), and 5 (unit 16; Figure 9). This lithofacies has trough cross beds and lacks mottled fabrics that would be indicative of bioturbation. Stratification is curved parallel and curved nonparallel (terminology from Campbell, 1967). Two bed sets are common, each 18 to 32 cm thick (Figure 9). Thickness of stratification ranges from ~0.5 to 4.0 cm thick (most are 0.5 to 1.0 cm).

The composition of the cross-bedded facies above the oolitic interval is 56% crinoids, 18% cement, 15% ooids, 9% bryozoans, and 2% brachiopods (Appendix 2; n = 1). This facies has foraminifera that constitute less than 1% of the average bulk
volume. Ooid grain size varies from 0.21 to 0.72 mm, with 0.3 to 0.6 mm common. Ooids are predominantly micritized, but concentric laminae are observable around some nuclei. Bioclasts (typically 1 to 3 mm crinoids) are interspersed within this facies. The bioclasts either have poorly developed oolitic coatings or lack coatings altogether. Most crinoid grains are highly abraded. Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Oolitic intraclasts may be present, vary from 1.0 cm to approximately 10 cm, have isopachous, bladed cement around ooids, are typically well rounded, and lack the compaction features seen in the host sediment.

Cross-Beded Oolite and Bioclastic Facies - Interpretations

The cross-bedded oolite and bioclastic facies are interpreted to have been deposited in shallow-water, high-energy environments. Thus, they are discussed together. Modern-day ooid-producing environments have been described (Ball, 1967; Hine, 1977; Harris, 1983, Major et al., 1996). Water depths for modern ooid shoals with trough and tabular cross beds range from the intertidal zone down to 5 m, with intertidal to 2 m the most significant for ooid formation (Ball, 1967; Loreau and Purser, 1973; Hine, 1977; Tucker and Wright, 1990; Major et al., 1996).

Trough cross bedding can originate both by migration of small and large-scale bedforms (Boggs, 1995). Trough cross bedding is common in beach shoreface deposits where longshore and tidal currents dominate (Inden and Moore, 1983) as well as other subtidal high-energy settings. The trough cross-bedded oolite and bioclastic lithofacies are interpreted to have formed in shallower than 5 m water depth on the basis of modern analogs producing similar structures (Ball, 1967; Loreau and Purser, 1973; Hine, 1977; Tucker and Wright, 1990; Major et al., 1996). Low-angle tabular cross bedding is well known in beach foreshore deposits, and this could well be its origin in the cross-bedded oolite facies. Features other than cross bedding that might indicate beach foreshore deposition can include fenestral fabrics, hardgrounds, rhizoliths, alternating coarse and less coarse laminations, reversal of dip, truncations, borings, encrustations, or an upward transition into subaerial exposure. As none of
these features have been found, it is difficult to interpret the low-angle tabular cross-bedded facies as foreshore deposits confidently. Any interpretation as such should be considered tentative. The isopachous, bladed cement within the oolitic intraclasts most likely formed penecontemporaneously with ooid deposition. Large, rounded oolitic intraclasts suggest that water energy (wave or tidal) must have remained high to break apart a cemented oolite and round it into oolitic intraclasts.

Comparison of specific modern analogs to the cross-bedded oolite facies is useful in constraining its origin and depositional environment. An appropriate modern analog must be associated with a ramp or gently sloping platform interior. It must be capable of producing trough cross-bedded and low angle tabular cross-bedded oolite and must be capable of resulting in a widespread, thin oolite after sea-level change.

Ooid shoals in the Bahamas (e.g. Joulters Cay, Cat Cay, Lily Bank, and Schooner Cay) are not good analogs. They are too thick and are situated at bank margins of isolated platforms rather than on ramps (Ball, 1967; Hine, 1977; Harris, 1983; Major et al., 1996).

Oolitic facies of the northeastern Yucatan shelf are similar to the cross-bedded oolite facies, but also contrast markedly in several ways. The Yucatan is probably a poor analog because mud is present within its oolitic deposits, oolite accumulations are thick (ranges from ~5 m to 8 m), lagoonal and tidal-flat facies are common, and there are significant eolian deposits (Ward and Brady, 1973).

Even on ramps, tidal bars, deltas, and channel fills are unlikely analogs. Many achieve significant thicknesses and are laterally restricted in distribution. For example, southern Arabian Gulf ooids of East Abu Dhabi and between Jebel Dhanna and Yas Islands are tidal bars and deltas (Evans et al., 1964; Loreau and Purser, 1973; Kirkham, 1998). These deposits attain significant thicknesses of 5 m (Loreau and Purser, 1973) and are laterally restricted in distribution.

Shoreline-associated oolitic deposits on ramps, however, appear to be reasonably good analogs. The Turks and Caicos Islands, British West Indies are
situated near the bank margin of an isolated platform. Ooid generation occurs in beach environments on the leeward side of the islands. Long Bay is an example from Caicos Island where ooid generation occurs in the beach swash zone down to ~3 m water depth by wind-generated waves (Lloyd et al., 1987). Beach sand is medium grained, well sorted, and consists of well-rounded, oolitically coated particles with only a few percent of uncoated skeletal grains (Lloyd et al., 1987). The sand is ~2.5 m thick at the low-tide strandline and thins rapidly to 0.5 m offshore. About 1 km offshore is a series of bar-like sand buildups that are laterally restricted and low relief (1.3 m; Lloyd et al., 1987). The sediments within these buildups are mostly pelletal, but ooids are also present (Lloyd et al., 1987). Sand wave migration most likely occurs episodically during storm events (Lloyd et al., 1987).

The present-day southern Arabian Gulf is commonly cited as a definitive modern example of a ramp and likely holds reasonable analogs for the cross-bedded facies (e.g. Loreau and Purser, 1973; Read, 1985; Tucker and Wright, 1990; Burchette and Wright, 1992). Southern Arabian Gulf ooids near Sabkha Matti are generated in the beach swash zone down to ~2 m (Loreau and Purser, 1973). Below 2 m, sediments grade laterally into skeletal sand within a short distance (Loreau and Purser, 1973). These shoreface oolitic sands consist of a series of elongate megaripples that attain a thickness of 1 m (Loreau and Purser, 1973). The sand flat near Sila is ~500 m wide and ~10 km long with sediments that are almost exclusively ooids (Loreau and Purser, 1973). The total width of the sand flat and adjacent eolian ooid sands of the coastal plain is slightly greater than 3 km and ~10 km long (Loreau and Purser, 1973), suggesting that the ooid-generating beach has migrated or that storms have transported the ooids.

Both the Turks and Caicos Island (Long Bay) and Southern Arabian Gulf (near Sabkha Matti) are examples where ooid deposition occurs within a beach environment on shallowly dipping surfaces. Megaripples are present at both Long Bay and near Sabkha Matti in up to 3 m water depth, which should produce cross bedding. Low-angle tabular cross beds would be produced in the swash zone. Thus,
the cross-bedded oolite and bioclastic facies of this study is interpreted to have formed between the swash zone and 3 m water depth, possibly in beach foreshore and shoreface environments.

Structureless Oolite Facies - Descriptions

This lithofacies is characterized by high ooid content, a mottled fabric, and lack of physical sedimentary structures (Figure 10A). Beds are 15 to 116 cm thick. A mottled fabric has been identified within many polished hand samples, and may indicate that bioturbation has destroyed physical sedimentary structures.

Average composition for the structureless oolite facies is 80% ooids, 15% cement, 3% crinoids, 1% brachiopods, and trace bryozoans (Table 1; Appendix 2; n = 5). Less abundant carbonate grains (<1%) consist of foraminifera. Ooid grain size varies from 0.14 to 0.75 mm, with 0.3 to 0.6 mm common (Figures 10B, C). Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Oolitic intraclasts may be present, range from 0.2 cm to approximately 10 cm in diameter, are typically well rounded, and lack the compaction features seen in the host sediment.

Structureless Oolite Facies - Interpretations

Any model for deposition of this facies must account for its widespread distribution. One hypothesis for the creation of this facies is generation within a high-energy, shallow marine environment that was similar to the possible beach deposits from the cross-bedded oolite facies. If deposition occurred within such an environment, some physical sedimentary structures should be preserved, but the only sedimentary structure found is a mottled fabric suggestive of bioturbation. Also, modern beaches or shoals are laterally restricted in distribution, suggesting that deposition of the structureless oolite facies occurred in a different setting.

Another hypothesis for the creation of this facies is transport of sediments away from the site of ooid generation (beach or shoal) into neighboring areas. Based on the high ooid content, it seems likely that the ooids formed in a beach or shoal environment. As ooids were transported away from their environment of generation
Figure 10. (A) Polished hand sample of structureless oolite facies. Note high ooid content (darker particles are crinoid nuclei) and homogeneous (bioturbated) nature of the sample. Sample 3.10. (B) Transmitted-light photomicrograph of structureless oolite facies showing ooids (OO) and late-stage cement (LC). Note micritized nature of ooids. (C) CL photomicrograph showing the same field of view as in B. Scale is 400 µm for B and C. Thin section 5.6.
by storms, the composition of sediment would not change significantly and laterally extensive deposits would result. If these sediments were transported by storms, normally graded beds, basal lags, or hummocky cross stratification might be present, but given the thorough bioturbation their presence is not expected.

The thorough bioturbation suggests either transport into a low-energy environment or bioturbation of beach or shoal deposits (cross bedded oolite/grainstone facies) in situ, perhaps associated with a relative rise in sea level. A shallow sand-flat environment is one possibility, but is unlikely. The deposits lack structures indicating tidal-flat deposition. In addition, the paucity of shoreface and foreshore deposits indicates that deposition at sea level was unlikely. Deposition offshore, in deeper water than the site of ooid generation is more likely. This interpretation is consistent with interstratified crinoidal carbonates, general paucity of muddy lagoonal deposits, and regional studies which show oolites that are interstratified with turbidites downslope to the South (Lisle, 1983).

The sediment from the structureless oolite facies was most likely either transported by storms or prevailing currents from the site of generation to a deeper, lower-energy environment where bioturbation prevailed, or was bioturbated in situ in beach or shoal environments after a relative rise in sea level. It is likely that water depth was deeper than 2 m.

*Structureless Oolite with Bioclastic Infill Facies - Descriptions*

This lithofacies is characterized by an abundance of ooids, lack of physical sedimentary structures, and presence of crinoids within subvertically oriented burrows. Beds are 11 to 30 cm thick (Figure 8). At location 7, *Chondrites* (Häntzschel, 1962; Bromley, 1996) was identified that had been filled with bioclastic grainstone (Figure 11A). Also, a mottled fabric indicates bioturbation within the oolite.

Average composition for the structureless oolite with bioclastic infill facies (including matrix and burrow fills) are 60% ooids, 20% crinoids, 19% cement, and 3% brachiopods (Table 1; Appendix 2; n = 2). Within the burrow fills, crinoids and
Figure 11. (A) Ichnofossil of Chondrites and bioturbation within the structureless oolite with bioclastic infill facies (SOBI). Burrows are filled with the overlying bioclastic grainstone (GS). Also note rounded intraclasts of oolite (Ol) near the base of the bioclastic grainstone facies. Pencil is 15 cm long. Location 7. (B) Transmitted-light photomicrograph of structureless oolite with bioclastic infill facies showing mixture of micritized ooids (OO) and crinoid fragments (CR), syntaxial overgrowths (SO), and late-stage cements (LC). (C) CL photomicrograph showing syntaxial overgrowths around crinoids and late-stage cement. Note primary concentric texture of oolitic coating (OC). Scale for both photomicrographs is 400 µm. Sample 7.5. (D) Polished hand sample of structureless oolite with bioclastic infill facies. Note subvertical crinoid patches. Sample 3.8.
cement dominate typically, commonly consisting of ~45% crinoids, ~30% ooids, and ~25% cement. Trace amounts of foraminifera are not listed, but contribute on average <1% of total rock volume. Ooid size ranges from 0.14 to 0.75 mm, with 0.3 to 0.6 mm common (Figures 11B, C). Crinoid fragments range from 0.4 to 3.0 mm and are present within the subvertical patches throughout the ooid-rich unit (Figure 11D). Pressure solution features are common (especially in ooid-dominated sections) as stylolites, overly close packing, and sutured grain contacts. In one place, a bed of crinoid-dominated sediments overlies this facies (unit 10, location 3, Figure 9; Appendix 1).

*Structureless Oolite with Bioclastic Infill Facies - Interpretations*

Shallow-water sediments can be transported to deeper water by storms or prevailing currents. Bioturbation can occur within this deeper-water environment, which can lead to open-burrow networks. It is also possible that these open-burrow networks can be filled with sediment during storm events.

The oolitic part of this facies is identical to the structureless oolite facies and is interpreted to have been deposited in the same manner (deposition below fair-weather wave base from storms or bioturbation of cross-bedded facies *in situ* after a sea-level rise). As burrows are filled with the bioclastic grainstone facies, already interpreted to have formed in deeper water than structureless oolite, bioclastic infill of the structureless oolite records a relative rise in sea level. Additionally, the laterally persistent nature of the crinoids support this interpretation. Wanless et al. (1988) documented bioturbation and infilling of open-burrow networks on a shallow marine platform. They showed that when storm waves from Hurricane Kate passed over the study area, open *Callianassa* burrow tubes were filled with mud, mollusks, and peloids, generating "tubular tempestites". The structureless oolite with bioclastic infill facies of this study is also interpreted to have formed by infilling of open-burrow networks during storm events after deepening.

In summary, the host oolitic sediments were most likely deposited either by storms or prevailing currents, or the sediments were deposited in a beach or shoal
environment and then burrowed during times of higher sea level. Following deposition, a crinoid-rich environment ensued, probably the result of a relative rise in sea level. When a storm occurred, it is likely that crinoids were deposited in the open burrows. The water depth could have been between 2 and 50 m.

Mudstone/Silty-Mudstone Facies - Descriptions

In most of the areas in which this facies was observed, it was found to fill karstic cavities developed within the Keokuk Limestone and Warsaw Formation. In one locality (C3; Figure 9; Appendix 1) this facies is interstratified with limestones and does not fill karstic cavities. As the karst fills are the norm, the descriptions below exclude the interstratified example of this facies at location C3.

This lithofacies is characterized by the content of siliciclastics, and, in places, flaser bedding at locations 3 and C2. Rocks consist of tan to gray mudstone or silty to very fine-grained sandstone with clay drapes over the silty to sandy component, and a matrix not effervescent in hydrochloric acid (Figures 12A, B). Beds are not laterally continuous at location 3, but are found in dissolitional pockets in the host limestone, about 50 cm long and 7 cm high. The contacts between the underlying units and this facies are abrupt because of the dissolution. Location C2 is a one-inch core, so it is impossible to determine the lateral extent at this location. Bioturbation is not present in this facies. Sedimentary structures are absent in the muddy intervals (Figure 12A), but flaser bedding may be present in the silty/sandy portions of the rocks (Figure 12B).

No body fossils are recognized in this lithofacies, therefore compositions were not determined. Grain size ranges from clay to very fine-grained sand.

Mudstone/Silty-Mudstone Facies - Interpretations

At the end of Mississippian, sea level fell substantially to create a world-wide unconformity (Ross and Ross, 1988). During development of this unconformity, karst features formed in Mississippian strata, and have been documented by several authors in southwestern Missouri and surrounding areas (e.g. Harris, 1985; Kaufman et al., 1988; Unklesbay and Vineyard, 1992).
Figure 12. (A) Karstic cavity with siliciclastic infilling. Karst development most likely occurred at the sub-Pennsylvanian unconformity, with infilling during the Early Pennsylvanian (Atokan?). Visible length of marker is 5.7 cm. Location 3. (B) Mudstone/Silty-Mudstone facies. Possible karst feature with siliciclastic infilling of sediment. Of note are the vertical fill of facies and lithoclasts within this facies. Vertical length of core in photograph is 66 cm. Location C2.
The mudstone/silty-mudstone facies most likely resulted from the filling of karstic cavities during Early Pennsylvanian sedimentation. Late Mississippian rocks in southwestern Missouri are carbonate, except for a few isolated siliciclastic examples in Barry County (Thompson, 1986). Morrowan rock units (sandstones) are present in southwestern Missouri, but are rare and localized (Harris, 1985). Atokan siliciclastic units of variable lithology are also localized, but are more abundant than Morrowan rock units; widespread sedimentation did not begin until the Desmoinesian (Harris, 1985). Kaufman et al. (1988) also reported cavities of varying size and morphology that were filled with shale and quartz sand from overlying Pennsylvanian formations (Desmoinesian).

On the basis of lithology, the likely age for deposition of this lithofacies is Atokan or Desmoinesian.

**Bioclastic Wackestone Facies - Descriptions**

Bioclastic wackestone is characterized by a high percentage of micrite and mud-supported textures. It is found only in the northernmost core, C3. Bedding is 1 to 80 cm thick. Mottled fabrics are not observed. No physical sedimentary structures are present.

Average compositions were not calculated for the bioclastic wackestone facies because it is volumetrically minor and only 1 sample was taken. Crinoids, brachiopods, and bryozoans are present. Grain size ranges from 0.04 to 0.21 mm in the long dimension, with 0.06 to 0.12 mm most common. Most grains are slightly to moderately abraded, but highly abraded grains also occur rarely. Pressure solution features are common as stylolites, overly close packing, and sutured grain contacts. Brachiopods are not present in sufficient quantities to discern preferred orientations.

**Bioclastic Wackestone Facies - Interpretations**

The northernmost core (C3) is the only location that does not contain the Short Creek Oolite and is the only one containing the bioclastic wackestone facies. The lime mud suggests a low-energy environment and biota suggest a normal marine source of grains. Deposition in a distal slope environment, in deeper water, could
explain the high mud content and biota, but this hypothesis seems unlikely given the northernmost geographic position. Alternatively, the high mud content could be caused by deposition in a lagoon behind a barrier.

Lagoons have been documented behind ooid-generating beaches in several modern-day environments (Loreau and Purser, 1973; Ward and Brady, 1973). These lagoonal deposits have a high mud content and variable percentage of ooids. The bioclastic wackestone lacks ooids, so it was likely not deposited behind an oolitic barrier.

The more likely explanation for this facies is deposition in a lagoon behind a bioclastic shoal. A bioclastic shoal environment would have a normal-marine biota, and it would provide a source of abraded fossils. Deposition behind such a shoal is consistent with the high mud content and location in the northernmost core.

**STRATIGRAPHY**

Facies shifts on carbonate ramps can be great, resulting from the interaction between the low-slope on the surface of deposition and even small fluctuations in relative sea level. Elrick and Read (1991) computed the inner-outer ramp gradient for an Early Mississippian ramp in present-day Wyoming and Montana to be 1-15 cm/km (0.00057-0.0086°); slopes were calculated from the change in estimated water depths of time-equivalent facies across the platform. Smith (1996) conducted a field-based study on the ramps adjacent to the Illinois Basin (Eastern “Shelf” and the Western “Shelf”) and suggested that the slope was probably never greater than 7 cm/km (0.004°) during deposition. In the current study, such slopes were considered for plotting a datum for correlation (Figure 9). Based upon the data from Elrick and Read (1991) and Smith (1996), it seems reasonable to use a southward shallowly sloping surface of approximately 3 cm/km for this ramp. The cross section is hung on the bottom of the oolite (or erosional equivalent) using a southward slope of 3 cm/km.

The widespread nature of the oolitic facies (Figure 9) is evidence for diachronous deposition. Detailed correlations are difficult given the lack of unique lithofacies. Within this study, the oolitic interval is divided into genetic units that are
nearly time-equivalent. Genetic stratigraphy was employed as a means of tracking relative sea-level change and relating it to stratigraphic architecture. The oolitic interval was chosen for analysis because of its specific links to water depth. Correlations should be considered as hypotheses most consistent with the stratigraphy and interpretations of depositional environments of the various lithofacies. Solid lines indicate high confidence in correlations and dashed lines indicate lower confidence in correlations.

One hypothesis for initial ooid deposition is that deposition began in distal areas (location 2) and was followed by the northward migration of ooid shoals updip due to a relative rise in sea level. This hypothesis is unlikely, however. Given this hypothesis and the assumption of a southward-dipping slope, subaerial exposure would be expected updip (north) during initial shallow-water deposition of oolite. No caliche laminated crusts, rhizoliths, autoclastic breccia, evaporites, blackened grains, meniscus or pendant cements, or change in cement stratigraphic patterns are observed across the surface below the oolite north of location 2. For this reason, it is unlikely that initial ooid deposition began in a downdip location.

A second hypothesis could be that ooid production began in updip areas (north) and may have prograded or been forced downdip as a result of a relative fall in sea level. Facies shifts forced downdip by relative falls in sea level commonly include downward, highly progradational shifts in facies, and have been referred to as 'forced regressive’ deposits (Hunt and Tucker, 1992) or lowstand deposits. If the first ooids were generated updip (north), the time-equivalent downdip facies should contain ooids that had been transported into deeper-water environments, mixed into graded bed, bioclastic packstone, and bioclastic grainstone lithofacies. Ooids mixed into these facies have not been found, however, below the Short Creek Oolite to the south. As oolite deposition proceeded and relative sea level continued to fall, the ooid deposition would have migrated to the south resulting in subaerial exposure of oolitic sediments updip (north). Evidence for subaerial exposure of the oolite is found to the north above unit 11 at location C2.
Both hypotheses have weaknesses that make interpretations difficult. A weakness of the transgressive oolite hypothesis (1) is an identical cement stratigraphy below and above the proposed subaerial exposure surface. A weakness of the regressive hypothesis (2) is that the strata lack ooids near the top of the crinoid-rich portions of the Keokuk Limestone. Even though no ooids have been found in the crinoidal carbonates underlying the Short Creek Oolite, the second hypothesis appears to be more likely and the following unit descriptions are based on this hypothesis.

Initial oolite deposits were of structureless oolite of unit 1 (Figure 9) at location C1, which suggests that ooids were transported south (downdip) to C1. Location C3 is ~115 km north of location C1, and would have been subaerially exposed during deposition of unit 1 and all later oolitic units. North of location C1 the sediments were likely exposed subaerially, although the only evidence for this is an erosional contact at location C3 (see dashed red line indicating subaerial exposure; Figure 9). Unfortunately, detailed study of this core was not possible because sampling was not allowed. Farther south (between locations C1 and C2) the structureless oolite of unit 1 changes facies to crinoid-dominated lithologies (bioclastic packstone and graded-bed facies) and is laterally continuous to the south.

Structureless oolite of unit 2 (Figure 9) at location C1 also suggests sediment were transported south (downdip). North of C1 the sediments were likely exposed subaerially, although the only evidence for this is an erosional contact at location C3 (see dashed red line indicating subaerial exposure; Figure 9). Farther south (between locations C1 and C2) structureless oolite of unit 2 changes facies to crinoid-dominated lithologies (bioclastic packstone, bioclastic grainstone, and graded-bed facies) and is laterally continuous to the south.

Structureless oolite of unit 3 (Figure 9) at locations C1 and C2 suggests sediment transport south (downdip). Because ooids are present at both C1 and C2, this suggests that the site of ooid generation had migrated south between unit 2 and unit 3 deposition, possibly related to sea-level fall (Figure 13). North of location C1
Figure 13. Curve that relates deposition of units (numbers to the right of the center line) to relative sea-level fluctuations. If the curve is left of the center line, it indicates that sea level is higher than Unit 11 at C2. This unit was chosen because vadose cements are present, and thus, sea-level position is known for that time. If the curve is right of the center line, it indicates that sea level is lower than Unit 11 at C2. This figure represents quantitative relative sea-level fluctuations based on the assumptions discussed in the text. The constraints discussed in the text are marked with a dot and letter. Note that all quantified relative sea-level changes do not "zero out" because some of them are minimum relative sea-level changes.
the sediments were likely exposed subaerially, although the only evidence for this is
an erosional contact at location C3 (see dashed red line indicating subaerial exposure;
Figure 9). Farther south (between locations C2 and 4) structureless oolite of unit 3
changes facies to crinoid-dominated lithologies (bioclastic packstone, bioclastic
grainstone, and graded-bed facies) and is laterally continuous to the south.

Structureless oolite of unit 4 (Figure 9) at locations C1 and C2 suggests that
sediments were once again transported south (downdip). North of location C1 the
sediments were likely exposed subaerially, although the only evidence for this is an
erosional contact at location C3 (see dashed red line indicating subaerial exposure;
Figure 9). Farther south (between locations C2 and 4) structureless oolite of unit 4
changes facies to crinoid-dominated lithologies (bioclastic packstone, bioclastic
grainstone, and graded-bed facies) and is laterally continuous to the south.

Structureless oolite of unit 5 (Figure 9) at location C2 suggests that sediments
were transported south (downdip). After deposition of unit 5, sea level probably
continued to fall to expose the sediments subaerially further north at locations C1, C2,
and C3 (red line in figure 9; A on Figure 13). Farther south (between locations C2 and 4)
structureless oolite of unit 5 changes facies to crinoid-dominated lithologies
(bioclastic packstone, bioclastic grainstone, and graded-bed facies) and is laterally
continuous to the south. At location C2, unit 5 (structureless oolite) is cemented with
isopachous, bladed cement, and the top has a sharp, erosive contact that may indicate
subaerial exposure.

Cross-bedded oolite at the base of unit 6 (Figure 9) at location 4 suggests
deposition at a beach or shoal after a relative fall in sea level (B on Figure 13). In
order to determine a minimum estimate for sea-level fall, one may assume that the
deepest water for deposition of cross-bedded oolite was 3 m and the shallowest water
for deposition of structureless oolite was 3 m deep. If the slope of the ramp were 3
cm/km, then the minimum amount that sea level fell between units 5 and 6 would
have been 1.68 m (the slope multiplied by the distance between locations C2 and 4; 3
cm/km * 56 km = 168 cm; B on Figure 13). North of location 4 sediments were
likely exposed subaerially, although the only evidence for this is an erosional contact. Farther south (between locations 4 and 6), cross-bedded oolite of unit 6 changes to structureless oolite facies. Between locations 9 and 7, structureless oolite facies of unit 6 changes to crinoid-dominated lithologies (bioclastic grainstone and graded-bed facies) and is laterally continuous to the south. Structureless oolite, within the top part of unit 6 at location 4 is likely due to bioturbation of cross-bedded oolite, related to sea-level rise that is associated with deposition of unit 10.

Cross-bedded oolite of unit 7 (Figure 9) at location 7 suggests deposition at a beach or shoal. If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 6 and 7 would have been 0.33 m (the slope multiplied by the distance downdip between locations 4 and 7; 3 cm/km * 11 km = 33 cm; C on Figure 13). North of location 7, sediments were likely exposed subaerially, although the only evidence for this is an erosional contact. Farther north and west (between locations 7 and 1) cross-bedded oolite of unit 7 changes facies to structureless oolite. Farther south and west (between locations 1 and 3) structureless oolite of unit 7 changes facies to crinoid-dominated lithologies (bioclastic grainstone, and graded-bed facies) and is laterally continuous to the south. At location 7, structureless oolite, in the upper part of unit 7 is likely related to bioturbation during a sea-level rise that is associated with deposition of unit 10.

Cross-bedded oolite facies of unit 8 (Figure 9) at location 3 suggests deposition at a beach or shoal. If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 7 and 8 would have been 0.39 m (the slope multiplied by the distance downdip between locations 7 and 3; 3 cm/km * 13 km = 39 cm; D on Figure 13). North of location 3 sediments were likely exposed subaerially, although the only evidence for this is an erosional contact. To the east (between locations 3 and 5) cross-bedded oolite of unit 8 changes facies to structureless oolite. To the west (between locations 5 and 2) and south (between locations 2 and 11) structureless oolite of unit 8 changes to graded-bed facies and is laterally continuous to the south. Structureless oolite and bioclastic infill in the upper part of unit 8 at
location 3 is likely related to bioturbation during a sea-level rise that is associated with deposition of unit 10.

Cross-bedded oolite facies of unit 9 (Figure 9) at location 2 suggests deposition occurred at a beach or shoal. If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 8 and 9 would have been 0.21 m (the slope multiplied by the distance downdip between locations 3 and 2; 3 cm/km * 7 km = 21 cm; E on Figure 13). North of location 2 sediments were likely exposed subaerially, although the only evidence for this is an erosional contact. Farther south (between locations 2 and 11) cross-bedded oolite of unit 9 changes to structureless oolite facies. The total relative fall in sea level calculated for units 6 through 9 is only 93 cm (Figure 13) and it assumes the same water depth for deposition of cross-bedded oolite. If this assumption is incorrect, however, deposition of units 6 through 9 could be caused by progradation without a relative sea level change, or even a minor relative sea-level rise. Structureless oolite and bioclastic infill in the upper part of unit 9 at location 2 is likely related to bioturbation during a sea-level rise that is associated with deposition of unit 10.

Unit 10 consists of ooid-rich units to the north (locations C1, C2, 4, 6, and 9) and bioclastic units or bioclastic infill of open-burrows to the south (locations 9, 7, 1, 3, 5, 2, and 11). Bioturbation of oolite in upper parts of units 6, 7, 8, and 9 and deposition of crinoids in burrows formed in oolite suggest a relative rise in sea level. The magnitude of this sea-level change can be determined from the water depths interpreted for the lithofacies observed. Cross-bedded oolite at location 2 is interpreted to form in water shallower than 3 m, whereas the bioclastic grainstone bed is interpreted to have formed at 10-50 m. The relative rise in sea level would have been a minimum of 7 m (F on Figure 13). As a result of this sea-level rise, it is probable that cross-bedded oolite of unit 10 (Figure 9) developed north of location C1 and that ooids were transported southward to deposit structureless oolite at locations C1, C2, 4, 6, and 9. North of location C1 sediments were likely exposed subaerially, although the only evidence for this is an erosional contact. Farther east (between
locations 9 and 7) and farther south (between locations 7 and 1), structureless oolite of unit 10 changes to a crinoid-rich burrow fill or bioclastic grainstone.

At location C2, cross-bedded oolite and vadose cements of unit 11 (Figure 9) suggest that deposition at a beach or shoal was followed by subaerial exposure. If updip deposition of structureless oolite of unit 10 (at C1) was in at least 3 m of water, then subaerial exposure of unit 11 (at C2) requires a minimum relative sea-level fall of 3.78 m, given an assumed paleoslope of 3 cm/km (G on Figure 13). It is possible that north of location C2, sediments were exposed subaerially, although the only evidence for this is an erosional contact. Farther south (between locations C2 and 4) cross-bedded oolite of unit 11 changes facies to structureless oolite. Given the subaerial exposure of unit 11 at location C2, it is possible that another beach or shoal system formed farther south and ooids were transported downdip (south).

Two hypotheses can be tested to determine the placement of the site of ooid generation for unit 12. The first hypothesis places ooid generation at location 4, but this is unlikely. If ooid generation for unit 12 began at location 4, another unit of oolitic sediment would be present beneath the cross-bedded oolite of unit 12 at location 7, but none is present. The second hypothesis places the site of ooid generation at location 7 (Figure 9). This seems to be the more likely hypothesis because the number of units, and their thickness, underlying unit 12 at location 7, are adequately explained. This interpretation is consistent with the presence of structureless oolite of unit 13 overlying unit 12 at location 7, requiring later transport of ooids from the north. The low-angle tabular cross-bedded oolite of unit 12 at location 7 suggests deposition in the foreshore. If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 11 and 12 would have been 2.01 m (the slope multiplied by the distance downdip between locations C2 and 7; 3 cm/km * 67 km = 201 cm; H on Figure 13). Vadose cements in unit 11, north and west of location 7, indicates subaerial exposure. South and west of location 7 cross-bedded oolite of unit 12 changes to structureless oolite facies and is laterally continuous to the south.
The low-angle tabular cross-bedded oolite of unit 13 (Figure 9) at location 4 suggests deposition in the foreshore. If the slope of the ramp were 3 cm/km, then the amount that sea level rose between units 12 and 13 would have been 0.33 m (the slope multiplied by the distance downdip between locations 7 and 4; 3 cm/km * 11 km = 33 cm; I on Figure 13). North of location 4 sediments likely were exposed subaerially. Farther south (between locations 4 and 6) cross-bedded oolite of unit 13 changes facies to structureless oolite and is laterally continuous to the south.

Cross-bedded bioclastic facies of unit 14 (Figure 9) at location 1 suggests deposition in a beach or shoal environment. If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 13 and 14 would have been 0.51 m (the slope multiplied by the distance downdip between locations 4 and 1; 3 cm/km * 17 km = 51 cm; J on Figure 13). Alternatively, it is possible that no sea-level change occurred. Unit 13 at location 4 is interpreted to have formed in the foreshore and unit 14 at location 1 is interpreted to have formed anywhere between 0 and 3 m water depth. North of location 1 sediments may have been exposed subaerially. Farther south (between locations 1 and 3) cross-bedded bioclastic unit 14 changes facies to structureless oolite and is laterally continuous to the south.

Cross-bedded bioclastic facies of unit 15 (Figure 9) at location 3 suggests deposition in a beach or shoal environment (the same as for unit 14). If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 14 and 15 would have been 0.21 m (the slope multiplied by the distance downdip between locations 1 and 3; 3 cm/km * 7 km = 21 cm; K on Figure 13). North of location 3 sediments may have been exposed subaerially. Farther east and south (between locations 3 and 5) cross-bedded bioclastic facies of unit 15 changes facies to structureless oolite and is laterally continuous to the south.

Cross-bedded bioclastic facies of unit 16 (Figure 9) at location 5 suggests deposition in a beach or shoal environment (the same as for units 14 and 15). If the slope of the ramp were 3 cm/km, then the amount that sea level fell between units 15 and 16 would have been only 0.09 m (the slope multiplied by the distance downdip
between locations 3 and 5; 3 cm/km \times 3 \text{ km} = 9 \text{ cm}; L \text{ on Figure 13}). Considering the depth range possible, no sea-level change is necessary. Further north and west of location 5 the sediments may be exposed subaerially. Further south and west (between locations 5 and 2) cross-bedded bioclastic facies of unit 16 changes facies to structureless oolite and is laterally continuous to the south.

Structureless oolite facies of unit 17 (Figure 9) at location C2 suggests transport of sediments to deeper water. The change from cross-bedded bioclastic facies (unit 16) at location 5 to overlying bioclastic grainstone of unit 17 indicates a relative rise in sea level (Figure 13). The magnitude of this sea-level change can be determined from the estimated water depths of lithofacies interpretations. Cross-bedded bioclastic facies (unit 16) at location 5 is interpreted to have formed in depths of 3 m or less, whereas bioclastic grainstone facies is interpreted to have formed at 10-50 m. The relative rise in sea level would have been a minimum of 7 m (M on Figure 13). Farther south (between locations C2 and 4) structureless oolite of unit 17 changes facies to crinoid-dominated lithologies (bioclastic grainstone, and graded-bed facies) and is laterally continuous to the south. This oolite is the uppermost bed of oolitic facies in the studied interval.

Bioclastic grainstone of unit 18 (Figure 9) at location 4 suggests deposition by storms. Only trace amounts of ooids are found within unit 18, suggesting that ooid generation was far to the north. This suggests that sea level may have continued to rise. Bioclastic grainstone and graded-bed facies of unit 18 are laterally continuous to the south. Bioclastic grainstone of unit 19 (Figure 9) at location 4 suggests deposition by storms. Sea level may have fallen because ooids are more abundant than in unit 18, suggesting that a beach or ooid shoal associated with unit 19 was present to the south of the one associated with unit 18. Bioclastic grainstone and graded-bed facies of unit 19 are laterally continuous to the south. After deposition of unit 19, ooid generation ceased in the area; crinoid-dominated sediments prevailed in strata above unit 19.
DISCUSSION

The Short Creek Oolite is a thin, but persistent oolitic sandbody that is present for more than 150 km along dip. No modern examples of such a widespread oolite exist. One reason why modern environments may not have a widespread oolite is because these systems have existed essentially at one sea-level position for only a short amount of time. At Long Beach in Turks and Caicos Islands, the radiometric age dates for the slightly oolitic, pelletal sands are 970 years BP, whereas the oolitic beach sands are 620 years BP (Lloyd et al., 1987). Ooids that formed near Isla Cancun in the Yucatan Peninsula are 750 ± 80 years BP (Ward and Brady, 1973). The ooids at the tidal bars between the islands of Yas and Jebel Dhanna in the Persian Gulf are 430 ± 170 years BP (Loreau and Purser, 1973). If these ooid-generating environments were subjected to several fluctuations in sea level, it would be probable that a thin, widespread oolite might result.

At the time of ooid deposition, seawater should have precipitated calcite, but the middle Mississippian was a time of transition from calcite- to aragonite-dominated seas (Sandberg, 1983). Original mineralogy is important for diagenetic alteration and will be discussed further within the Diagenesis section. If the original mineralogy was aragonite, one might find preservation of aragonite (relics should be present), relatively coarse calcite mosaics that replaced the aragonitic ooids, or oomolds (Sandberg, 1983), however, none of these features were observed and relatively little alteration of ooids occurred other than micritization. Based on the time of deposition, lack of neomorphic textures, and generally good preservation of ooids, it is likely that the original mineralogy was calcite.

Several examples of broad, sheet-like ancient oolites have been described. The High Tor Limestone and individual Gully Oolite units are middle Mississippian oolites in southwest Britain that have thin, sheet-like geometries (Burchette et al., 1990). These units were interpreted to have been deposited on a slope of ~40 cm/km, which is much steeper than that assumed for the ramp of the Short Creek Oolite. Individual units in the Gully Oolite are several meters thick and are similar to the
Short Creek Oolite; both have long distances of facies migration influenced by minor base-level fluctuations and lacked a lagoonal facies (Burchette et al., 1990).

The Short Creek Oolite is not similar to many other well-known Mississippian oolitic units of the United States. Some of these oolitic units form laterally extensive sheets, like the Short Creek Oolite, but many of those have a thickness much greater than a few meters. Others are laterally restricted in distribution and are in no way analogous to the laterally extensive Short Creek Oolite. For example the Ste. Genevieve Limestone of the Illinois basin originated as ooid shoals, but the aerial extent of these carbonate sand bodies are significantly restricted compared to the Short Creek Oolite. The dimensions are on the order of 0.2-3 km wide, up to 10 km long, and no more than 8 m thick (Carr, 1973; Cluff, 1986). The slopes on which they were deposited may have been steeper, as great as 9.5 m/km (Zuppann, 1993).

The stratigraphic study of the Short Creek Oolite has documented its initial deposition in association with a minor relative fall in sea level of only 10 m (units 1-9; Figure 13). This fall may represent the lowest extent of a more major relative sea-level fall documented by Ross and Ross (1988) near the Osagean-Meramecian boundary and may be part of the same relative fall documented by Rankey (2003) for the Peerless Park Member of the Keokuk Limestone and by Franseen (1999) for the Keokuk Limestone. Short Creek Oolite deposition was affected by a later minor relative rise and fall in sea level of 7 m (Figure 13). This was followed by progradation (units 13-16) at approximately the same sea level position as was achieved during the earlier Short Creek lowstand (units 6-9; Figure 13). Finally, sea level appeared to rise during deposition of the uppermost Short Creek Oolite units (units 17-19; Fig. 13) with a magnitude of at least 7 m. Overall, the Short Creek Oolite was deposited when sea level was near its lowest position. Although it was deposited during minor sea level changes, it could easily be classified as a lowstand deposit.
DIAGENESIS

An ultimate goal of carbonate diagenetic studies is to gain an understanding of the processes associated with sediment lithification and porosity evolution predictable on the basis of setting and sea-level history. Previous studies have demonstrated that integrated petrographic (transmitted-light and cathodoluminescence) techniques are useful in correlating regionally extensive events of calcite cementation to surfaces of subaerial exposure (Meyers, 1974; 1978; Meyers and Lohmann, 1985; Moore and Druckman, 1981; Kaufman et al., 1988; Nieman and Read, 1988; Goldstein, 1991; Frank and Lohmann, 1995, among others).

This paper presents a framework for evaluating early diagenetic features associated with carbonates deposited on a ramp system. Specifically, the purpose of the diagenetic analysis in this study is to: 1) constrain timing and genesis of selected cements within the Keokuk Limestone, Short Creek Oolite, and Warsaw Formation; 2) semi-quantitatively identify bulk-volume cement within the major lithofacies; 3) determine if early cementation affected compaction of grains; 4) determine if a predictable pattern of compaction and porosity evolution can be discerned amongst major lithofacies throughout the study area; 5) integrate fluid inclusion microthermometry and stable isotopic data within a petrographic framework (transmitted-light and cathodoluminescence); and 6) evaluate the implications for petroleum exploration. Pore types are classified using the system proposed by Choquette and Pray (1970). Porosity estimates (minus cement) were determined semi-quantitatively using the visual comparison chart of Terry and Chilingar (1955).

Paragenetic Sequence

The paragenesis consists of 19 events, most of which have affected all of the outcrops and cores sampled for this study. The relative timing of each diagenetic event is summarized in Figure 14. The paragenesis is subdivided into early-, intermediate-, and late-stage events. Early-stage diagenetic events (events 1-3) occurred prior to deposition of the Warsaw Formation. For example, events 1-3 are
Figure 14. The paragenetic sequence for carbonates from this study (Keokuk Limestone and Warsaw Formation). Paragenetic events that are early stage occurred prior to Warsaw deposition based on field and microscopic observations. Intermediate-stage events occurred after Short Creek and Warsaw deposition but prior to sediment infill of karstic cavities at the Mississippian-Pennsylvanian boundary. Late-stage events occurred after sediment infill of karstic cavities at the Mississippian-Pennsylvanian boundary. Dashed lines indicate that the relative timing is ambiguous. The length of the boxes is not considered to be a quantitative representation of absolute duration.
<table>
<thead>
<tr>
<th>Diagenetic Events</th>
<th>Early Stage</th>
<th>Intermediate Stage</th>
<th>Late Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,2) Isopachous, Bladed Cement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1,2) Micritization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Pendant Cement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) Syntaxial Cement NL1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) Microfracture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6) Syntaxial Cement BL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7) Dissolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(8,9) Syntaxial Cements ML2, NL2, ML3, NL3, ML4, NL4, ML5, NL5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(8,9) Recrystallization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10) Syntaxial Cements ML6, NL6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(11) Dissolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12) Syntaxial Cements ML7, NL7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(13) Silicification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(14) Mechanical Compaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(15) Cements SL8, NL8, SL9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(16,17,18,19) Grain-to-Grain Pressure Solution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(16,17,18,19) Dolomitization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(16,17,18,19) Pyritization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(16,17,18,19) Stylolitization</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
pre-Warsaw (early-stage) because they are cross-cut along the margins of oolitic intraclasts. The pendant cements at the top of the Short Creek Oolite at C2 are also pre-Warsaw (early-stage) because they are not present in the overlying Warsaw Formation. Intermediate-stage diagenetic events (events 4-14) occurred after Short Creek Oolite deposition, but prior to Pennsylvanian sedimentation. It will be shown later that initial Pennsylvanian deposition in this area was likely Atokan in age. Events 4-14 are cut across by karst filled by this Atokan sediment. Late-stage diagenetic events (15-18) post-date formation of the karst in the Mississippian strata, occurred after Pennsylvanian sedimentation had started, and are also found in Pennsylvanian strata (Kaufman et al. 1988).

Harris (1982) established a calcite cement and dolomite zonal stratigraphy for Mississippian strata in southeastern Iowa and limited portions of western Illinois. Kaufman et al. (1988) conducted a field- and lab-based research project on the calcite cement stratigraphy of the Burlington and Keokuk Limestones in western Illinois and eastern and central Missouri using the nomenclature of Harris (1982). Six regionally correlative cement zones (II, III, IV, V, VI, and II') in the Burlington and Keokuk Limestones were distinguished by their luminescent intensity, relative Fe$^{2+}$ content, interzonal dissolution features, thickness, position within the zonal sequence, and the internal consistency of their timing relative to other diagenetic features, such as cement fracturing and calcite dissolution (Kaufman et al., 1988). Kaufman et al. (1988) found that cross-cutting relationships with sub-Pennsylvanian paleokarst features provided the best evidence for constraining the timing of cements II, III, and IV as predating Pennsylvanian deposition (Desmoinesian in their estimation); cements V and VI precipitated after Pennsylvanian sedimentation resumed. On the basis of cathodoluminescence characteristics and cross-cutting relationships, my observations can be compared directly to those of Kaufman et al. (1988):
Kaufman et al. (1988) suggested that cement zones II, III, and IV precipitated in a meteoric-phreatic environment. They cited cement morphology and low magnesium content as evidence that these cements did not precipitate within a marine environment. The exact timing of cements II, III, and IV were not able to be determined by Kaufman et al. (1988), but they speculated that meteoric waters associated with subaerial exposure during the mid-Meramecian, pre- and Early Chesterian, or pre-Pennsylvanian could have led to precipitation of these cements.

Manger and Tillman (2003) stated that four episodes of subaerial exposure were present in the southern Ozark region from the Late Mississippian to Early Pennsylvanian: 1) base of the Chesterian; 2) Mississippian-Pennsylvanian boundary; 3) within the upper Morrowan Series; and 4) Morrowan-Atokan boundary. Because my study area is to the north (updip) of the area that Manger and Tillman (2003) studied, it is possible that fewer exposure events existed, but that they were of greater duration. The major subaerial exposure event in my study area was the sub-Pennsylvanian unconformity that may have lasted from the Chesterian to the Atokan or Desmoinesian, but the exact timing cannot be established because of nondeposition or erosion.

Whereas Kaufman et al.'s (1988) evidence for cementation before deposition of Pennsylvanian sediments is irrefutable, the diagenetic environment for that cementation can be questioned. Frank and Lohmann (1995) found that similar cements in the Lake Valley Formation in New Mexico were precipitated by meteoric-marine mixing-zone waters. I hypothesize that some of the cements (II, III, and IV) identified by Kaufman et al. (1988) were actually precipitated in an environment...
other than meteoric-phreatic, and propose to test this with fluid inclusion and stable isotopic data.

**Event 1 or 2 - Precipitation of Isopachous, Bladed Cement.**— Isopachous, bladed cement is found only within oolitic intraclasts, where it reduced from 10 to 30% of the interparticle porosity (Figures 15A, B). Isopachous, bladed cement encrusts ooids and consists of 40-60 µm-long blades of cement with terminations that form acute angles. It is clear in plane-polarized light. Under cathodoluminescence illumination, isopachous, bladed cement varies from slightly to moderately luminescent, and has a blotchy appearance. Isopachous, bladed cement appears to retard compaction. Spalled fragments of isopachous, bladed cement indicates that minor compaction occurred after precipitation.

**Event 1 or 2 – Micritization.**— Micrite envelopes are observed in every thin section from this study. Micrite envelopes range from 4 to 70 µm thick, and are commonly developed around the edges of crinoid fragments, ooids, bryozoans, and to a lesser extent brachiopods (Figures 4, 5, 10, 11, 15, 16). Crinoid fragments that were extensively micritized were not overgrown by intermediate-stage cements (NL1-NL7).

**Event 3 - Precipitation of Pendant Cement.**— Pendant cements are observed only in thin section C2.7 (Figure 16) from bed 11 at location C2. These cements are volumetrically minor, occluding ~5% of the interparticle porosity within this thin section. Pendant cements consist of 5-75 µm-thick asymmetric crusts around the bottoms of ooids (Figure 16). Individual crystals terminate with acute angles. These cements vary from non- to moderately luminescent. Adjacent to these pendant cements is cement SL8 (event 15).

**Event 4 - Precipitation of Syntaxial Cement (NL1).**— NL1 is observed in many thin sections of the graded bed, bioclastic packstone, and bioclastic grainstone facies. It also precipitated around crinoids within the cross-bedded oolite and bioclast facies and structureless oolite with bioclastic infill facies. Although common, cement NL1 only reduced 1-10% of the interparticle porosity, with ~3% common (Figures
Figure 15. (A) Transmitted-light photomicrograph of early-stage isopachous, bladed cements (IB) and late-stage cement (LC) (cements SL8 and NL8) from oolitic intraclasts of the structureless oolite facies. Note that fabrics are open and have not been compacted because of early-stage cementation. (B) CL photomicrograph showing the same field of view as A. A non-luminescent cement appears after IB, and may be NL1, NL2, NL3, NL4, NL5, NL6, NL7, or NL8, but is probably NL 7 or NL8. Scale is 200 μm in both images. Thin section C2.5.
Figure 16. (A) Transmitted-light photomicrograph showing early-stage pendant cement (PC) and late-stage equant cement (LC) (either SL8 or SL9). (B) CL photomicrograph of the same image as A. Note the patchy fabrics (PF), suggestive of recrystallization. Scale for A and B is 200 µm. Thin section C2.7.
17, 18). NL1 is clear in plane-polarized light, and formed only as overgrowths on crinoids. NL1 consists of non-luminescent cement that ranges from 1 to 50 µm (commonly 2-40 µm) thick.

**Event 5 - Microfracture.**— Small microfractures are observed within sample 8.6 (Figure 18). Within this sample, the fractures have an insignificant volume, and have been occluded by cement BL (event 6; Figure 18). Fractures are 30-38 µm long and only a few µm wide. The fractures must postdate NL1 because they cut across it. The fractures are filled by cement BL, therefore the fractures must predate that cement. It is possible that these microfractures were the result of early compaction.

**Event 6 – Precipitation of BL.**— This cement is best developed in sample 8.6 (Figure 18), but also occurs in many thin sections where crinoids are present. This cement is volumetrically insignificant; ~1% of the interparticle porosity was reduced (Figure 18). BL consists of a very thin band of <1 to 5 µm thick overgrowths around crinoids. BL is brightly luminescent under cathodoluminescence illumination.

**Event 7 - Dissolution.**— Dissolution after BL is observed within sample 8.6 (Figure 18). Cements NL1 and BL were partially dissolved and later occluded by cement ML2 (event 8 or 9; Figure 18).

**Event 8 or 9 – Precipitation of ML2, NL2, ML3, NL3, ML4, NL4, ML5, and NL5 Cements.**— These calcite cements are observed in every thin section of graded bed, bioclastic packstone, and bioclastic grainstone facies, as well as many of the cross-bedded bioclastic facies and structureless oolite with bioclastic infill facies. These cements reduced pore space considerably in the graded bed, bioclastic packstone, and bioclastic grainstone lithofacies, from ~5-70% of interparticle porosity, with ~35% common (Figures 17, 18). In the structureless oolite and structureless oolite with bioclastic infill lithofacies, this cement occluded 1-7% of interparticle porosity, with an average of 3%. All of these cements are clear in plane-polarized light, and formed only as overgrowths on crinoids. The following cement descriptions are based on cathodoluminescent petrography. ML2 consists of alternating slightly, moderately, or brightly luminescent cement (commonly
Figure 17. CL photomicrograph showing the cement stratigraphy used throughout this study. Note dissolution feature after NL6. Crinoid (CR) and Ooids (OO) are labeled on photo. Scale for this image is 200 µm. Thin section C2.6.
Figure 18. CL photomicrograph showing most of the intermediate-stage cement stratigraphy (NL1-ML6) employed for this study, with microfractures and dissolution noted. Note that microfractures cut across NL1 and are filled with BL. This may represent early cementation followed by compaction. Scale for this image is 200 µm. Thin section 8.6b.
moderately luminescent). ML2 ranges from a few to \(~110\ \mu m\) (commonly \(3-10\ \mu m\)) thick (Figures 17, 18). NL2 consists of non-luminescent cement that ranges from 1 to \(~120\ \mu m\) (commonly \(2-9\ \mu m\)) thick. In places, a brightly luminescent "hairline" cement is present within NL2. ML3 consists of moderately to brightly luminescent cement that ranges from 1 to \(30\ \mu m\) (commonly \(2-5\ \mu m\)) thick. NL3 consists of non-luminescent cement that ranges from \(a\) to \(50\ \mu m\) (commonly \(2-9\ \mu m\)) thick. ML4 consists of moderately to brightly luminescent cement that ranges from 1 to \(30\ \mu m\) (commonly \(2-5\ \mu m\)) thick. NL4 consists of non-luminescent cement that ranges from 1 to \(6\ \mu m\) (commonly \(1-2\ \mu m\)) thick. ML5 consists of moderately luminescent cement that ranges from 1 to \(35\ \mu m\) (commonly \(2-10\ \mu m\)) thick. NL5 consists of non- to slightly luminescent cement that ranges from \(3\) to \(85\ \mu m\) (commonly \(4-30\ \mu m\)) thick. Cements NL1-NL7 (events 8 or 9, 10, and 12) precipitated prior to Pennsylvanian sedimentation based on cross-cutting relationships with sub-Pennsylvanian paleokarst infill (Figure 19).

**Event 8 or 9 – Recrystallization.**— Recrystallized cements are not observed in every thin section, but appear to be scattered in the study area. Where cements were recrystallized, the original cements had reduced interparticle porosity from 1 to \(~10\%\), with \(~5\%\) common (Figure 20). Recrystallized cements consist of 10 to \(~250\ \mu m\)-thick cloudy cement where the original cements, NL1-NL5, were dissolved partially and later refilled with cement. Cloudiness of recrystallized cements is the result of the high density of aqueous fluid inclusions. The scale of individual cement patches varies from 5 to \(~50\ \mu m\) and have aqueous fluid inclusions that are from 2 to 15 \(\mu m\). These patches have variable luminescence under cathodoluminescence illumination, from non- to moderately luminescent.

Timing of recrystallization can be evaluated using cathodoluminescence by comparing the cathodoluminescent characteristics of non-recrystallized parts of cement and of patches that cross-cut the original cement. It is clear that some recrystallization must have occurred after precipitation of NL5 because parts of that cement have been dissolved and refilled with cement. No cements after NL5 were
Figure 19. (A) Transmitted-light photomicrograph showing Pennsylvanian siliciclastic karst fill (KF) after intermediate-stage cements (IC). (B) CL photomicrograph of the same image as A. Scale for A and B is 200 μm. Thin section 3.12.
Figure 20. (A) Transmitted-light photomicrograph showing recrystallized intermediate-stage cements (RC) around a crinoid (CR). Late-stage cement SL8 occludes remaining pore space. (B) CL photomicrograph of the same image. Scale for both images is 400 µm. (C) CL photomicrograph of the same image, but expanded to show patchy fabrics indicative of recrystallization. Scale for this image is 200 µm. Thin section 1.5.
recrystallized. The question that remains is when recrystallization of cements began. Recrystallization of cements may have begun after precipitation of NL1, NL5, some time in between, or possibly even much later (ML6 or later). Recrystallization of cements most likely began after NL1 and ended after NL5 based on the fluid inclusion data (this will be discussed later).

Some growth zones appear to have been recrystallized preferentially. One explanation is that some of the NL1-NL5 cement zones may have been composed of high-Mg calcite, making them more susceptible to recrystallization.

**Event 10 - Precipitation of cement zones ML6 and NL6.**— These cements are observed in most thin sections of the graded bed, bioclastic packstone, and bioclastic grainstone facies, as well as many of the cross-bedded bioclastic facies and structureless oolite with bioclastic infill facies, but were only rarely observed in the structureless oolite facies. These cements reduced from 5-90% of the interparticle porosity, with ~10% common where present (Figure 17). Both ML6 and NL6 are clear cements in plane-polarized light, and formed only as overgrowths on crinoids. ML6 consists of thin alternations of non- to moderately or slightly to moderately luminescent cements that are 3 to 225 µm (commonly 15-75 µm) thick. NL6 consists of non- to slightly luminescent cement that is 1 to 50 µm (commonly 1-30 µm) thick.

**Event 11 - Dissolution.**— Dissolution after NL6 is observed in several samples throughout the study area (Figure 17). Dissolution occurred at the outer margin of NL6 and created scalloped crystal terminations. This dissolution must postdate cement NL6 and predate ML7 because the scalloped surface cuts NL6 and is overgrown by ML7.

**Event 12 - Precipitation of ML7 and NL7.**— These cements are rather uncommon and only reduce 1-3% of the interparticle porosity, with 1% common where present (Figure 17). Both ML7 and NL7 are clear cements in plane-polarized light, and formed only as overgrowths on crinoids. ML7 consists of moderately luminescent cement that ranges from 1 to 60 µm (commonly 3-50 µm) thick. NL7
consists of non-luminescent cement, in some cases with a brightly luminescent "hairline". It ranges from 1 to 60 μm (commonly 1-10 μm) thick.

**Event 13 - Silicification.**— Silicification occurs throughout the study area, but only occurs within the bioclastic packstone, bioclastic grainstone, and graded bed lithofacies. The silicification is most extensive near Joplin, Missouri. Silica clearly replaced the host material, and cross cut the intermediate cements (events 8 or 9, 10, and 12; Figure 21). Field observations reveal that silicification occurred prior to significant compaction because relict structures of carbonate grains in cherts do not exhibit the compactional features, such as grain-to-grain pressure dissolution or stylolites, so common in the unsilicified limestone.

It is possible that the dominance of chert near Joplin could represent a depositional feature where silica was localized due to biological influence, or it could represent localization of diagenetic fluids. The relationship between the chert within the Keokuk Limestone or Warsaw Formation to others in the Joplin District (Grand Falls Chert) is unknown (Thompson and Fellows, 1969).

**Event 14 - Mechanical Compaction.**— Compaction occurred after precipitation of NL7 and silicification (Figures 5 and 22). In sample 3.2, unlithified lime mud was compressed into the remaining pore space after precipitation of ML6 (Figure 22). Aragonite- and high-magnesium calcite-dominated lime muds are susceptible to cement dissolution-precipitation processes (Lasemi et al., 1990). The squeezing of lime mud into the remaining pore space after precipitation of cement NL7 indicates that the mud remained unlithified until compaction. It suggests that the lime mud was low-magnesium calcite because it was not dissolved or cemented, it remained unlithified throughout early- and intermediate-stage meteoric, mixed, and marine diagenesis. Compaction will be discussed in more detail in the Porosity section.

**Event 15 - Precipitation of SL8, NL8, and SL9.**— Nearly every thin section from this study, regardless of lithofacies type, contains SL8, NL8, and SL9 (Figure 17). These cements occluded all remaining pore space in every lithofacies. Cements
Figure 21. (A) Outcrop photograph showing replacive nature of chert. Note how chert cuts across stratification. Pencil is 15 cm long and rests on the bedding surface. (B) Transmitted-light photomicrograph of a gastropod shell where silicification (silica) has replaced the shell and geopetal sediment. Cement SL8 (late-stage cement) precipitated after silicification because of superpositional relationships. Scale is 400 µm. (C) CL photomicrograph showing the same field of view as in B. Scale is 400 µm. (D) CL photomicrograph showing the upper chamber of the gastropod from the same field of view as in A and B. Scale is 200 µm
Figure 22. (A) Transmitted-light photomicrograph showing intermediate-stage cement (up to and including ML6) within an intraparticle pore in a crinoid. Cement precipitated until pore space was occluded by micrite, which was probably a result of mechanical compaction. (B) CL photomicrograph of the same image. Scale for both images is 400 μm. (C) CL photomicrograph of the same image, but expanded to show cements and micrite better. Scale for this image is 200 μm. Thin section 3.2.
SL8, NL8, and SL9 are coarsely crystalline or equant in plane-polarized light. SL8 commonly consists of sector-zoned, slightly luminescent cement that ranges from 1 to ~400 µm thick (commonly ~100 µm thick; Figure 17). NL8 is 1 to ~15 µm (commonly 3-10 µm) thick, non-luminescent, and exhibits no zoning under cathodoluminescence (Figure 17). SL9 is nearly homogeneous, moderately luminescent, and is 3 to ~800 µm thick (Figure 17). SL9 is the last cement and occludes all remaining porosity, therefore there is no typical thickness.

**Event 16, 17, 18, or 19 — Grain-to-Grain Pressure Dissolution.**

Compaction features are common within all lithofacies from this study. Some grains show grain-to-grain pressure dissolution, whereas others have interpenetrating fabrics (Figure 5). Cement SL9 was precipitated before this type of compaction because it is truncated by the compacted grains (Figure 5). These fabrics indicate that significant compaction of sediments occurred.

**Event 16, 17, 18, or 19 - Dolomitization.** — Dolomite is uncommon within samples from this study. Where present, it is typically composed of individual dolomite crystals that are 5 to ~150 µm in long dimension, commonly 25 to 75 µm. The dolomite appears light to dark gray and cloudy in plane-polarized light. Where present, it commonly replaced micrite within the graded bed or bioclastic packstone lithofacies, but in places it replaced cement SL8 or SL9 (Figure 23). Where present, dolomite commonly occupies only minor amounts of rock volume (1 to a few %), but sample 3.12 has up to 60% dolomite. Under cathodoluminescence, dolomite crystals are red, moderately luminescent, and do not exhibit compositional zoning. Dolomitization postdates SL9 because it cuts across that cement.

Mississippi Valley-type ore deposits (MVT) are common as calcite, saddle dolomite, barite, and sphalerite throughout the study area. They have been estimated to occur during the Late Pennsylvanian to Early Permian in the Ozark region of Missouri, Arkansas, Kansas, and Oklahoma (Wu and Beales, 1981; Wisniowiecki et al., 1983; Leach et al., 1984; Rowan et al., 1984; Leach and Rowan, 1986). The dolomite and pyrite from this study (events 16, 17, or 18) cross cut both SL8 and
Figure 23. (A) Transmitted-light photomicrograph showing dolomite (D) cutting across late-stage cement SL8. Note the different stages of dolomite development. (B) CL photomicrograph of the same image as A. Note that dolomite is red, randomly distributed, and cuts across all fabrics throughout the image. Scale for both images is 200 μm. Thin section 3.12.
SL9, thereby suggesting an MVT origin for these. Kaufman et al. (1988) also suggested that MVT deposits cut across cements V and VI (SL8-SL9 in my study).

**Event 16, 17, 18, or 19 - Stylolitization.**— Stylolites are common throughout all of the lithofacies. Stylolites cut across cement SL9, but no cross-cutting relationship could be established with the dolomite. Lack of pyrite concentration within stylolites suggests that stylolitization occurred before pyritization.

**Event 16, 17, 18, or 19 - Pyritization.**— Pyrite is present at every measured section in varying proportions, but cores C2 and C3 have prodigious amounts of pyrite. The pyrite in thin sections from C2 and C3 is scattered within individual thin sections and cuts across all cement zones and grains. Pyritization postdates stylolitization because pyrite is not concentrated along the stylolites. Pyritization also postdates SL9 because it cuts across that cement. For these reasons, the pyrite is thought to be replacive.

*Porosity*

Cementation and compaction are the two major processes of porosity occlusion in most limestones (Meyers and Hill, 1983) and the major processes by which porosity was reduced and occluded in the rocks of this study. For this study, the effects of compaction and cementation are related to original lithofacies control and timing in relation to the sub-Pennsylvanian unconformity. Data presented are: porosity that existed at the time of deposition; porosity that remained after precipitation of the last cement predating Pennsylvanian sedimentation (intermediate-stage); the relation between lithofacies and the amount of cementation; and the relation between lithofacies and the amount of compaction.

Semi-quantitative intergranular porosity estimates were made on samples from the Keokuk Limestone, Short Creek Oolite, and Warsaw Formation. Original porosities for non-compacted areas within the bioclastic grainstone facies are 40-50%, with a mean of 42% (n = 8; Figures 24A, B). Intermediate-stage cements reduce 11-36% (average 18%) of the rock volume (events 8 or 9, 10, and 12; Figure 24A). Late-stage cements occlude 6-32% (average 24%) of the rock volume (event
Porosity for Non-Compacted Areas of Grainstone Lithofacies

Porosity (%) of Grainstone Lithofacies Through Time

Cross Plot Comparing % Crinoids and % Intermediate-Stage Cement
Figure 24. (A) Graph depicting the original porosity determined from non-compacted areas in the grainstone lithofacies. (B) Graph depicting the original porosity (%), porosity remaining (%) after intermediate-stage cementation, porosity remaining (%) after compaction, and % rock volume removed by compaction (ave original porosity minus % cement). Data presented are for grainstone lithofacies. (C) Cross plot comparing % crinoids and % intermediate-stage cement in grainstones. (D) Cross plot comparing % crinoids and % rock volume removed by compaction in grainstones. (E) Cross plot comparing % intermediate-stage cement and % rock volume removed by compaction in grainstones.
Enos and Sawatsky (1981) studied Holocene carbonate sediments from Florida and the Bahamas and found that original porosity for grainstones ranged from 40-53%, with a mean of 45%. Meyers and Hill (1983) conducted a compaction study on Mississippian skeletal limestones in New Mexico and found that skeletal grainstones started with 38-53% porosity in non-compacted areas of thin sections, with a conservative mean of 42%. Unfortunately, original intergranular porosities for the bioclastic packstone facies could not be determined because all areas of the thin sections showed evidence of compaction.

Based on theoretical calculations, the original porosity for a perfectly sorted oolite would be 26-48%, depending on the packing configuration of the ooids (Graton and Fraser, 1935). Investigators (Graton and Fraser, 1935) have estimated that the porosity for randomly packed spheres is 35%. The oolitic intraclasts with isopachous, bladed cement have an average volume of cement of 32% (n = 2; Figures 24A, B) with only minor compaction features present. For this study, the percent cement from the oolitic intraclasts is used as the initial porosity in the structureless oolite facies. In oolitic intraclasts of this facies, the early-stage isopachous, bladed cement reduce 8-14% (average 11%) of the rock volume (event 1; Figure 24A; Appendix 3). Intermediate-stage cements reduce 3% of the rock volume (events 8 or 9, 10, and 12; Figure 24A), and late-stage cements occlude 15-21% (average 18%) of the rock volume (event 15; Figure 24A). No analyses are reported here for structureless oolite lacking isopachous cements because of the prevalence of compaction fabrics.

The non-compacted areas of thin sections of cross-bedded oolite facies started with 30-48% porosity, with a mean of 37% (n = 3; Figures 24A, B). Intermediate-stage cements reduce 7-24% (average 13%) of the rock volume (events 8 or 9, 10, and 12; Figure 24A) and late-stage cements occlude 13-30% (average 24%; event 15; Figure 24A) of the rock volume.

The non-compacted areas of the thin section of cross-bedded bioclastic facies started with 40% porosity (n = 1; Figures 24A, B). Intermediate-stage cements
reduce 17% of the rock volume (events 8 or 9, 10, and 12; Figure 24A) and late-stage cements occlude 23% (event 15; Figure 24A) of the rock volume.

The non-compacted areas of thin sections of structureless oolite with bioclastic infill facies started with 31-50% porosity, with a mean of 37% (n = 3; Figures 24A, B). Intermediate-stage cements reduce 11-28% (average 20%) of the rock volume (events 8 or 9, 10, and 12; Figure 24A) and late-stage cements occlude 9-26% (average 17%) of the rock volume (event 15; Figure 24A).

The original porosity for the bioclastic packstone lithofacies could not be determined due to compaction. For the bioclastic packstone facies, intermediate-stage cements NL1-NL7 reduce 3-14% (average 10%) of the rock volume and late-stage cements occlude 1-3% (average 2%) of the rock volume.

One goal of this research has been to determine the relationship between lithology and amount of porosity that remained at the end of intermediate-stage cementation as a means of evaluating the effect of unconformity-related diagenesis on porosity evolution of reservoir facies. Porosity at the end of intermediate-stage diagenesis was determined for each lithofacies by first assuming an original porosity using the mean original porosity from non-compacted areas, measuring the rock volume occupied by early- and intermediate-stage cement, and subtracting that volume from the original porosity assumed. For this to represent the porosity at the end of the intermediate stage, it must be assumed that early- and intermediate-stage cements have not been removed by grain-to-grain pressure solution.

The bioclastic grainstone facies would have had an average of 31% porosity (ranges from 25 to 40%) at the end of the intermediate stage (Figure 24B; Appendix 3). The structureless oolite would have had an average of 29% porosity (ranges from 25 to 31%) at the end of the intermediate stage (Figure 24B; Appendix 3). The cross-bedded oolite facies would have had 33% porosity (ranges from 31 to 35%) at the end of the intermediate stage (Figure 24B; Appendix 3). The cross-bedded bioclastic facies would have had 28% porosity at the end of the intermediate stage (Figure 24B; Appendix 3). The structureless oolite with bioclastic infill facies would have had
31% (ranges from 30 to 31%) porosity at the end of the intermediate stage (Figure 24B; Appendix 3). According to these data, the four grainstone lithofacies had approximately the same volume of pore space open at the end of intermediate-stage cementation (averages are 29-31%). At the end of the early and intermediate stages, all grainstone lithofacies appear to have retained high porosities and would have made good reservoir facies, despite the long history of unconformity-related diagenesis.

Crinoidal grainstones started with higher porosity than oolitic grainstones, yet after, intermediate-stage diagenesis, both lithologies had similar porosity. This suggests that more cement was precipitated for crinoid-dominated lithologies during unconformity-related diagenesis. To evaluate the extent of this lithologic control, percent crinoids was plotted against percent intermediate-stage cements; a positive correlation was found (Figure 24C; Appendix 3). Thus, it appears that the presence of crinoidal nuclei promotes the precipitation of intermediate-stage cement.

Grainstone lithologies that resist compaction ultimately can preserve more porosity. Considering that the crinoidal nuclei promoted precipitation of intermediate-stage cements, one could hypothesize that the samples with the greater volumes of crinoids resisted compaction. Compaction would be resisted because the greater amounts of crinoids would have led to increased intermediate-stage cementation; the cements would stabilize the rock fabric. Apparently, this hypothesis, however, is not correct. The percent of rock volume removed by compaction (percent compaction) was calculated by subtracting the percent rock volume of early-, intermediate-, and late-stage cements from the average non-compacted original porosity. There is no correlation between percent compaction and percent crinoids or between percent compaction and percent intermediate-stage cement (Figures 24D, E).

Considering the complex mechanisms that control the amount of physical and chemical compaction, one might expect lithologic controls on porosity remaining after compaction. To calculate porosity remaining after compaction, one must
assume that all compaction occurred before precipitation of the late-stage cements, and thus, porosity remaining after compaction would be equal to percent of rock volume composed of late-stage cement. Within the bioclastic grainstone facies, rock volume of late-stage cement is 11%; within the structureless oolite facies, it is 12%; within the cross-bedded oolite facies, it is 13%; within the cross-bedded bioclastic facies, it is 12%; and within the structureless oolite with bioclastic infill facies, it is 13%. For grainstone facies, it appears that lithology does not affect the amount of porosity remaining after compaction. The bioclastic packstone facies was compacted by a different mechanism than the grainstones. Packstone facies were compacted through mechanical squeezing of lime mud into pore space, whereas grainstones compacted mostly by grain-to-grain pressure solution. Whereas the original porosity of the packstones is unknown, they now contain a rock volume of only 2% late-stage cement (Appendix 3). This suggests that, where lime mud is present, nearly all porosity can be reduced by mechanical compaction. Thus, packstone lithologies with similar original mineralogy and diagenetic histories to those studied here, are not likely to preserve high porosity after burial.

**Geochemistry and Origin of Isopachous, Bladed Cement**

**Stable Isotopic Data.**— Two microsamples were drilled from two thin sections to remove isopachous, bladed cement from within oolitic intraclasts (Appendix 4). δ¹⁸O values are -7.40‰ and -3.65‰ (average = -5.53‰), and δ¹³C values are 2.79‰ and 3.36‰ (average = 3.07‰) (Figure 25; Appendix 4).

**Interpretation.**— Isopachous, bladed cements are well known in marine phreatic diagenetic environments (James and Choquette, 1990). This cement is best interpreted, however, from relationships observed in the field, where it is present only within oolitic intraclasts and sample C2.5. The timing for this cement is most likely penecontemporaneous with deposition because oolitic intraclasts were cemented prior to deposition of the overlying bed. If cementation were penecontemporaneous with ooid deposition, the cementing fluids were most likely marine. The bladed crystal morphology with an acute angle indicates that the original mineralogy was calcite.
Figure 25. δ\textsuperscript{18}O and δ\textsuperscript{13}C values for diagenetic phases observed. White rectangle with red boundary is the estimated value for marine calcite precipitated from Osagean-Meramecian seawater (Mii et al., 1999). Gray rectangle is the estimated value for marine calcite precipitated from Morrowan seawater (Mii et al., 1999).
Recrystallized Cement

Crinoids

Bo (‰ VPDB)

SL8-SL9

ML6

NL1-NL7

Isopachous, Bladed Cement

Pendant Cement

Recrystallized Cement

δ¹³C (‰ VPDB)

δ¹⁸O (‰ VPDB)
The two stable isotope analyses do not coincide with known marine isotopic values for that time, but it is possible that the cement had recrystallized slightly, as evidenced by the patchy cathodoluminescence. It is also possible that contamination of the samples occurred during drilling for isotopic samples.

**Geochemistry and Origin of Pendant Cement**

**Stable Isotopic Data.**— Only one thin section with pendant cement (C2.7) was found within this study. The δ¹⁸O value is -4.43‰ and the δ¹³C value is 2.94‰ (Figure 25; Appendix 4).

**Interpretation.**— Petrography indicates that these cements precipitated in a vadose environment before deposition of the Warsaw Formation and that they were originally calcite. It appears that some portions of the pendant cement may have been recrystallized because it has a patchy distribution of non- and moderately luminescent cement, similar to the recrystallized cement (event 8 or 9; Figure 18B). The δ¹⁸O and δ¹³C values from my study may indicate a meteoric origin, but it is possible that these cements were partially recrystallized by marine or mixing-zone fluids (event 8 or 9). If this occurred, various δ¹⁸O and δ¹³C values can result (Figure 26).

**Geochemistry and Origin of Intermediate-Stage Syntaxial Cements (NL1, BL, ML2, NL2, ML3, NL3, ML4, NL4, ML5, NL5, ML6, NL6, ML7, and NL7)**

**Fluid Inclusion Petrography.**— Fluid inclusions are typically absent within the intermediate-stage syntaxial cements, giving it a clear appearance under transmitted light (Figures 17, 18). The aqueous fluid inclusions that are present are one-phase (liquid) and two-phase (liquid with a small gas bubble) at room temperature. Fluid inclusions have not necked down after a phase change because all-liquid inclusions are not petrographically paired with vapor-rich inclusions. All-liquid inclusions are in both small and large size ranges, suggesting that the absence of a bubble is not the result of significant metastability. All-liquid fluid inclusions indicate entrapment below about 50°C and are those that have not been altered by thermal reequilibration (Goldstein, 1993). Inclusions have negative crystal shape and are 3 to 9µm in long dimension. Fluid inclusions are concentrated in growth zones
Partial recrystallization of marine cement in meteoric water

- **A)** Recrystallization of marine cement in meteoric water in a closed system.
- **B)** Recrystallization of marine cement in meteoric water in an open system.
- **C)** Recrystallization of marine cement in meteoric water in a partially open and closed system.
- **D)** Mixing between meteoric and marine fluids that have equal amounts of dissolved carbon.
- **E)** Mixing between meteoric and marine fluids that have different amounts of dissolved carbon.
- **F)** Mixing between meteoric and marine fluids. Meteoric end members have variable δ¹³C. Physical mixture between meteoric and marine calcite end members. H) Physical mixture between meteoric and marine calcite end members. Meteoric end members have variable δ¹³C. Modified from Csoma (2003).

Figure 26. Various patterns of δ¹⁸O and δ¹³C produced by partial recrystallization of marine cements in meteoric water (A, B, C), mixing between marine and meteoric fluids (D, E, F), and physical mixing between meteoric and marine calcite (G, H). A) Recrystallization of marine cement in meteoric water in a closed system. B) Recrystallization of marine cement in meteoric water in an open system. C) Recrystallization of marine cement in meteoric water in a partially open and closed system. D) Mixing between meteoric and marine fluids that have equal amounts of dissolved carbon. E) Mixing between meteoric and marine fluids that have different amounts of dissolved carbon. F) Mixing between meteoric and marine fluids. Meteoric end members have variable δ¹³C. G) Physical mixture between meteoric and marine calcite end members. H) Physical mixture between meteoric and marine calcite end members. Meteoric end members have variable δ¹³C. Modified from Csoma (2003).
parallel to the cement substrate (Figure 27). Luminescence in inclusion-rich growth zones preserves concentric zoning and lacks evidence for recrystallization. The petrographic evidence supports a primary origin associated with cement growth. Six inclusions were measured from locations 1, 11, and C2 (Appendix 5).

**Fluid Inclusion Microthermometry.**—After stretching the originally all-liquid inclusions, the fluid inclusions were frozen to clear solid phases when cooled to about -50°C. At the instant the inclusions froze, a subtle jerk (a change in bubble shape, volume, or position) was commonly observed, but sometimes no jerk could be detected. Upon warming the frozen inclusions, no crystal mosaics or orange-peel textures were observed. FIA 22 has four Tm ice measurements from cement NL5, three of 0.0°C, and one of -0.1°C (Figure 28; Appendix 5). FIA 23 has two measurements from ML6 of -3.0°C and -2.9°C (Figure 28; Appendix 5).

**Stable Isotopes.**—Eleven microsamples were drilled from 8 locations (Appendix 4). The cements are not large enough to sample individual growth zones (except ML6 at location 11), and therefore, most measurements combine various proportions of cement zones NL1-NL7. The δ¹⁸O values range from -8.20‰ to -4.55‰ (average = -6.22‰) and the δ¹³C values range from -0.15‰ to +3.44‰ (average = +2.27‰) (Figure 25). No definitive trends with respect to geographic location or stratigraphic position can be differentiated from the data set. Crinoids that were drilled have δ¹⁸O values that range from -7.54‰ to -3.57‰ (average = -5.02‰) and δ¹³C values that range from -0.18‰ to +4.27‰ (average = +2.49‰), values similar to or more positive than NL1-NL7 (Figure 25; Appendix 4).

**Strontium Isotopic Data.**—One microsample of moderately luminescent cement (ML6) was obtained from location 11 (Appendix 6). The total concentration of Sr in this sample is 93 ppm (Figure 29; Appendix 6). The ⁸⁷Sr/⁸⁶Sr ratio is 0.70875±2 (Appendix 6).

**Interpretation.**—Cathodoluminescence petrography indicates an alternation of reduced Mn-poor and Mn-rich diagenetic environments. Cement stratigraphy (Kaufman et al., 1988 and this study) indicates precipitation before deposition of
Figure 27. Overlain transmitted-light and CL photomicrograph of recrystallized cement showing distribution of all-liquid fluid inclusions and their Tm Ice data. Scale is 40 µm for both images. Chip 1.5b8.
Figure 28. Histogram of final melting temperatures of ice (Tm ice) for originally all-liquid fluid inclusions from this study (recrystallized cement, NL5, and ML6). The inclusions are primary, originally all-liquid fluid inclusions that have been stretched in the laboratory to generate vapor bubbles.
Final melting temperature of ice (°C)

Number of measured inclusions

-3.0 -2.8 -2.6 -2.4 -2.2 -2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0

FIA 1  FIA 7  FIA 13  FIA 19
FIA 2  FIA 8  FIA 14  FIA 20
FIA 3  FIA 9  FIA 15  FIA 21
FIA 4  FIA 10  FIA 16  FIA 22
FIA 5  FIA 11  FIA 17  FIA 23
FIA 6  FIA 12  FIA 18
Figure 29. Plot showing $^{87}\text{Sr}/^{86}\text{Sr}$ versus total Sr (in ppm) for selected samples.
Atokan sediments, perhaps associated with later Mississippian unconformities and the sub-Pennsylvanian unconformity. All-liquid inclusions and cement stratigraphy disprove a high-temperature origin. \( T_m \) ice data (-0.1° and 0.0°C) from cement zone NL5 most likely indicate precipitation from meteoric or slightly brackish waters during subaerial exposure. \( T_m \) ice data (-3.0° and -2.9°C) from ML6 suggest inclusion entrapment from slightly evaporated marine waters. The most likely explanation for this is an episode of brine reflux.

\( \delta^{18}O \) values for least-altered North American brachiopods of Meramecian, Chesterian, Morrowan, and Atokan age vary from -3.8 to -0.2‰, and \( \delta^{13}C \) values vary from 1.8 to 4.5‰ (Mii et al., 1999). Compared to these \( \delta^{18}O \) values, it is not possible that cements NL1–NL7 were precipitated entirely from marine waters. The stable isotopic data from cements NL1-NL7 suggest physical mixtures of either cement precipitated from meteoric, marine, and evaporated water, meteoric and mixed waters, or meteoric, mixed, marine, and evaporated waters (Figures 25, 26).

Dissolution features after cement zones BL (event 7; Figure 18) and NL6 (event 11; Figure 17) may indicate an influx of calcite-undersaturated meteoric water, or mixed water, possibly resulting from one of four subaerial exposure events between the Chesterian and Atokan (Manger and Tillman, 2003). It is possible that the dissolution event after BL may be at the Mississippian-Pennsylvanian boundary, and the dissolution event after NL6 may be within the upper Morrowan series or at the Morrowan-Atokan boundary.

Frank and Lohmann (1995) used detailed micron-scale sampling methods to analyze individual cement zones’ isotopic signature from the Lake Valley Formation (Osagean) in New Mexico. They suggested that regionally extensive mixing between marine and meteoric water was responsible for cementation of alternating luminescent and non-luminescent cements that are similar in cathodoluminescence to NL1-NL7. Zone 2 from Frank and Lohmann (1995) consisted of meteoric-marine mixing zone cement with \( \delta^{18}O \) values from -5.7 to -2.5‰ (PDB) and \( \delta^{13}C \) values from 1.5 to 3.0‰ (PDB). Their data have similar ranges to the values for NL1-NL7,
and may indicate that at least some of cements NL1-NL7 precipitated within a meteoric, marine or mixed environment.

The $^{87}\text{Sr}/^{86}\text{Sr}$ value for ML6 from location 11 is more radiogenic than either Mississippian or Pennsylvanian seawater (McArthur et al., 2001). The cement stratigraphic data, however, show that cements NL1-NL7 precipitated prior to deposition in the Pennsylvanian (Atokan or Desmoinesian at the latest). The radiogenic Sr value likely represents acquisition of radiogenic Sr from argillaceous rocks through which this fluid likely moved during a time of Pennsylvanian reflux.

**Geochemistry and Origin of Recrystallized Cement**

**Fluid Inclusion Petrography.**— Fluid inclusions are primary to recrystallization because they are the size and shape of the recrystallized cement patches, and lack orientation in the growth direction. Aqueous fluid inclusions contain both two-phase (liquid and gas) and one-phase (liquid) fluid inclusions at room temperature. Fluid inclusions have not necked down after a phase change because all-liquid inclusions are not petrographically paired with vapor-rich inclusions. All-liquid inclusions are in both small and large size ranges, suggesting that the absence of a bubble is not the result of significant metastability. All-liquid fluid inclusions indicate entrapment below about 50°C and are those that have not been altered by thermal reequilibration (Goldstein, 1993). All-liquid inclusions have negative crystal shapes and range from 2 to 15 µm, with most measured inclusions 7 to 10 µm. Two-phase fluid inclusions exhibit relatively consistent high liquid-to-vapor ratios (L:V ratios).

Recrystallized cement containing the studied fluid inclusions was inspected under cathodoluminescence after microthermometry. The inclusions were categorized according to the luminescence of the cement containing them. FIAs were determined according to the luminescence of the cement in which the inclusion was entrapped and the relative position within the recrystallized cement patch. If measured fluid inclusions were within close proximity to one another (−50 µm), and within a patch with the same luminescence, then they were categorized as belonging
to the same FIA. Twenty-one FIAs were identified in the recrystallized cement from locations 1, 4, C1, C2, and C3 (Appendix 5).

**Fluid Inclusion Microthermometry.**— Freezing measurements were conducted in the same manner for these inclusions as for those in the intermediate-stage cements. No crystal mosaics or orange-peel textures were observed during the warming process. Final melting temperature of ice (Tm ice) measurements from originally all-liquid fluid inclusions within the recrystallized cement range from -2.0° to 0.0°C from 30 fluid inclusions (Figures 28, 30; Appendix 5). Eleven measurements are 0.0°C, 17 measurements are from -1.8° to -0.1°C, and 2 are from -2.0° to -1.9°C (Appendix 5). Inclusions with Tm ice measurements from -2.0° to -1.9°C come from luminescent patches. Inclusions with Tm ice measurements from -1.8° to -0.5°C come from moderately luminescent patches. Inclusions with Tm ice measurements of -0.2°C to 0.0°C come from non-luminescent and moderately luminescent patches.

**Stable Isotopic Data.**— Seven microsamples were drilled from the recrystallized cement (event 8 or 9) from 6 locations (Appendix 4). The δ¹⁸O values range from -8.87‰ to -5.17‰ (average = -6.73‰) and the δ¹³C values range from 0.60‰ to 3.30‰ (average = 1.92‰; Figure 25; Appendix 4).

**Strontium Isotopic Data.**— Three microsamples from the recrystallized cement (event 8 or 9) were drilled from 3 locations (Appendix 6). The total concentrations of Sr in these samples range from 130 to 167 ppm (Figure 29; Appendix 6). The ⁸⁷Sr/⁸⁶Sr of samples are 0.70805±2, 0.70811±2, and 0.70823±2 (Figure 31; Appendix 6).

**Interpretation.**— The petrographic observations indicate that recrystallization of these cements occurred after precipitation of NL1 and possibly before ML6, leading to an interpretation that recrystallization predated deposition of Pennsylvanian sediments. Similarities between luminescence of original cement and recrystallized patches suggest that precipitation of ML2-NL5 was coincident with recrystallization. Fluid inclusions constrain diagenetic environments well for these
Figure 30. Histogram of final melting temperatures of ice (Tm ice) from primary, all-liquid fluid inclusions in recrystallized cements (RC). No measurements from NL5 or ML6 are reported. Originally all-liquid fluid inclusions were stretched in the laboratory to generate vapor bubbles. Percent of seawater involved in seawater-freshwater mixing is calculated using the seawater salt-equivalent model of Goldstein and Reynolds (1994). Freshwater is indicated by Tm ice measurements of 0.0°C, whereas –1.9°C indicates normal seawater salinity, 3.5wt.% seawater salt equivalent.
Percent seawater involved in mixing

Final melting temperature of ice (°C)

Number of measured inclusions

FIAs from recrystallized cement
Figure 31. $^{87}\text{Sr}:{^{86}\text{Sr}}$ ratios for three samples of recrystallized cement (Appendix 6) compared to ages and $^{87}\text{Sr}:{^{86}\text{Sr}}$ ratios for seawater during the Carboniferous (Mississippian and Pennsylvanian). If the cements are marine in origin, then the age can be inferred from the dated record of marine $^{87}\text{Sr}:{^{86}\text{Sr}}$ (McArthur et al., 2001). Upper dashed line indicates upper confidence limit on age and lower dashed line indicates lower confidence limit on age. The solid line between the dashed lines indicates the McArthur et al. (2001) best fit. Shaded area shows age constraints interpreted from the $^{87}\text{Sr}:{^{86}\text{Sr}}$ data generated. Deposition of sediments occurred at approximately 345 Ma. Modified from McArthur et al. (2001).
Carboniferous 298 to 354
cements because sampling techniques are such that individual cement crystals can be
analyzed at a resolution not possible for isotopic analysis. All-liquid inclusions
indicate low temperature for recrystallization. Pennsylvanian seawater salinities have
not been published, but modern concentrations of salts in normal seawater are 35-
36% seawater-salt equivalent (Tm ice = -1.9°C). Other ancient seawater values have
been reported and have similar salinities to the modern (Johnson and Goldstein, 1993;
Goldstein and Reynolds, 1994), thus Mississippian or Pennsylvanian seawater fluid
inclusions should also have Tm ice measurements near -1.9°C. Tm ice measurements
of 0.0°C have been documented to represent a meteoric origin. Fluid inclusion
measurements that result from meteoric-marine mixing-zone fluids should have Tm
ice measurements between the meteoric and marine end members of -1.9° and 0.0°C.
Tm ice measurements indicate that fluids had compositions responsible for
recrystallization ranged in salinity from marine to meteoric.

Stable isotopic interpretations are poorly constrained because the analyses
consist of an amalgamation of varying proportions of the recrystallized patches and
original cement zones. The stable isotopic data for recrystallized areas of cement
have similar values to intermediate-stage cements that have not recrystallized. This
supports the assertion that precipitation of intermediate-stage cements was largely
coincident with their recrystallization (Figures 25, 26).

The ⁸⁷Sr/⁸⁶Sr ratios from the recrystallized cement have best-fit ages of 320.9
Ma ± 1.3 (0.70805), 318.8 Ma ± 1.4 (0.70811), and 314.1 Ma ± 1.5 (0.70823)
(McArthur et al., 2001; Figure 31; Appendix 6). Alternative interpretations of 301.1
Ma ± 1.0, 299.1 Ma ± 1.5, and 294.4 Ma ±4.6 (McArthur et al., 2001) are unlikely,
because recrystallization was prior to Pennsylvanian deposition. Based on the cement
stratigraphy and ⁸⁷Sr/⁸⁶Sr data, the most likely timing for recrystallization was during
late Chesterian through Atokan time. During these times, there was influx of
meteoric water, likely linked to subaerial exposure and development of one or more
unconformities, and marine water, likely linked to marine inundations of Chesterian,
Morrowan, or Atokan age.
**Geochemistry and Origin of Late-Stage Cements (SL8, NL8, and SL9)**

**Stable Isotopes.**—Twenty-one microsamples were drilled from 11 locations (Appendix 4). The $\delta^{18}$O values range from -11.78%o to -7.30%o (average = -9.32%o) and the $\delta^{13}$C values range from -6.24%o to 3.14%o (average = +0.53%o) (Figure 25; Appendix 4).

**Interpretation.**—Cement stratigraphy (Kaufman et al., 1988 and this study) indicates that late-stage cements precipitated after deposition of Pennsylvanian sediments (Figure 19), but prior to Mississippi Valley-type mineralization. Two possible hypotheses can be discussed for the origin of these cements: 1) by low-temperature deep meteoric circulation, or 2) at high temperature.

If late-stage cements precipitated from cool, deeply circulating meteoric waters, recharge could have taken place during Middle Pennsylvanian, Late Pennsylvanian, or Early Permian subaerial unconformities, or during Pennsylvanian non-marine sedimentation (Kaufman et al., 1988). Wojcik (1991) and Wojcik et al. (1997) studied the diagenesis of Pennsylvanian rocks from the Cherokee basin in southeastern Kansas. The stable isotopic data from early calcite cements from Pennsylvanian limestones cluster into two groups. The first group has $\delta^{13}$C values that range from 0.8%o to 2.4%o (PDB) and $\delta^{18}$O values that range from -10.1%o to -7.3%o (PDB). The $\delta^{18}$O data was interpreted to represent precipitation from depleted meteoric water at low temperature. The $\delta^{13}$C data from the first group was interpreted to represent either low water/rock ratio or a system where organic carbon was not present in sufficient amounts. In the second group, the $\delta^{18}$O values range from -9.0%o to -7.7%o and are interpreted to represent low-temperature meteoric waters. The $\delta^{13}$C values range from -4.0%o to -1.4%o and may represent increased interaction with soil-gas CO$_2$. Most of the late-stage cements from my study ($\delta^{18}$O values -11.78%o to -7.30%o and $\delta^{13}$C values -2.24%o to 3.14%o) have similar values to those of Wojcik, and thus, the late-stage cements of my study may have precipitated from depleted meteoric water at low temperature.
As temperature increases during burial, the calcites precipitated should exhibit progressively more negative oxygen isotopic compositions (Moore and Druckman, 1981; Anderson and Arthur, 1983; Moore, 1985; Choquette and James, 1990) unless an isotopically positive fluid is delivered to the system (Wojcik et al., 1997). The carbon isotopic composition of most subsurface cements in limestones is generally rock buffered, so it commonly will show little variation and is commonly enriched with $^{13}$C (Moore, 2001). In contrast, some late cementation events, particularly those involved with thermochemical sulfate reduction associated with thermal degradation of hydrocarbons in excess of 100°C, can exhibit very negative carbon isotopic compositions (Heydari and Moore, 1989; Heydari, 1997; Machel, 2001). The wide range of $\delta^{13}$C values found in the late-stage cements and especially the extremely negative $\delta^{13}$C values could be related to thermochemical sulfate reduction. The oxygen isotopic values cannot be used to discriminate between precipitation at high or low temperature, but it is interesting to note that the oxygen isotopic compositions of the late-stage calcites are similar to fractionation-corrected compositions measured by Wojcik et al. (1997) for hydrothermal dolomites.

On the basis of stable isotopic and petrographic data, it is impossible to distinguish between the low-temperature meteoric and high-temperature hypotheses.

**IMPLICATIONS FOR PETROLEUM RESERVOIRS**

Sedimentologic and diagenetic models useful in predicting porosity distribution are important for petroleum exploration. In this study, sedimentologic and diagenetic controls on porosity evolution were related to sea-level history, position on ramp, original lithology, and original mineralogy.

The oolitic units studied are thin, widespread, and were deposited on a shallowly dipping ramp, possibly in association with systems of beaches. Such thin deposits of oolites have such thin pay zones that they normally are not considered as volumetrically significant reservoirs. The shallowly dipping ramp setting led to major facies migrations as a result of only minor relative changes in sea level. This would lead to complex porosity and permeability heterogeneities for production of
hydrocarbons if such a reservoir were exploited. Thicker oolitic deposits, which would likely make better reservoirs, are those that have formed in shoal environments in association with paleotopographic elements or steeper slopes that localized their formation. The oolitic strata studied are best classified as lowstand deposits because they were deposited at the lowest relative sea-level position. Such lowstand carbonates typically lack early events of subaerial exposure, which would have led to stabilization of grains and at least minor cementation of interparticle porosity. Highstand deposits, however, typically have longer periods of early subaerial exposure, which encourage cementation and stabilization of grains. Early interparticle cements help retard grain-to-grain pressure solution (Meyers, 1980). Thus, lowstand oolitic carbonates lacking such early cements may have more overly close packing and less interparticle porosity than highstand oolites.

Original mineralogy of the ooids in lowstand systems should also have an effect on reservoir character. As observed in this study, ooids with originally calcite mineralogy are typically not subject to dissolution and should not be expected to produce hydrocarbons from oomoldic pores. Early and late dissolution of originally aragonitic ooids, however, is common (Moore and Druckman, 1981; Swirydczuk, 1988). In lowstand settings, where grain-to-grain pressure solution has increased the area of contact among grains, oomoldic pores should lead to high porosity and high permeability. It has also been shown in this study that lime mud remained unlithified throughout early- and intermediate-stage cementation because it was originally calcitic. This has important implications for porosity reduction because if calcitic lime mud is deposited, it will be squeezed into remaining pore space during mechanical compaction, thus reducing pore throats and porosity. A packstone lithology, with an originally calcite mineralogy for the lime mud, would make a poor hydrocarbon reservoir.

Many models for exploration of hydrocarbon reservoirs are guided by models relating porosity to unconformities and history of meteoric diagenesis (Budd et al., 1995). Kaufman et al. (1988) suggested that within the crinoid-rich grainstones,
intermediate-stage cements precipitated from meteoric waters during subaerial exposure. This study, however, has shown that although meteoric waters were important for precipitation of intermediate-stage cements around crinoids, mixing zone, marine, and reflux fluids also precipitated cement and greatly reduced pore space. The influence of marine and evaporated marine water indicates that new models must be formulated for prediction of porosity in carbonate reservoirs.

Normally, one might hypothesize that crinoidal grainstones would have different porosities than oolitic grainstones, owing to original differences in porosity and differing diagenetic history. This study confirms that crinoidal grainstones started with higher porosity than oolitic grainstone, but that rapid cementation around crinoidal nuclei evened out the effect after the intermediate stage of diagenesis, yielding lithologies with essentially the same porosities. One might also hypothesize that the preferential cementation around crinoids would protect crinoidal lithologies (preferentially over oolitic lithologies) from porosity reduction caused by later grain-to-grain pressure solution. No distinction in amount of compaction was found between oolitic and crinoidal grainstones; grain-to-grain pressure solution affects them equally despite the greater amount of intermediate-stage cement in the crinoidal grainstones. After early- and intermediate-stage cementation and pressure solution, pore space and permeability is greatly reduced and essentially the same for oolitic and crinoidal grainstones.

**CONCLUSIONS**

This study emphasizes the sedimentologic origin and early- and intermediate-stage diagenetic history of the Keokuk Limestone, Short Creek Oolite, and Warsaw Formation, which were deposited on a shallowly dipping Mississippian ramp system in the Mid-continent of the United States. The research involves detailed field- and core-based sedimentologic and stratigraphic interpretations, transmitted-light and cathodoluminescence petrography, fluid inclusion microthermometry, and stable (C and O) and Sr isotopic analyses.
Bioclastic packstone, bioclastic grainstone, and graded bed lithofacies were deposited by storms in a mid-ramp setting, likely in water depths of 10-30 m. Tabular cross-bedded oolite facies formed in the foreshore of beach systems, whereas trough cross-bedded oolite and bioclastic facies formed in the shoreface or offshore, most likely in water depths of 0-3 m. The sediments within the structureless oolite and structureless oolite with bioclastic infill lithofacies were generated in association with beaches, and were transported by storms into adjacent areas, probably in 2-10 m water depth.

The Short Creek Oolite initially was deposited in response to a minor relative fall in sea level of only 10 m, and may represent the lowest extent of a more major relative sea-level fall near the Osagean-Meramecian boundary. Short Creek Oolite deposition was affected by a later minor relative rise and fall in sea level of 7 m, which was followed by progradation and a relative sea-level rise of at least 7 m. Overall, the Short Creek Oolite was deposited when sea level was near its lowest position. Because this ramp is shallowly dipping, major facies migrations resulted from only minor relative changes in sea level. This facies migration would lead to complex internal heterogeneities for production of hydrocarbons if such a reservoir were exploited. Such thin oolites, however, are unlikely to be exploited.

The isopachous, bladed and pendant cements (early stage) were precipitated either penecontemporaneously or immediately after deposition, probably from marine and meteoric waters respectively. It has been suggested that intermediate-stage cements were precipitated from meteoric waters during events of subaerial exposure, but this study documents that meteoric, marine, mixed, and slightly evaporated marine waters were responsible for precipitation of these cements. Intermediate-stage cements precipitated after deposition of the Warsaw Formation, but before sedimentation resumed in the Pennsylvanian. The precipitation of cement from marine and evaporated marine water indicates that new models must be formulated for prediction of porosity in carbonate reservoirs. It can no longer be assumed that
meteoric diagenesis associated with subaerial exposure is the only factor leading to precipitation of such cements.

All four grainstone facies initially had high porosity. Even though a lithologic control was found for cementation of intermediate-stage cements (greater volumes of intermediate-stage cements are related to greater percent crinoids), the volume of pore space remaining after early- and intermediate-stage diagenesis was approximately equal for both ooid and crinoidal grainstones. Compaction through grain-to-grain pressure solution affects both oolitic and crinoidal grainstones the same, despite the greater amount of intermediate-stage cement in the crinoidal grainstones. Mechanical compaction affected the lithofacies differently. Porosity in the grainstone lithologies was not altered significantly by mechanical compaction. The porosity of packstones was reduced by mechanical compaction because the originally calcitic lime mud was not lithified early and was squeezed into the pores. Packstone lithologies of original calcite mineralogy make poor hydrocarbon reservoirs because calcitic lime mud may remain unlithified during burial.

Lowstand settings generally lack long periods of early subaerial exposure, thereby promoting later grain-to-grain pressure solution and increased contact area among grains. Lowstand oolitic carbonates lacking such early cements may have more overly close packing and less interparticle porosity than highstand oolites. If the original mineralogy of ooids were calcite, ooids typically would not be subject to dissolution. During times of originally aragonite seas, however, development of oomoldic porosity should lead to high porosity and high permeability within lowstand oolites, a creating a petroleum reservoir with favorable characteristics.
REFERENCES


Häntzschel, W., ed, 1962, Trace fossils and Problematica: Treatise on Invertebrate Paleontology, Lawrence, KS, GSA and University of Kansas Press, 259 p.


Harris, D. C., 1982, Carbonate cement stratigraphy and diagenesis of the Burlington Limestone (Mississippian), southeast Iowa, western Illinois [M.S. Thesis]: State University of New York-Stony Brook, 296 p.

Harris, J. W., 1985, Stratigraphy and depositional environments of the Krebs Formation—Lower Cherokee Group (Middle Pennsylvanian) in southeastern Kansas [M. S. Thesis]: University of Kansas-Lawrence, 139 p.


Speer, J. H., 1951, Short Creek oolite horizon in Ottawa County, Oklahoma [M.S. Thesis]: University of Oklahoma-Norman, 83 p.


Thompson, T. L., and Fellows, L. D., 1969, Stratigraphy and conodont biostratigraphy of Kinderhookian and Osagean rocks of southwestern


Vaden, D. W., 1987, Petrology and diagenesis of the Short Creek Oolite Member of the Boone Formation, Northeast Oklahoma [M.S. Thesis]: Oklahoma State University-Stillwater, 196 p.


### Appendix 1

This appendix includes the legal description locations of measured sections and the measured sections from field work.

### Location of Outcrop and Core Measured Sections

<table>
<thead>
<tr>
<th>Measured Section</th>
<th>Section</th>
<th>Township</th>
<th>Range</th>
<th>Latitude(15 S)</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NE 1/4, SE 1/4, NE 1/4</td>
<td>27</td>
<td>T. 27 N</td>
<td>R. 33 W</td>
<td>0365202 N</td>
</tr>
<tr>
<td>2</td>
<td>NW 1/4, NE 1/4, SW 1/4</td>
<td>3</td>
<td>T. 25 N</td>
<td>R 31 W</td>
<td>0382751 N</td>
</tr>
<tr>
<td>3</td>
<td>SW 1/4</td>
<td>16</td>
<td>T. 26 N</td>
<td>R. 32 W</td>
<td>0372622 N</td>
</tr>
<tr>
<td>4</td>
<td>NW 1/4, NW 1/4</td>
<td>33</td>
<td>T. 29 N</td>
<td>R. 31 W</td>
<td>0382677 N</td>
</tr>
<tr>
<td>5</td>
<td>SE 1/4, SW 1/4, NE 1/4</td>
<td>27</td>
<td>T. 26 N</td>
<td>R. 30 W</td>
<td>0393579 N</td>
</tr>
<tr>
<td>6</td>
<td>NW 1/4, NW 1/4, SE 1/4</td>
<td>10</td>
<td>T. 28 N</td>
<td>R. 32 W</td>
<td>0374866 N</td>
</tr>
<tr>
<td>7</td>
<td>SE 1/4, SW 1/4, SE 1/4</td>
<td>1</td>
<td>T. 27 N</td>
<td>R. 30 W</td>
<td>0397421 N</td>
</tr>
<tr>
<td>8</td>
<td>NW 1/4, SW 1/4, NW 1/4</td>
<td>14</td>
<td>T. 34 S</td>
<td>R. 25 E</td>
<td>0353341 N</td>
</tr>
<tr>
<td>9</td>
<td>NE 1/4, SE 1/4, NE 1/4</td>
<td>2</td>
<td>T. 27 N</td>
<td>R. 32 W</td>
<td>0376606 N</td>
</tr>
<tr>
<td>11</td>
<td>C, SE 1/4, NE 1/4</td>
<td>35</td>
<td>T. 22 N</td>
<td>R. 28 W</td>
<td>0417457 N</td>
</tr>
<tr>
<td>C1</td>
<td>NE 1/4, NE 1/4</td>
<td>21</td>
<td>T. 38 N</td>
<td>R. 32 W</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>NE 1/4</td>
<td>6</td>
<td>T. 34 N</td>
<td>R. 29 W</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>NW 1/4, SW 1/4</td>
<td>27</td>
<td>T. 11 S</td>
<td>R. 24 E</td>
<td></td>
</tr>
</tbody>
</table>
MEASURED SECTION KEY

- OOID  ---  ---  ---  CARBONACEOUS SHALE

- OOLITIC INTRA CLAST  ---  ---  ---  SILTY SHALE

- CRINOID FRAGMENT (NON-ABRADED) DIFFERING SIZES  ---  ---  ---  SHALE

- CRINOID FRAGMENT (SLIGHTLY ABRADED) DIFFERING SIZES

- CRINOID FRAGMENT (MODERATELY TO HIGHLY ABRADED) DIFFERING SIZES

- BRACHIOPOD

- RUGOSE CORAL

- FENESTRATE BRYOZOAN

- RAMOSE BRYOZOAN

- PELOID

- BURROW

- NORMALLY GRADED BED

- TROUGH CROSS BEDS

- TABULAR CROSS BEDS

- SIGMOIDAL BEDS

- PLANAR LAMINATION

- CHERT NODULE

- STYLOLITE

- LITHOCLAST

- KARST WITH SHALE INFILL

4.10 SAMPLE NUMBER (LOCATION . SAMPLE NUMBER)
Section Name: 9

Location: South of Alsea, MO, north side of railroad tracks.

NE 1/4, SE 1/4, NE 1/4, sec. 3, T. 37 N., R. 32 W.

[Diagram of a section showing layers and features with measurements and comments]

Comments:

- 2.0 m
- 9.5 m
- 9.4 m
- 9.3 m
- 9.2 m
- 9.1 m
- 9.0 m

Note: The diagram includes a scale and various layers labeled with their respective measurements.
### Comments

Karst feature with siliciclastic infill.
Clasts are probably Early Pennsylvanian.

Vertical sediment fill.
Siltstone and very fine-grained sandstone. No effervescence.
Pendant and meniscus cements.
APPENDIX 2

This appendix includes the bulk volumes for selected thin sections from the bioclastic packstone, bioclastic grainstone, cross-bedded facies, structureless oolite (and intraclasts of structureless oolite), and structureless oolite with bioclastic infill.

The following headings are used in the spreadsheet containing the bulk volume data:

**Thin section** = Thin section from which bulk volumes were determined

% **Crinoids** = The bulk volume of crinoids per thin section

% **Ooids** = The bulk volume of ooids per thin section

% **Mud** = The bulk volume of mud per thin section

% **Bryozoans** = The bulk volume of bryozoans per thin section

% **Brachiopods** = The bulk volume of brachiopods per thin section

% **Early** = The bulk volume of early-stage, isopachous cement per thin section

% **Intermediate** = The bulk volume of intermediate-stage cements (NL1-NL7) per thin section

% **Late** = The bulk volume of late-stage cement (SL8-SL9) per thin section
<table>
<thead>
<tr>
<th>thin section</th>
<th>% crinoids</th>
<th>% ooids</th>
<th>% mud</th>
<th>% bryozoans</th>
<th>% brachiopods</th>
<th>% early</th>
<th>% intermediate</th>
<th>% late</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bioclastic Packstone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1.7</td>
<td>56</td>
<td>0</td>
<td>20</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>C2.2</td>
<td>68</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>6.7</td>
<td>60</td>
<td>0</td>
<td>17</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>1.1</td>
<td>62</td>
<td>0</td>
<td>16</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>5.3</td>
<td>49</td>
<td>0</td>
<td>13</td>
<td>25</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>2.3</td>
<td>55</td>
<td>0</td>
<td>35</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>64</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>AVE</td>
<td>59</td>
<td>0</td>
<td>18</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td><strong>Bioclastic Grainstone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3.4</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>C1.1</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>C2.3</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>4.9</td>
<td>52</td>
<td>17</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>4.8</td>
<td>55</td>
<td>12</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>8.4</td>
<td>44</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>1.5</td>
<td>52</td>
<td>15</td>
<td>0</td>
<td>12</td>
<td>1</td>
<td>0</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>3.1</td>
<td>63</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>2.7</td>
<td>67</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>2.5a</td>
<td>38</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>11.5</td>
<td>53</td>
<td>20</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>AVE</td>
<td>57</td>
<td>6</td>
<td>0</td>
<td>12</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td><strong>Cross-Bedded Oolite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>21</td>
<td>57</td>
<td>0</td>
<td>tr</td>
<td>4</td>
<td>0</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>4.4</td>
<td>4</td>
<td>77</td>
<td>0</td>
<td>tr</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>5.6</td>
<td>12</td>
<td>65</td>
<td>0</td>
<td>tr</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>C2.7</td>
<td>10</td>
<td>73</td>
<td>0</td>
<td>tr</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>AVE</td>
<td>12</td>
<td>68</td>
<td>0</td>
<td>tr</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Thin Section</td>
<td>% Crinoids</td>
<td>% Ooids</td>
<td>% Mud</td>
<td>% Bryozoans</td>
<td>% Brachiopods</td>
<td>% Early</td>
<td>% Intermediate</td>
<td>% Late</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
<td>---------</td>
<td>-------</td>
<td>-------------</td>
<td>---------------</td>
<td>---------</td>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Cross-Bedded Bioclastic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>54</td>
<td>14</td>
<td>0</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td><strong>Structureless Oolite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cl.5</td>
<td>4</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>4.6b</td>
<td>2</td>
<td>79</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>3.1</td>
<td>3</td>
<td>84</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>5.4</td>
<td>1</td>
<td>83</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>4</td>
<td>79</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>AVE</td>
<td>3</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td><strong>Intraclasts of Structureless Oolite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1.6</td>
<td>2</td>
<td>68</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>18</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>C2.5</td>
<td>4</td>
<td>59</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>18</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>AVE</td>
<td>3</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>18</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td><strong>Structureless Oolite with Bioclastic infill</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>18</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>7.5</td>
<td>21</td>
<td>57</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>AVE</td>
<td>20</td>
<td>59</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>7</td>
<td>13</td>
</tr>
</tbody>
</table>
This appendix includes the bulk volumes for selected thin sections from the bioclastic grainstone, structureless oolite, cross-bedded facies, and structureless oolite with bioclastic infill. The following headings are used in the spreadsheet containing the stable isotopic data:

- **Thin section** = Thin section from which bulk volumes were determined
- **% Crinoids** = The bulk volume of crinoids per thin section
- **% Ooids** = The bulk volume of ooids per thin section
- **% Mud** = The bulk volume of mud per thin section
- **% Bryozoans** = The bulk volume of bryozoans per thin section
- **% Brachiopods** = The bulk volume of brachiopods per thin section
- **% Early** = The bulk volume of early-stage, isopachous cement per thin section
- **% Intermediate** = The bulk volume of intermediate-stage cements (NL1-NL7) per thin section
- **% Late** = The bulk volume of late-stage cement (SL8-SL9) per thin section
- **% Compaction** = The bulk volume of compaction (average non-compacted initial porosity minus % early- and intermediate-stage cement) per thin section
- **% Initial Porosity** = The bulk volume of cement within non-compacted areas per thin section
% Porosity Remaining After Intermediate = The porosity remaining after early- and intermediate-stage cementation per thin section

% Porosity Remaining After Compaction = The porosity remaining after compaction per thin section
## Appendix 3

<table>
<thead>
<tr>
<th></th>
<th>thin section</th>
<th>% crinoids</th>
<th>% ooids</th>
<th>% mud</th>
<th>% bryozoans</th>
<th>% brachiopods</th>
<th>% early</th>
<th>% intermediate</th>
<th>% late</th>
<th>% compaction</th>
<th>% initial porosity remaining after intermediate</th>
<th>% porosity remaining after compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bioclastic Grainstone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3.4</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>17</td>
<td>8</td>
<td>17</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>C1.1</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>17</td>
<td>8</td>
<td>12</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>C2.3</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>17</td>
<td>7</td>
<td>18</td>
<td>18</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>4.9</td>
<td>52</td>
<td>17</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>8</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>55</td>
<td>12</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>44</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>11</td>
<td>29</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>52</td>
<td>15</td>
<td>12</td>
<td>1</td>
<td>0</td>
<td>12</td>
<td>8</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>63</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>15</td>
<td>17</td>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>67</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>15</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5b</td>
<td>38</td>
<td>0</td>
<td>35</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>14</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td>53</td>
<td>20</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>13</td>
<td>22</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>57</td>
<td>6</td>
<td>12</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>11</td>
<td>20</td>
<td>42</td>
<td>31</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td><strong>Structureless Oolite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c1.5</td>
<td>4</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>14</td>
<td>15</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6b</td>
<td>7</td>
<td>39</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>12</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>3</td>
<td>84</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>20</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>1</td>
<td>83</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>13</td>
<td>17</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>4</td>
<td>79</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>16</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>13</td>
<td>16</td>
<td>32</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td><strong>Cross-Bedded Oolite Facies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>21</td>
<td>57</td>
<td>0</td>
<td>tr</td>
<td>4</td>
<td>0</td>
<td>6</td>
<td>12</td>
<td>19</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>4</td>
<td>77</td>
<td>0</td>
<td>tr</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>21</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>12</td>
<td>65</td>
<td>0</td>
<td>tr</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>15</td>
<td>18</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2.7</td>
<td>10</td>
<td>73</td>
<td>0</td>
<td>tr</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>12</td>
<td>22</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
<td>68</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>13</td>
<td>20</td>
<td>37</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td><strong>Cross-Bedded Bioclastic Facies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>54</td>
<td>14</td>
<td>0</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>9</td>
<td>12</td>
<td>16</td>
<td>40</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td><strong>Structureless Oolite with Bioclastic Infill</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>18</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>13</td>
<td>18</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>21</td>
<td>57</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>13</td>
<td>17</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>20</td>
<td>59</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>7</td>
<td>13</td>
<td>18</td>
<td>37</td>
<td>31</td>
<td>13</td>
</tr>
</tbody>
</table>
APPENDIX 4

This appendix includes all stable isotopic data obtained for various cements from this study. The following headings are used in the spreadsheet containing the stable isotopic data:

Thin section = Thin section from which sample was obtained

$\delta^{18}O\ (V\text{-PDB}) = $ Oxygen isotopic composition of various cements expressed in delta value notation in per mil ($\%$) relative to V-PDB.

$\delta^{13}C\ (V\text{-PDB}) = $ Carbon isotopic composition of various cements expressed in delta value notation in per mil ($\%$) relative to V-PDB.

CB = Crinoid

BRACH = Brachiopod

FI = Recrystallized cement

IC = Cements NL1 – NL7

ML6 = Cement ML6

LC = Cements SL8 – SL9

SC = Isopachous, bladed cement

PEN = Pendant cement
### Appendix 4. Stable Isotopic Data

<table>
<thead>
<tr>
<th>Thin</th>
<th>$\delta^{18}$O (V-PDB)</th>
<th>$\delta^{13}$C (V-PDB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 CB</td>
<td>-5.716</td>
<td>1.380</td>
</tr>
<tr>
<td>2.7 CB</td>
<td>-4.528</td>
<td>1.697</td>
</tr>
<tr>
<td>2.8 CB</td>
<td>-6.026</td>
<td>0.978</td>
</tr>
<tr>
<td>3.1 CB</td>
<td>-5.051</td>
<td>3.357</td>
</tr>
<tr>
<td>3.1 Brach</td>
<td>-5.109</td>
<td>2.338</td>
</tr>
<tr>
<td>3.4 CB</td>
<td>-5.426</td>
<td>2.606</td>
</tr>
<tr>
<td>3.12 CB</td>
<td>-6.628</td>
<td>-0.180</td>
</tr>
<tr>
<td>4.6b CB</td>
<td>-4.695</td>
<td>1.228</td>
</tr>
<tr>
<td>4.8 CB</td>
<td>-5.677</td>
<td>1.693</td>
</tr>
<tr>
<td>4.9 CB</td>
<td>-5.455</td>
<td>2.976</td>
</tr>
<tr>
<td>6.6 CB</td>
<td>-5.813</td>
<td>3.210</td>
</tr>
<tr>
<td>7.5 CB</td>
<td>-4.462</td>
<td>3.315</td>
</tr>
<tr>
<td>8.4 BRACH</td>
<td>-4.469</td>
<td>2.088</td>
</tr>
<tr>
<td>8.4 CB</td>
<td>-7.584</td>
<td>1.809</td>
</tr>
<tr>
<td>8.7 CB</td>
<td>-3.843</td>
<td>2.531</td>
</tr>
<tr>
<td>9.2 CB</td>
<td>-5.758</td>
<td>3.170</td>
</tr>
<tr>
<td>11.1 CB</td>
<td>-4.158</td>
<td>3.549</td>
</tr>
<tr>
<td>11.4 CB</td>
<td>-4.261</td>
<td>3.590</td>
</tr>
<tr>
<td>c1.1 CB</td>
<td>-3.566</td>
<td>4.268</td>
</tr>
<tr>
<td>c1.6 CB</td>
<td>-4.906</td>
<td>3.406</td>
</tr>
<tr>
<td>c2.1 CB</td>
<td>-4.511</td>
<td>4.140</td>
</tr>
<tr>
<td>c2.11 CB</td>
<td>-4.071</td>
<td>3.817</td>
</tr>
<tr>
<td>c2.5 CB</td>
<td>-4.305</td>
<td>-0.060</td>
</tr>
<tr>
<td>c2.7 CB</td>
<td>-3.833</td>
<td>2.612</td>
</tr>
<tr>
<td>c3.4 CB</td>
<td>-5.677</td>
<td>2.752</td>
</tr>
<tr>
<td></td>
<td>AVERAGE</td>
<td>-5.021</td>
</tr>
<tr>
<td></td>
<td>MINIMUM</td>
<td>-7.584</td>
</tr>
<tr>
<td></td>
<td>MAXIMUM</td>
<td>-3.566</td>
</tr>
<tr>
<td>1.5 FI</td>
<td>-6.939</td>
<td>1.164</td>
</tr>
<tr>
<td>2.7 FI</td>
<td>-5.172</td>
<td>0.600</td>
</tr>
<tr>
<td>2.8 FI</td>
<td>-6.896</td>
<td>1.339</td>
</tr>
<tr>
<td>4.8 FI</td>
<td>-5.350</td>
<td>3.300</td>
</tr>
<tr>
<td>c1.1 FI</td>
<td>-6.916</td>
<td>2.169</td>
</tr>
<tr>
<td>c2.1 FI</td>
<td>-8.870</td>
<td>1.820</td>
</tr>
<tr>
<td></td>
<td>AVERAGE</td>
<td>-6.691</td>
</tr>
<tr>
<td></td>
<td>MINIMUM</td>
<td>-8.870</td>
</tr>
<tr>
<td></td>
<td>MAXIMUM</td>
<td>-5.172</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3.1 IC</td>
<td>-7.100</td>
<td>-0.152</td>
</tr>
<tr>
<td>4.6c IC</td>
<td>-5.267</td>
<td>1.999</td>
</tr>
<tr>
<td>4.8 IC</td>
<td>-8.200</td>
<td>3.015</td>
</tr>
<tr>
<td>4.9 IC</td>
<td>-5.847</td>
<td>3.236</td>
</tr>
<tr>
<td>6.6 IC</td>
<td>-7.086</td>
<td>3.031</td>
</tr>
<tr>
<td>7.5 IC</td>
<td>-5.980</td>
<td>2.355</td>
</tr>
<tr>
<td>8.4 IC</td>
<td>-5.960</td>
<td>1.348</td>
</tr>
<tr>
<td>8.7 IC</td>
<td>-6.434</td>
<td>0.763</td>
</tr>
<tr>
<td>c2.11 IC</td>
<td>-4.547</td>
<td>3.437</td>
</tr>
<tr>
<td>c3.4 IC</td>
<td>-5.075</td>
<td>2.918</td>
</tr>
<tr>
<td>11.1 ML6</td>
<td>-6.970</td>
<td>3.051</td>
</tr>
<tr>
<td>1.5 LC</td>
<td>-8.925</td>
<td>-0.316</td>
</tr>
<tr>
<td>2.2 LC</td>
<td>-8.210</td>
<td>-0.098</td>
</tr>
<tr>
<td>2.7 LC</td>
<td>-8.707</td>
<td>-5.624</td>
</tr>
<tr>
<td>2.8 LC</td>
<td>-11.087</td>
<td>-2.238</td>
</tr>
<tr>
<td>3.1 LC</td>
<td>-9.398</td>
<td>-2.129</td>
</tr>
<tr>
<td>3.4 LC</td>
<td>-9.548</td>
<td>-6.240</td>
</tr>
<tr>
<td>3.12 LC</td>
<td>-11.775</td>
<td>-0.998</td>
</tr>
<tr>
<td>4.6b LC</td>
<td>-10.199</td>
<td>2.961</td>
</tr>
<tr>
<td>4.6c LC</td>
<td>-9.360</td>
<td>2.845</td>
</tr>
<tr>
<td>4.9 LC</td>
<td>-8.447</td>
<td>2.937</td>
</tr>
<tr>
<td>4.9 LC</td>
<td>-10.718</td>
<td>0.061</td>
</tr>
<tr>
<td>6.6 LC</td>
<td>-10.688</td>
<td>3.143</td>
</tr>
<tr>
<td>8.4 LC</td>
<td>-8.902</td>
<td>-0.185</td>
</tr>
<tr>
<td>9.2 LC</td>
<td>-9.112</td>
<td>2.659</td>
</tr>
<tr>
<td>11.1 LC</td>
<td>-9.982</td>
<td>2.377</td>
</tr>
<tr>
<td>11.4 LC</td>
<td>-7.297</td>
<td>3.105</td>
</tr>
<tr>
<td>c1.1 LC</td>
<td>-7.316</td>
<td>2.303</td>
</tr>
<tr>
<td>c1.6 LC</td>
<td>-9.650</td>
<td>1.001</td>
</tr>
<tr>
<td>c2.1 LC</td>
<td>-9.477</td>
<td>2.006</td>
</tr>
<tr>
<td>c2.5 LC</td>
<td>-8.704</td>
<td>2.290</td>
</tr>
<tr>
<td>c3.4 LC</td>
<td>-8.312</td>
<td>1.322</td>
</tr>
<tr>
<td>4.6b SC</td>
<td>-7.404</td>
<td>2.785</td>
</tr>
<tr>
<td>c2.5 SC</td>
<td>-3.652</td>
<td>3.363</td>
</tr>
</tbody>
</table>
APPENDIX 5

This appendix includes the fluid inclusion microthermometric data measured throughout this study. The following headings are used in the spreadsheet containing the fluid inclusion data:

**Chip** = Chip from which the measurements were made. The first indicator is the thin section. The second indicator is the specific chip from that thin section. The third indicator is the cement location where the inclusions were measured. Samples with only one indicator only had one suitable fluid inclusion for microthermometry. Example: “1.5b8” Thin section 1.5. Chip b. Cement location 8.

**Tm ice** = Melting temperature of ice (in °C) determined by cycling with bubble present.

**Original CL zone** = Cement where the inclusion is located. When two or three CL zones are listed it gives the possible cements where the inclusions are located, but the exact zone is unknown. A question mark indicates that the original cement zone was unable to be determined.

**FIA #** = Fluid Inclusion Assemblage number

**Luminescence** = Luminescence of cement from which the measurement was obtained.
Appendix 5. Fluid Inclusion Data.

Fluid Inclusion-Rich Cement (Recrystallized)

<table>
<thead>
<tr>
<th>Chip</th>
<th>Tm ice</th>
<th>Original CL zone</th>
<th>FIA #</th>
<th>Luminescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5b8</td>
<td>0.0</td>
<td>NL1, ML2, NL2</td>
<td>1</td>
<td>L</td>
</tr>
<tr>
<td>1.5b8a</td>
<td>0.0</td>
<td>NL1</td>
<td>1</td>
<td>L</td>
</tr>
<tr>
<td>1.5e2b</td>
<td>0.0</td>
<td>NL1, NL2</td>
<td>2</td>
<td>NL</td>
</tr>
<tr>
<td>1.5e2b</td>
<td>0.0</td>
<td>NL1, NL2</td>
<td>2</td>
<td>NL</td>
</tr>
<tr>
<td>1.5e2b</td>
<td>0.0</td>
<td>NL1, NL2</td>
<td>2</td>
<td>NL</td>
</tr>
<tr>
<td>1.5e2b</td>
<td>0.0</td>
<td>NL2, NL3</td>
<td>3</td>
<td>NL</td>
</tr>
<tr>
<td>c2.11a</td>
<td>0.0</td>
<td>?</td>
<td>4</td>
<td>L</td>
</tr>
<tr>
<td>c2.7v2</td>
<td>0.0</td>
<td>?</td>
<td>5</td>
<td>L</td>
</tr>
<tr>
<td>c2.7v3</td>
<td>0.0</td>
<td>ML4, ML5</td>
<td>6</td>
<td>L</td>
</tr>
<tr>
<td>c2.7v3</td>
<td>0.0</td>
<td>ML4, ML5</td>
<td>6</td>
<td>L</td>
</tr>
<tr>
<td>c2.7v3</td>
<td>0.0</td>
<td>NL3, NL4, NL5</td>
<td>7</td>
<td>NL</td>
</tr>
<tr>
<td>4.8e</td>
<td>-0.1</td>
<td>NL1, NL2, NL3</td>
<td>9</td>
<td>NL</td>
</tr>
<tr>
<td>c2.11a</td>
<td>-0.1</td>
<td>?</td>
<td>4</td>
<td>L</td>
</tr>
<tr>
<td>c2.7v</td>
<td>-0.1</td>
<td>Pendant</td>
<td>10</td>
<td>NL</td>
</tr>
<tr>
<td>c3.4</td>
<td>-0.1</td>
<td>ML2, ML3</td>
<td>11</td>
<td>L</td>
</tr>
<tr>
<td>c3.4</td>
<td>-0.1</td>
<td>ML2, ML3</td>
<td>11</td>
<td>L</td>
</tr>
<tr>
<td>4.8e</td>
<td>-0.2</td>
<td>NL1, NL2, NL3</td>
<td>9</td>
<td>NL</td>
</tr>
<tr>
<td>4.8e</td>
<td>-0.2</td>
<td>NL1, NL2, NL3</td>
<td>9</td>
<td>NL</td>
</tr>
<tr>
<td>c1.1d2</td>
<td>-0.2</td>
<td>?</td>
<td>13</td>
<td>L</td>
</tr>
<tr>
<td>c1.1d2</td>
<td>-0.2</td>
<td>?</td>
<td>14</td>
<td>L</td>
</tr>
<tr>
<td>1.5b7a</td>
<td>-0.5</td>
<td>NL1</td>
<td>15</td>
<td>L</td>
</tr>
<tr>
<td>1.5b7a</td>
<td>-0.5</td>
<td>NL1</td>
<td>15</td>
<td>L</td>
</tr>
<tr>
<td>c3.4</td>
<td>-0.5</td>
<td>ML2, ML3</td>
<td>16</td>
<td>L</td>
</tr>
<tr>
<td>c1.1d2</td>
<td>-0.7</td>
<td>?</td>
<td>17</td>
<td>L</td>
</tr>
<tr>
<td>c1.1d2</td>
<td>-0.8</td>
<td>?</td>
<td>18</td>
<td>L</td>
</tr>
<tr>
<td>c3.4</td>
<td>-1.6</td>
<td>ML2, ML3, ML4</td>
<td>19</td>
<td>L</td>
</tr>
<tr>
<td>c3.4</td>
<td>-1.9</td>
<td>ML3, ML4, ML5</td>
<td>20</td>
<td>L</td>
</tr>
<tr>
<td>1.5b8</td>
<td>-2.0</td>
<td>NL1</td>
<td>21</td>
<td>L</td>
</tr>
</tbody>
</table>

NL5 and ML6 Cements

<table>
<thead>
<tr>
<th>Chip</th>
<th>Tm ice</th>
<th>CL zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5b8</td>
<td>0.0</td>
<td>NL5</td>
</tr>
<tr>
<td>1.5b7</td>
<td>-0.1</td>
<td>NL5</td>
</tr>
<tr>
<td>1.5e2b</td>
<td>0.0</td>
<td>NL5</td>
</tr>
<tr>
<td>c2.7v2</td>
<td>0.0</td>
<td>NL5</td>
</tr>
<tr>
<td>1.5e1</td>
<td>-2.9</td>
<td>ML6</td>
</tr>
<tr>
<td>11.1</td>
<td>-3.0</td>
<td>ML6</td>
</tr>
<tr>
<td>11.1</td>
<td>-3.0</td>
<td>ML6</td>
</tr>
</tbody>
</table>
APPENDIX 6

This appendix includes the strontium isotope data obtained during this study.

The following headings are used in the spreadsheet containing the strontium isotope data:

**Thin section** = Thin section from which sample was obtained

**Cement** = Cement from which sample was obtained

**87/86 corr** = The measured $^{87}\text{Sr}/^{86}\text{Sr}$ value normalized using the NBS 987 Sr standard having a value of 0.710250

**Sr (ppm)** = Concentration of total Sr in the sample (in ppm)

**Sample mass (mg)** = Sample mass (mg)

**Total Sr (µg)** = Amount of Sr analyzed (µg)

**Sample/blank** = ratio of sample Sr to blank Sr
## Appendix 6

### Sr Isotope Data

<table>
<thead>
<tr>
<th>Thin Section</th>
<th>Cement</th>
<th>87/86 corr</th>
<th>Sr ppm</th>
<th>Sample mass (mg)</th>
<th>Total Sr (µg)</th>
<th>Sample/Blank</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1.1</td>
<td>Recrystallized</td>
<td>0.708227</td>
<td>134.12</td>
<td>0.0007</td>
<td>0.094</td>
<td>182</td>
</tr>
<tr>
<td>4.8</td>
<td>Recrystallized</td>
<td>0.708111</td>
<td>166.86</td>
<td>0.0004</td>
<td>0.069</td>
<td>134</td>
</tr>
<tr>
<td>1.5</td>
<td>Recrystallized</td>
<td>0.708052</td>
<td>129.75</td>
<td>0.0013</td>
<td>0.174</td>
<td>337</td>
</tr>
<tr>
<td>11.1</td>
<td>ML6</td>
<td>0.708752</td>
<td>92.72</td>
<td>0.0009</td>
<td>0.079</td>
<td>153</td>
</tr>
</tbody>
</table>