Variations in the Depositional Environment of the Lower Cincinnatian Kope Formation

Thomas K. Mahan

Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses

Part of the Geology Commons

Recommended Citation
https://scholarworks.wmich.edu/masters_theses/4433

This Masters Thesis-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Master's Theses by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
VARIATIONS IN THE DEPOSITIONAL ENVIRONMENT OF THE LOWER CINCINNATIAN KOPE FORMATION

by

Thomas K. Mahan

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
August 1980
ACKNOWLEDGMENTS

I am most grateful to William B. Harrison, III, first for suggesting this project, and then for his wholehearted enthusiasm and encouragement throughout the conduct of this study. Also, I would like to thank Richard N. Passero and W. Thomas Straw for the suggestions and advice they offered during the course of the lab work for this study, and, additionally, for their suggestions for improving the final manuscript. Also, special appreciation is extended to the family of W. B. Harrison, Sr., in Erlanger, Kentucky, for their thoughtfulness and generosity in providing me a home for the duration of my field investigations. Finally, for her boundless understanding and helpful suggestions throughout the project, my sincere appreciation goes to my wife, Hallie. Her skills as editor and typist for preliminary drafts of this manuscript were a great asset. I am grateful to the Department of Geology for a two-year teaching assistantship in support of both this project and the preliminary coursework. Also, lab equipment and facilities were provided by the Geology Department. Funding was provided by the Graduate College, Western Michigan University, in research and travel awards to the author.

Thomas Kent Mahan, Jr.
VARIATIONS IN THE DEPOSITIONAL ENVIRONMENT
OF THE LOWER CINCINNATIAN KOPE FORMATION

Thomas K. Mahan, Jr., M.S.
Western Michigan University, 1981

In northern Kentucky, the Upper Ordovician (Lower Cincinnatian) Kope Formation outcrops as a series of interbedded, laterally discontinuous limestone lenses and beds enclosed in a silty shale unit. Six stratigraphic sections within a 20-mile radius were sampled and measured and two of these were described in detail to characterize the variations in the environmental setting wherein the Kope Formation was deposited.

The shale lithology is homogeneous throughout this formation whereas the bioclastic limestones vary widely in faunal composition, texture, cross-sectional shape, and thickness. Apparently, the depositional style for the fine-grained, terrigenous sediment remained almost constant through Early Cincinnatian time, whereas the recurring interactions between depositional events and biotic community assemblages allowed for the development of the limestone beds. Depositional events probably included storm-wave winnowing of marine sediments and influxes of terrigenous silt. Preservation of different stages of short-term, successional communities accounts for the variations in biotic constituents in the limestone.
TABLE OF CONTENTS

ACKNOWLEDGEMENT ........................................ ii
LIST OF FIGURES ........................................... v
LIST OF TABLES ............................................ viii
INTRODUCTION ............................................. 1
   Paleogeographic Setting .................................. 5
PREVIOUS WORK ........................................... 9
METHODS OF STUDY ........................................ 20
   Study Area .............................................. 20
   Field Methods ......................................... 21
   Petrographic Methods .................................. 22
   Laboratory Methods .................................... 22
STRATIGRAPHIC NOMENCLATURE AND LATERAL VARIATIONS .... 26
GENERAL PETROLOGY OF THE CINCINNATIAN SERIES ......... 33
   Limestone Petrography .................................. 36
   Insoluble Residue ...................................... 37
   Shale and Siltstone Petrography ....................... 39
PETROGRAPHY OF THE KOPE FORMATION ...................... 40
   Limestone Petrography .................................. 40
   Summary of Bioclastic Fabrics ......................... 54
   Diagenesis .............................................. 61
   Siltstone Petrography .................................. 61
   Distribution of Bioclastic Sediments, Matrix Material and Cement .................................. 65
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Index map of study area and location of measured stratigraphic sections</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Lower section of the Kope Formation (RR Section)</td>
<td>3</td>
</tr>
<tr>
<td>3.</td>
<td>Broken, in situ fossils enclosed in shale beds</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>Tectonic events in northern Kentucky and southern Ohio during Ordovician time</td>
<td>7</td>
</tr>
<tr>
<td>5.</td>
<td>Nomenclature and approximate lateral relations between Upper Champlainian and Cincinnatian lithostratigraphic units of the Cincinnati Region</td>
<td>16</td>
</tr>
<tr>
<td>6.</td>
<td>Vertical correlations among measured stratigraphic sections</td>
<td>23</td>
</tr>
<tr>
<td>7.</td>
<td>Close-up of a section of the Kope with irregular bedding</td>
<td>34</td>
</tr>
<tr>
<td>8.</td>
<td>Laterally discontinuous beds of limestone and siltstone</td>
<td>35</td>
</tr>
<tr>
<td>9.</td>
<td>Classification for Kope limestones</td>
<td>42</td>
</tr>
<tr>
<td>10.</td>
<td>Examples of criteria used to identify primary sparry calcite cement</td>
<td>44</td>
</tr>
<tr>
<td>11.</td>
<td>Examples of criteria used to identify neomorphic (recrystallized) spar</td>
<td>45</td>
</tr>
<tr>
<td>12.</td>
<td>Rippled limestone bed in lower section of Kope Formation (RR Section)</td>
<td>47</td>
</tr>
<tr>
<td>13.</td>
<td>Series of starved ripples near Sanfordtown, Ky., (MP Section)</td>
<td>48</td>
</tr>
<tr>
<td>14.</td>
<td>Close-up of starved ripple</td>
<td>49</td>
</tr>
<tr>
<td>15.</td>
<td>Upper surface of limestone bed with articulated crinoid and Cryptolithus cephalon</td>
<td>51</td>
</tr>
<tr>
<td>16.</td>
<td>Upper surfaces of limestone beds with articulated crinoids and calyx</td>
<td>52</td>
</tr>
</tbody>
</table>
17. Limestone slab with five different microfacies
18. Grainstone fabric in a limestone slab
19. Poorly washed grainstone fabric in limestone slab
20. Partially winnowed packstone in a limestone slab
21. Packstone fabric in a limestone slab
22. Wackestone fabric in limestone slab
23. Calcitic nodules in upper part of siltstone slab
24. Numerous burrows in a siltstone slab
25. Siltstone with rippled upper surface
26. Hummocky cross-bedding in a siltstone slab
27. Moving averages of vertical trends in faunal distributions of the Kope Formation
28. Moving averages of vertical trends in mean grain size, spar, and mud content throughout the composite thickness of the Kope Formation
29. Inferred distributions of abundant faunas in central Appalachian, Upper Ordovician environments
30. Adaptations of Edenian brachiopods to unstable substrate
31. Adaptations of crinoids to variable substrates
32. Brachiopods succeeded upward by bryozoans
33. Brachiopods and bryozoans in a limestone slab succeeded upwards by crinoids, trilobites, and mollusks
34. Pioneer brachiopods stabilize the soft, muddy substrate
35. Succession by bryozoans on stabilized substrate
36. Mature community developed on the remains of pioneer and successional organisms
37. Distribution of modern organisms typical of Edenian fossil assemblages
38. Size/velocity diagram ..... 105
39. Depth/velocity diagram ..... 106
40. Isolated benthic communities at various stages of successional development ..... 109
41. Fining-upward sequence of bioclastic debris and mud after passage of storm ..... 110
42. Shallow disruption of substrate after less-intense storm activity ..... 111
43. Bioclastic storm debris reworked into ripples on the newly formed substrate ..... 113
44. Secondary successional communities developed on bioclastic storm debris ..... 114
45. Sequence of bioclastic fabrics ..... 115
46. Grainstone fabric of well-winnowed bioclasts in limestone slab ..... 116
47. Packstone fabric of in situ bryozoans in a limestone slab ..... 117
48. Packstone fabric formed at a distance from the zone of maximum water turbulence ..... 118
49. Integrated model featuring multiple modes of deposition ..... 121
<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Percent of the allochem fraction of abundant taxa in Cincinnatian Series limestones</td>
<td>38</td>
</tr>
<tr>
<td>2. Comparative tables of Upper Ordovician fauna</td>
<td>77</td>
</tr>
<tr>
<td>3. Percent microfacies from the composite section of the Kope Formation according to mode of deposition</td>
<td>125</td>
</tr>
</tbody>
</table>
INTRODUCTION

The Cincinnatian Series (Upper Ordovician) Kope Formation is an alternating carbonate-shale sequence that outcrops in a wide elliptical pattern over the Cincinnati Arch in southern Ohio and northern Kentucky. The location of the study area is in northern Kentucky approximately 10 miles south of Cincinnati, Ohio (Fig. 1).

The Kope Formation is characterized as a sequence of shale with interbedded limestone and siltstone beds (Fig. 2). Shale comprises 75% to 85% of the unit and encloses the discontinuous beds of limestone and siltstone. Limestone beds are richly fossiliferous whereas the shale and siltstones may contain only scattered fossils. Very thin lenses of fossil debris occur parallel to bedding in shale (Fig. 3).

Throughout this century the highly fossiliferous rocks of the type Cincinnatian have been recognized as "veritable museums of past life" (Martin, 1975, after Pettijohn, 1957, p. 348). Paleontologists have collected and described these fossils in great detail, but only in recent years have investigators begun to turn their attention to the history of the rocks themselves. Many investigators, however, have approached the study of these rocks from the standpoint of observations of hand specimens, lithologic descriptions, and stratigraphic correlations. The data were then used to support a proposed, all-encompassing model that attempted to describe the various processes at work within the depositional environment. These processes included such physical events as sedimentation and water turbulence, and such
Figure 1. Index map of study area and location of outcrop sections.
Figure 2. Lower section of the Kope Formation. (RR Section)
Figure 3. Broken, in situ fossils enclosed in shale beds.
biological events as colonization of the substrate and community development. It is these processes and their interrelationships that will be the major focus of this study. The textural and compositional variations of the rocks, and especially the limestones, make it difficult to identify a single model that will adequately describe the total environment of deposition of the rocks. Therefore, a specific objective of this study will be to consider, in detail, the microscopic variations in texture and composition as they occur in a composite stratigraphic section, and then to suggest a mechanism that will adequately explain all the primary variations in depositional style for the rocks in that section. This mechanism may then be generally applied to the entire region.

Paleogeographic Setting

During the early Paleozoic Era, the region of the east-central United States was a broad, structurally-passive continental shelf (King, 1977). It was bounded to the southeast by a shelf break beyond which was the deeper water of the proto-Atlantic Ocean basin. King (1977) suggested that carbonate deposition was favored because this region was located within the subtropics and there were no erosional highlands nearby to provide terrigenous clastic sediment which would have inhibited carbonate precipitation. Consequently, an extensive carbonate platform 3000 meters thick accumulated through the Late Cambrian and Early Ordovician Periods (Fig. 4a).

During early Middle Ordovician time, declining sea level or a slight uplift of the continent resulted in a major regional marine
regression (Datt & Batten, 1976). This change probably marks the onset of subduction of the proto-Atlantic oceanic plate beneath the North American continental plate (Bird & Dewey, 1970). As a tectonic highland emerged and developed along the continental rise and slope, the carbonate shelf subsided to form the Appalachian Basin (Fig. 4b). Deposits laid down during the previous 30 million years were abruptly exposed to subaerial weathering and erosion. These were rapidly stripped off and deposited in the subsiding Appalachian Basin as widespread, sheetlike units of clastic sediment (Datt & Batten, 1976). These clastic wedges and sheets accumulated and became the interbedded layers of siltstone and shale of the Martinsburg and Normanskill Formations in the central and northern Appalachians. The Bald Eagle, Oswego, and Juniata Sandstones are nearshore deltaic and floodplain counterparts of the Martinsburg.

Apparently, the sea flooded the craton during the Late Ordovician and thereby set the stage for the development of an epeiric sea. The expanding Taconic landmass to the east continued to shed terrigenous sediment into the Appalachian Basin as clastic wedges that formed on the flanks of the rising landmass, and fine-grained silt and clay as suspended material which was carried far offshore to the center of the basin (Rodgers, 1971). These clastic deposits spread to the northwest as broad sheets of detritus thinning and tapering in that direction (King, 1977). Bird and Dewey (1970) proposed that as the Ordovician drew to a close, the clastic wedges prograding basinward nearly filled the basin with sediment (Fig. 4c). This gradual shallowing of the Late Ordovician sea resulted in a shoaling environment in which was
CONTINENTAL SHELF

A. EARLY ORDOVICIAN

APPALACHIAN BASIN

B. MIDDLE ORDOVICIAN

TACONIC OROGEN

C. LATE ORDOVICIAN

Figure 4. Tectonic events in northern Kentucky and southern Ohio during Ordovician time (modified from Bird & Dewey, 1970).
deposited the sequence of thin, interbedded carbonates and shale that overlies the Kope Formation.

The Ordovician Period was characterized by extensive, long-term, continental submergence accompanied by a mild and uniform climate, and many new shallow marine ecological niches became available that were not present during the Cambrian (Neuman, 1976). Notable changes occurred in the brachiopod population, the inarticulate groups of the Cambrian being largely superseded by the articulate forms of the Ordovician. Other important changes were the development and expansion of bryozoans and graptolites, and the proliferation of mollusks, particularly the gastropods (Neuman, 1976). By the end of the Ordovician, most of the primary groups of benthic marine animals capable of being preserved as fossils had appeared.
Among the earliest of the Cincinnatian workers were Orton (1873) and Foerste (1905). Their studies provided the stratigraphic framework for subsequent investigations, but the profusion of fossils in these rocks encouraged later workers to study the paleontologic rather than the lithologic characteristics of the rocks. Therefore, early classification of the Upper Ordovician in the study area was determined on the basis of biostratigraphic criteria. The most commonly used biostratigraphic classification scheme has been that of Bucher, Caster, and Jones (1945) with subsequent revision by Caster, Dalvé, and Pope (1955; 1961). A great deal of confusion was created when time-stratigraphic and biostratigraphic nomenclature was not distinguished from the lithostratigraphic classification of Orton and Foerste. The inconsistencies that exist among these classifications have been recognized by many authors, especially with regard to field relationships. Compounding these problems is the lack of lateral continuity of limestone beds and the occurrence of gradational contacts between lithologies.

In the early 1960's, a number of workers (Weiss, Sweet, and Norman) began to emphasize the distinction between the types of classifications that were used. Furthermore, interest began to develop in the study of the depositional environment of the Cincinnatian rocks and in the analysis of their original sediments. Also, paleontologic studies became less descriptive and workers began to
investigate community structure and the paleoecology of the Cincinnatian seas. During this time, a joint mapping venture between the United States Geological Survey and the Kentucky Geological Survey was initiated, and, as a part of this larger undertaking, Cincinnatian stratigraphy and lithologic boundaries were restudied. The result of this work was a classification of rock-stratigraphic units that was based on such lithologic parameters as differences in relative percentages of shale and limestone, changes in bedding style, and thickness and texture.

In 1962, Fox proposed that the alternating shales and limestones were the result of pulses of terrigenous sediment from land sources, combined with fluctuations in water temperature which affected the pH and resulted in the precipitation of calcium carbonate. His methodology required that several stratigraphic sections be measured and described to provide such quantitative data as distributions of lithologic types, bedding thicknesses, and insoluble residues. Also, in an effort to define assemblage zones and interpret original community structure, the paleoecology of the fossils was studied by the enumeration of species and the determination of their relative abundances on fossiliferous bedding planes. The distribution of organisms was interpreted as being heavily influenced by the same physical and chemical processes that controlled the type of sediment that was deposited.

Weiss and Sweet (1964), in an effort to resolve some of the inconsistencies that were inherent in earlier classification schemes, proposed that these rocks be renamed the Kope Formation after the Kope
Hollow section at Levanna, Ohio, and that the formational contacts be assigned on the basis of lithologic characteristics rather than changes in the fossil assemblages enclosed in the rocks. Initially, these rocks were named the Eden Shales by Orton (1873) after the Edenian Stage, the time-stratigraphic interval to which the strata were assigned. However the similarity between the formational name and the time-stratigraphic name caused much confusion among the workers in this area. Weiss and Sweet also proposed to assign the upper and lower boundaries of the Kope Formation on the basis of changes in the clastic ratio and in the bedding index. The clastic ratio was defined as the thickness of terrigenous rocks divided by the thickness of limestone rocks in each 0.9 meter interval of measured section. The measured sections extended from within the underlying Point Pleasant Formation through the Kope and into the overlying Fairview Formation. The bedding index was calculated as the number of beds in each successive 0.9 meter interval multiplied by 100 and divided by the thickness of the interval. Logs of moving averages were produced for the clastic ratio as well as for the bedding index.

Scotford (1965) investigated the Cincinnatian shales to develop quantitative data for a better understanding of the depositional environment, diagenesis, and spatial and temporal variations. One hundred fifty-eight specimens from four groups of samples were analyzed to determine the relative percentages of the sand, silt, and clay fractions. X-ray diffraction was used to indicate which clay minerals were present and the elemental composition of the shales was determined by X-ray spectrochemical analysis. One group of samples
was collected from a core to provide data on the vertical variations, and the other three groups were each collected from different geographic locations for data concerning lateral variations. Comparison of data from each of the four groups revealed persistent vertical and lateral uniformity in texture, mineralogy, and chemistry of the shales. These findings further indicated that the Cincinnati Arch was not structurally active during the time of deposition of these sediments. Scotford suggested that the shales formed in a somewhat higher-energy regime than did the limestones of recrystallized carbonate ooze which require very calm conditions. Lateral discontinuity of the limestones further indicated that the energy fluctuations were the result of the changing pattern of current flow in a shallow basin rather than the result of events such as storms, that occurred through time.

Ford (1967) described and mapped individual rock units in an effort to clarify Cincinnatian stratigraphy and paleogeography. The rocks were classified according to Weiss and Norman (1960), and clastic-ratio and bedding-index curves were developed using logs of moving averages. These logs were then used to substantiate field observations. His interpretation suggested that deposition occurred in environments with variable levels of energy. Coarse-grained carbonates were deposited on topographic highs where energy was greatest, whereas finer-grained bioclastic rocks and shale were deposited at progressively lower energy levels along the flanks of the topographic highs and in depressions between the highs.

In 1969, Anstey and Fowler proposed that the "Eden Shale" (Kope Formation) was deposited in deeper, quieter water than the underlying
Lexington Limestone (Point Pleasant Formation) which they felt represented a shoal environment. Furthermore, they suggested a shallowing-upward trend for the Eden and its overlying counterpart. They felt that the micritic limestone beds represented bryozoan communities which developed on topographic highs of the sea floor, whereas the sparry limestone beds resulted from periodic storms that produced layers of winnowed bioclasts. Their investigations involved outcrop exposures at seven localities in the tri-state area of Ohio, Kentucky, and Indiana. These were measured in detail and described as to lithologic type. Additionally, the mean and standard deviation of the thicknesses of each lithologic type per each three-meter interval of section were calculated. Interpretations were derived from the comparisons of trends of lithologic types and bed thicknesses vertically through the section. The beds of the Eden Shale are not sufficiently continuous to suggest universal changes in environmental conditions, therefore the interbedded nature of the shale and limestone in the section was interpreted as the result of local events rather than cyclic sedimentation. However, large-scale sedimentary cycles caused by major sea-level changes in the Cincinnatian environment were considered.

Bassarab and Huff (1969) did a detailed study of the clay mineralogy of the Kope and overlying Fairview Formations from two sections in northern Kentucky that cross the lithologic contact between the two formations. Mudstone and shale samples from these two locations were disaggregated, settled, and pipetted onto slides, and these were studied in untreated, glycolated, and heated forms with
X-ray diffraction. Additionally, several samples were observed with an electron microscope. Comparison of these data with the paleo-current data of Hofman (1966) exhibited good correlation between dominant current directions and variations in abundance of chlorite and vermiculite between the two formations. The abundance of chlorite and vermiculite in the Fairview Formation was notably less than that found in the Kope Formation, and the dominant current directions of sediment transport were westerly for the Kope and southerly for the Fairview (Hofman, 1966). These observations therefore suggest a predominantly easterly source for the Kope Formation, possibly from the partially degraded chloritic schists of the rising Taconic highlands, and a more northerly source of sediment for the Fairview Formation, such as the weathered plutonic rocks of the Canadian Shield.

Lorenz (1973) analyzed Upper Ordovician benthic community ecology in north-central Kentucky in a study of the geographic and stratigraphic variations in faunal composition, density, and diversity within the relatively homogeneous environment of the Cincinnatian Series. More than 44,000 fossil invertebrates were collected and identified from 11 localities. Stratigraphic sections from two of the localities, which represent almost complete exposures of the Edenian section, were measured and described in detail. These sections were used to study the sequential patterns of faunal variation through time. Acetate peels of each fossil-bearing stratum were taken to supplement bedding-plane counts of faunal densities and diversities. Lithologic compositions were estimated from counts of 250 points on the peels. Shell length and width of brachiopods were employed as rough measures
of morphological variation. All of these data were subsequently compared using computer analysis.

Lorenz (1973) recognizes two geographically isolated and taxonomically distinct level-bottom communities in this region during Edenian time. In northern Kentucky, the Onniella-Sowerbyella community had a greater numerical abundance of species and was more diverse than the Rafinesquina-Zygospira community to the south. Lorenz suggested that the environmental setting became less stable toward the central part of Kentucky where episodic inundations by widespread blankets of mobile silt altered the substrate conditions and buried existing communities. The distribution and variations in abundance of the opportunistic brachiopod Rafinesquina indicate that it was uniquely adapted to this unstable substrate where competition for the environment was reduced. As conditions stabilized, however, normal marine fauna reappeared and gradually increased in size and diversity until the next inundation by silt.

In 1971, Sweet and Bergström published the summary of their conclusions regarding the temporal relationship between strata in the type standard of the Cincinnatian Series, and those of the Trenton Group in New York and Ontario which comprise the standard of the Champlainian Series in the upper part of the North American Middle Ordovician. Their correlations, based on conodont studies, between the Champlainian Lexington Limestone and Cincinnatian Kope and Clays Ferry Formations, and formations of the Trenton Group of New York and Ontario indicate an appreciable overlap in the intervals of time represented by these two standard sections. Consequently, they proposed a revised time-stratigraphic classification (Fig. 5) wherein
Figure 5. Nomenclature and approximate lateral relations between upper Champlainian and Cincinnatian region (Sweet & Bergstrom, 1972, after Brown & Lineback, 1966; Ford, 1967; Osborne, 1968; Weiss & Sweet, 1964; Peck, 1966; Black et al., 1965; Wier & Greene, 1965; and Wier et al., 1965).
the boundary between the Cincinnatian Series and the Champlainian Series was drawn at the top of the Shermanian Stage to clear up the confusion concerning the location of the boundary between these two series without overlapping them or leaving gaps between them at locations outside the type areas.

The bryozoan fauna and its paleoenvironment in the Kope Formation (Eden Shale) was studied by Anstey and Perry (1972). This study was based on a sample of 535 sectioned zooaria, or fragments of zooaria, of trepostome bryozoans from seven measured stratigraphic sections. Cluster analyses produced the presence-absence data for 61 qualitative taxonomic characteristics which were used to develop a diagnostic key. This key was used to group specimens with similar characteristics and the groups were then correlated with their stratigraphic position. Vertical and lateral lithologic changes resulting from variations in water agitation and depth, and the clastic sedimentation rate were reflected in parallel changes in the distribution, abundance, and diversity of the bryozoans. Apparently the water agitation was greatest, suggesting a minimum depth, at the beginning and end of Eden sedimentation, and was least, suggesting maximum water depth, near the middle of Edenian time. Additionally, the water was generally shallower and more turbid in the southern part of the basin than in the northern part.

Martin (1975) measured and sampled a composite vertical sequence of Cincinnatian limestones from sections in outcrop at eight localities to determine the petrographic characteristics of the rocks and thereby to interpret their origin. Samples were taken at intervals of
approximately one meter unless otherwise indicated by outcrop characteristics. Ultimately, 500 thin sections were produced and 300 point counts per slide of the constituents were made. Comparisons among petrographic data from different positions in the composite section suggested that the lower part of the section was developed in a deeper, quieter environment than was the higher part of the section. Additionally, a model was proposed whereby the organisms of a benthic community created a wave baffle which reduced levels of water energy. These low-energy environments promoted the simultaneous accumulation of bioclastic debris and carbonate ooze. Communities were terminated when mud thrown into suspension by periodic storms was swept over the communities and smothered them.

MacDaniel (1976) proposed to synthesize recent petrographic and environmental analyses of previous workers and to combine these with a study of the regional stratigraphic paleontology of the entire Cincinnatian sequence. He presented a model to explain major sedimentary and community patterns and explored their interrelationships. Forty-seven localities were measured and described according to a standardized data sheet that was developed especially for this study. The criteria recorded on the data sheet related to indicators of the sedimentary and paleontological environment, such as dominant limestone classes noted, sedimentary and biogenic structures, degree of breakage, and abrasion of fossils, etc. Cluster analyses were made from presence-absence data to provide groupings for community analyses. Four intergradational sedimentary environments were recognized in an onshore-offshore array, and each was represented by a characteristic
suite of rocks. Also, four distinct brachiopod- and bryozoan-dominated communities were recognized. The brachiopod communities were apparently related to water depth and distance from shore, whereas the mollusk and bryozoan distributions reflected the variations in turbulence and high clastic sediment influx. The geographical distribution of the sedimentary environments and fossil communities apparently migrated back and forth across the Cincinnati region in response to fluctuations in water depth during the Late Ordovician.
METHODS OF STUDY

Study Area

Two sections were selected for this study because together they represent 91% of the Kope Formation and also because of their proximity to each other. The two sections are approximately 400 meters apart which increases the likelihood that they represent the same environment of deposition. Vertical variations in the composite section should, therefore, reflect changes in the environment instead of differences in location. The lower exposure is 110 feet (33 meters) thick and is located at the intersection of Highway 8 and Highway 445, approximately one mile south of Fort Thomas, Kentucky. The base of this sequence is approximately 20 feet (6 meters) higher than the lower contact of the Kope Formation, so the lowest strata of the Kope Formation were inaccessible. The upper section is approximately 175 feet (53 meters) thick and includes strata of the overlying Fairview Formation. It is a recent exposure south of Fort Thomas on Interstate 275 just before the highway crosses the Ohio River. The contact between the two formations occurs 100 feet (30 meters) above the highway and, in spite of the gradational nature of the contact, it is identifiable as a decrease in shale content and bedding thickness. Correlation between these two sections was accomplished by the use of an altimeter and geologic maps of the area. Also the lower section was measured and described upward to a position that was calculated to overlap the stratigraphic position of the base of the upper section. Both of these
sections occurred as a series of offset benches approximately 20 feet (6 meters) thick cut into the hillside by the highway construction company to reduce erosion. The base of each succeeding bench was covered to some extent by talus so that sampling in these areas was locally limited.

**Field Methods**

A datum was selected for each section as near the base as possible. An easily defined horizon was chosen in both sections -- a distinctive limestone bed in the lower section and the adjacent road surface in the upper section. Lithologies in both sections were measured to the nearest inch relative to the respective datum. Concurrently, each bed was described in detail as to gross lithology, bedding style and thickness, grain size, and any recognizable fossils. Also, any evidence of bioturbation or primary sedimentary structures were noted. Paleocurrent indicators were also noted as to direction. Samples of each limestone and siltstone bed were collected for laboratory study. Several limestone beds were also sampled a second time at some distance along the bed where lateral changes in texture or bedding were noted. All lithologic samples were taken from beds that were in place so that upper and lower surfaces could be identified. Shale samples were taken from freshly excavated, unweathered sites; however, preservation of the intact specimens met with only limited success.

A number of additional outcrops were studied within a 20-30 mile radius to observe lateral variations that might occur. Samples were taken for petrographic analysis and comparisons. Also, notes and
measurements were made on paleocurrent indicators, such as flute casts and ripples. Finally, these outcrop sections were correlated (Fig. 6) using an altimeter and geologic maps of the area.

**Petrographic Methods**

Limestone and well-cemented siltstone samples were slabbed normal to bedding and then polished and sprayed with clear acrylic. Poorly cemented rocks were impregnated with epoxy cement prior to slabbing and polishing. Microscopic structures and bedding laminations were compared in the shale samples with those noted in the siltstones to determine whether they had a common depositional history. However, satisfactory thin sections were produced only after the shale specimens were impregnated with epoxy, and this process tended to obscure or disrupt the bedding contacts. Acetate peels were also attempted but met with limited success. One hundred thin sections of the fine-grained rocks were ultimately produced to supplement the study of the polished slabs, of which there were more than 200.

**Laboratory Methods**

Laboratory studies consisted primarily of petrographic analyses of carbonate fabrics and their interrelationships. Polished slabs were used instead of thin sections for most of these studies because the surface of a slab reveals a larger area and a more representative cross-section of the rock than does a thin section. The polished slabs were first inspected to determine the constancy of the fabric throughout the slab. If the composition and texture were relatively
Figure 6. Measured stratigraphic sections that correspond to outcrop locations on Index Map, Fig. 1.
constant over the entire surface, a count of 100 grains was made across the middle of the slab. Where several different fabrics were represented in a single slab, 100 grains of each fabric were counted. A clear acetate grid having points inscribed at 2 mm intervals was placed on the slab and a binocular microscope was used for counting grains. Grain constituents were noted and identified at each grid intersection and measured to the nearest 0.5 mm with the aid of an ocular micrometer. Fossil grains were identified to phylum or class, but could usually be described down to order or genus through the extensive use of Introductory Petrography of Fossils by Horowitz and Potter (1971). In addition to the grain counts, other observations included texture (sorting, bedding, grain orientation, etc.); rock description (mean grain size, abundant grain types, texture, and Dunham rock name); type of contact with adjacent lithologies, and thickness. Other miscellaneous observations included the presence of mudclasts and their size and orientation; burrows and their size and orientation, and any other additional grains such as peloids or pyrite.

Thin sections were stained with alizarin red-S to distinguish calcite and aragonite from dolomite, clay matrix, or quartz. Point counts were made to determine modal composition of fine-grained rocks.

The diversity trends in the Kope Formation were described in terms of petrographic fossil diversity which is defined as "the total number of all dissimilar fossil types seen in thin section" (Smosna and Warshauer, 1978). This allows the non-paleontologist to tabulate and plot a first approximation of total and mean diversity for successive microfacies.
Finally, the 22,600 data points were normalized by the common petrographic procedure of expressing the counts of each constituent in each bed as a percentage of the total. These percentages represented the overall composition of each rock. Mean grain sizes were calculated for all species as well as the overall mean grain size for each rock. These data were plotted as comparative logs of relative abundance and logs of moving averages to compare possible trends upward through the section.

All samples and specimens referred to or figured in this study are reposited in the Geology Department, Western Michigan University, Kalamazoo, Michigan, under the care and supervision of W. B. Harrison III.
STRATIGRAPHIC NOMENCLATURE AND LATERAL VARIATIONS

The Cincinnati, Ohio, region is the type area of the Cincinnatian Series which encompasses approximately 20,000 square miles and lies mostly to the south in north-central Kentucky and also in parts of southwestern Ohio and southeastern Indiana (Sweet & Bergström, 1971).

The type Cincinnatian Series includes a number of rock formations (Fig. 5) characterized by variations in shale and carbonate abundance and also by the texture and composition of the limestones. Formation contacts are gradational to a greater or lesser degree, depending on the formation and the geographic location. Complex intertonguing relationships and lateral variations in both lithology and thickness further characterize these strata (Hay, 1977).

To the west, in Indiana, the Maquoketa Group (mostly Cincinnatian Series) was described by Gray (1972) as a section that is approximately 1000 feet (300 meters) thick in eastern Indiana, and thins dramatically to 200 feet (60 meters) at the western border of the state. Calcareous, gray shale predominates throughout the section; however, brown, carbonaceous shale characterizes the lowermost part of the group. Limestone constitutes approximately 20% of the total rock composition, according to Gray, and occurs mostly in the upper part of the formation. In the east, the limestones are predominately biomicrudite and biosparrudite, and in the northwestern part of the state a coarse sparry dolomite is widespread (Gray, 1972). Depositionally, the Maquoketa forms a wedge of fine-grained, terrigenous
clastic rocks that spread across the state from an eastern source. Depositional provinces included shelf environments to the south and east, and to the southwest a deep basin environment produced black shale facies.

In central Kentucky, the entire Upper Ordovician is less than 200 meters thick, but in Ohio and Indiana the same interval is more than 250 meters thick (MacDaniel, 1976).

The basal Kope Formation was characterized by Gibbons (1973) as a sequence of interbedded shale and limestone. Shale comprises approximately 75-80% of the unit and is described as medium-gray and light bluish-gray in color, weathering to a greenish-gray or dark-yellowish-orange. It is laminated, calcareous, and mostly silty, and occurs in beds up to 6 feet (2 meters) thick. Fossils are rare but occur locally. The limestone comprises 20-25% of the formation and is of two main types. The first type noted by Gibbons comprises approximately two-thirds of the limestones and is finely- to coarsely-crystalline, medium-gray in color, and contains abundant whole and broken fossils. These limestones occur in discrete, regular to irregular beds up to 12 inches (30 cm) thick, averaging 8 inches (20 cm) thick. The other type, comprising one-third of the total limestones, is fine-grained, argillaceous and silty, medium- to dark-gray in color, and weathers to a dark-yellowish-orange. Many authors refer to these fine-grained beds simply as siltstones (Gibbons, 1973). They occur mostly in regular beds up to 8 inches (20 cm) thick, and are in part laminated or cross-laminated. Also these beds are fossil-poor to barren and occur mostly in the lower 75 feet (23 meters) of
the unit. A number of the beds appear to be more laterally extensive than other siltstones or limestones, but their homogeneous character prevents positive correlation of these beds between sections.

The structure of this area is simple and straightforward because the beds have a regional dip of less than one-half degree. Commonly, the dip is no more than one or two meters per kilometer.

Sweet and Bergström (1971) noted that the Kope Formation generally spans the entire Edenian Stage except where it migrates upward, encroaching into the Maysvillian Stage at locations in southeastern Indiana and eastern Kentucky. It ranges in thickness from around 200 feet (60 meters) in southeastern Indiana (Brown & Lineback, 1966) to 270 feet (80 meters) near Maysville, Kentucky (Peck, 1966). In eastern Indiana, the Kope (subsurface) grades downward into a brown shale of pre-Cincinnatian age (Gray, 1972). In northern Kentucky and southern Ohio, the Kope rests on the Point Pleasant Formation which is Middle Ordovician and possibly earliest Cincinnatian in some locations (Weiss & Sweet, 1964). Also in southern Ohio, Ford (1967) recognized the Grand Avenue Member, a unit that is 11 feet (3.5 meters) thick and occurs approximately 30 feet (9 meters) below the top of the Kope. This unit has a lower clastic content and higher bedding index than the Kope proper.

Overlying the Kope Formation in southeastern Indiana is the Dillsboro Formation, which is described by Brown and Lineback (1966). This formation includes all of the Maysvillian Stage and the Richmondian Stage up to the Saluda Formation. The Kope-Dillsboro contact is conformable and is described by Brown and Lineback as a gradational
increase in limestone abundance. The lower Dillsboro Formation consists of moderately thick beds of rubbly-weathering, argillaceous limestone and calcareous shale. The thickness of this unit ranges from 300 to 325 feet (90 to 100 meters). The contact between the interbedded shale and limestone strata of the Dillsboro and the dolomite beds of the overlying Saluda Formation represents one of the most distinctive lithologic boundaries in the Cincinnatian Series (Brown & Lineback, 1966). The unit itself is also quite distinctive as a northward-thinning wedge of dolomitic limestone, dolomitic mudstone, and dolomite. The lower part of the unit also contains a conspicuous zone of corals (Brown & Lineback, 1966). The lower beds gradually lose their distinctive dolomitic nature to the north as the entire unit thins from about 60 feet (18 meters) at the Ohio River to 9 feet (3 meters) in the subsurface in east-central Indiana. The Whitewater Formation overlies the Saluda and thickens northward as the Saluda thins. This formation consists of several types of limestone interbedded with calcareous shale. Limestones range from thin-bedded and fossiliferous to medium-bedded and unfossiliferous, to rubbly-weathering, argillaceous limestone. The Whitewater thins from 83 feet (25 meters) in the subsurface in Wayne County southward to a feather edge in the southeastern corner of Indiana (Brown & Lineback, 1966). A disconformity marks the top of the formation and separates it from the Silurian Brassfield.

In southwestern Ohio, Ford (1967) recognized three rock units that correlated with the lower part of the Dillsboro to the west. Upward from the gradational Kope contact, these consisted of the
Fairview Formation, the Miamitown Shale and the Bellevue Limestone. The rocks of the upper Dillsboro generally correlated with an unnamed complex of intertonguing facies ranging from thin, interbedded limestones to predominant shale and mudstones. The Fairview is slightly more than 100 feet (30 meters) thick and is in conformable contact with the Kope in southwestern Ohio. It consists mostly of medium-bedded limestone and shale with a 65% overall clastic content (Ford, 1967). The Miamitown Shale is a thin shale that overlies the Fairview, and consists of shale and mudstone with a few thin, widely-spaced limestone interbeds, very similar to Kope lithologies. The limestones contain a characteristic faunal assemblage that includes forms of Lophospira, Cyclonema, and Byssonychia. The unit is 5 feet (1.5 meters) thick in Cincinnati and thickens to 35 feet (10 meters) near Miamitown, Ohio, the type section. Ford noted that above the Miamitown Shale at Cincinnati, the Bellevue Limestone occurs as a sequence of medium- to thin-bedded limestone and shale in which thin-bedded, massive coquinite predominates. At the type section in Cincinnati, the unit is 25 feet (8 meters) thick, but thins to a feather edge northwestward and disappears 4 miles north of Miamitown (Ford, 1967). The Bellevue Limestone and the Fairview Limestone both reach their maximum thickness to the southeast where the Bellevue may represent a northwesterly tongue of the Grant Lake Formation (Fig. 5).

To the southeast, near the Maysville area, the Maysvillian Stage and Richmondian Stage strata were observed by Peck (1966) to exhibit lateral variation. As in the other locations, the Fairview conformably overlies the Kope and consists of closely interbedded limestone and
shale. Limestone makes up 50-60% of the formation, containing medium- to coarse-grained bioclasts in the lower part of the formation and fine-grained, silty limestone with few fossils in the upper part (Peck, 1966). Above the Fairview in this eastern location, the Grant Lake Limestone is recognized by Peck. It is transitional with the Fairview and consists primarily of irregularly-bedded, argillaceous limestone and minor interbedded shale. The limestone is 70-90% of the formation and consists of a micro-grained to medium-grained, poorly-sorted, argillaceous limestone matrix supporting large, random, fossil fragments and whole fossils (Peck, 1966). Bedding is thin, very irregular, and rubbly-weathering. Gray, calcareous shale occurs as irregular partings and thin beds separating limestone layers. Total thickness is approximately 110 feet (34 meters). Overlying the Grant Lake is the Richmondian Stage Bull Fork Formation consisting of alternating shale and limestone where the shale increases upward from 20% of the formation near the base to 80% near the top (Peck, 1966). Shale occurs as thin partings and seams, and as sets from 1 inch to 4 feet (2 cm to 125 cm) thick between limestone beds. Limestones are of three types, according to Peck, and vary in texture, grain size and type, and bedding. The formation is about 200 feet (60 meters) thick in the type area and thins to the south. The strata at the top of the Cincinnatian Series in the Maysville area is described as the Preachersville Member of the Drakes Formation. At this location, it is recognized by Peck as the northern extension of the upper part of the Preachersville Member in its type area in south-central Kentucky. The unit is described as consisting of calcareous to dolomitic mudstone
and minor interbedded dolomitic limestone and dolomite. Mudstone makes up approximately 90% of the unit, and dolomite and limestone occur as thin lenses and pods of fine- to medium-grained rock with sparse, poorly-preserved fossils (Peck, 1966). At this location, the Preachersville is 25-30 feet (8-9 meters) thick and is apparently in conformable contact with the overlying Silurian Brassfield Formation.
GENERAL PETROLOGY OF THE CINCINNATIAN SERIES

According to Gibbons (1973), the rocks of the Cincinnatian Series are composed of interbedded, irregular, very thin- to thin-bedded, medium-gray, fine- to coarse-grained, fossiliferous limestones and massive- to fissile-bedded, gray, sparsely fossiliferous siltstones, all enclosed in a fissile shale (Fig. 7). The individual limestone beds are laterally discontinuous and extend for a few meters to hundreds of meters, but are most commonly observed to pinch out within several tens of meters into the surrounding shale section (Fig. 8). The proportion of shale and mudstone to limestone varies a great deal vertically through the section and from one geographic location to another, but is generally observed to be greater in the lower and upper strata and more nearly equal in the middle of the stratigraphic section (Martin, 1975). In the southern exposures of Cincinnatian Series strata, the rocks are noticeably siltier and more calcitic and dolomitic than those in southeastern Indiana and southwestern Ohio (Weir & Greene, 1965; Weir, Greene, & Simmons, 1965). Also, the total section is nearly 20 meters thinner in the southern Cincinnati region (Sweet & Bergström, 1971).

Bedding contacts are mostly gradational throughout the 700 foot (210 meter) thick sequence, however some beds exhibit sharp contacts locally. The lower surfaces of a number of limestones and mudstones reveal flute casts and other small-scale scour fillings and lineations. Also, rippled beds are present in all formations of this sequence,
Figure 7. Close-up of a section of the Kope. Note irregular bedding that varies laterally.
Figure 8. Laterally-discontinuous beds of limestone and siltstone that pinch and swell.
although they vary a great deal in wavelength and amplitude. Starved ripples have been observed at one location in the Kope. The average wavelength is approximately 75 cm and the amplitude is about 6 cm (Potter & Pettijohn, 1963). Regionally, the beds of this section dip less than one-half degree, but this figure varies with the geographic location.

**Limestone Petrography**

Bioclasts and carbonate mud accumulated in a ratio of 40 to 60% in the lower two-thirds of the series, and in a ratio of 23 to 70% in the upper part (Martin, 1975). Approximately 80-85% of the Cincinnatian limestones represent poorly sorted, coarse-grained carbonates that can be classed as biomicropseudosparrudites and biopseudosparrudites. Martin (1975) suggests that during the diagenetic development of these rocks, much of the original carbonate mud was converted, through neomorphism (Folk, 1965), to microspar (Folk, 1959; 1965) and pseudospar (Folk, 1965). Folk defines microspar as consisting of calcite crystals ranging in size from 5-30 μm, and pseudospar as crystals larger than 30 μm. He states that modern carbonate muds, and probably ancient ones, accumulate as a "soup of tiny calcite or aragonite grains" (Folk, 1965, p. 28). During diagenesis, microspar develops as the aragonite inverts to calcite and the entire sediment converts to a mass of subequant 1-3 μm calcite polyhedra (Folk, 1965). If the original carbonate mud continues to invert to coarser and coarser grains, it will cross the arbitrary limit of 30 μm and become pseudospar (Folk, 1965). Bathurst (1975) further suggests that the
evolution of neomorphic fabrics may be related to the development of lithification of the sediments. He proposes that the longer that lithification is delayed the more time there is for neomorphism to proceed. A calcite pseudospar may thus represent the maximum possible delayed lithification and likewise the mostly widely-spaced, original nuclei, because lithification is delayed only when the nucleation sites of neomorphic spar are widely dispersed (Bathurst, 1975). Likewise, a microspar may be the result of less-delayed lithification and micrite only slightly delayed lithification with closely-spaced nuclei (Bathurst, 1975). Bathurst recognizes pre-existing calcite crystals as the nuclei for neomorphism. These crystals may occur as bioclastic debris or secondary calcite crystals from earlier neomorphism.

Prior to the conversion of carbonate mud to microspar and pseudospar, the average Cincinnatian limestone would be classified as a biomicrudite (Folk, 1959), wackestone, or packstone (Dunham, 1962), depending on the relationship of grains to mud (Harris & Martin, 1979). Carbonate mud in these limestones is composed, at least partially, of biodetrital fines from the micritization of skeletal remains by mechanical processes and boring organisms (Lobo & Osborne, 1973). Grains consist mostly of fossils and fossil fragments with only scattered intraclasts or pellets. Martin (1975) observed that most bioclasts belong to one of seven groups of invertebrates with bryozoans as the most numerically abundant group (Table 1).

**Insoluble Residue**

The fraction of insoluble residue present in the limestones
<table>
<thead>
<tr>
<th>CINCINNATIAN SERIES FORMATIONS</th>
<th>BRYOZOA</th>
<th>BRACHIOPODS</th>
<th>ECHINODERMS</th>
<th>TRILOBITE</th>
<th>OSTRACODES</th>
<th>PELECYPODS</th>
<th>GASTROPODS</th>
<th>CORALS</th>
<th>ALGAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHITEWATER</td>
<td>34%</td>
<td>17%</td>
<td>18%</td>
<td>5%</td>
<td>17%</td>
<td>&gt;1%</td>
<td>&gt;1%</td>
<td>3%</td>
<td>6%</td>
</tr>
<tr>
<td>SALUDA</td>
<td>25</td>
<td>5</td>
<td>16</td>
<td>1</td>
<td>32</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>LIBERTY</td>
<td>30</td>
<td>21</td>
<td>32</td>
<td>13</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>WAYNESVILLE</td>
<td>20</td>
<td>35</td>
<td>22</td>
<td>14</td>
<td>&lt;1</td>
<td>&gt;1</td>
<td>3</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>ARNHEIM</td>
<td>20</td>
<td>38</td>
<td>22</td>
<td>6</td>
<td>&lt;1</td>
<td>9</td>
<td>&gt;2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mc MILLAN</td>
<td>38</td>
<td>35</td>
<td>18</td>
<td>7</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAIRVIEW</td>
<td>35</td>
<td>36</td>
<td>13</td>
<td>13</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KOPE</td>
<td>38</td>
<td>27</td>
<td>21</td>
<td>10</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE</td>
<td>30</td>
<td>28</td>
<td>21</td>
<td>9</td>
<td>7</td>
<td>2</td>
<td>&gt;1</td>
<td>&gt;2</td>
<td>&gt;1</td>
</tr>
</tbody>
</table>

Table 1. Percent composition of the mean components and the percent of the allochem fraction of faunal groups and algae in the Cincinnatian Series limestones (modified from Martin, 1975).
ranges from 4 to 38% by weight and consists of sand- and silt-sized quartz and clay minerals (Martin, 1975). Clay minerals generally comprise the greater proportion of the residues.

**Shale and Siltstone Petrography**

The discontinuous limestone beds and lenses of the Cincinnatian are enclosed in gray, argillaceous to silty, barren to fossiliferous, massive- to fissile-bedded shales. These shales have been exhaustively investigated by Bassarab and Huff (1969); Butler and Scotford (1973); Scotford (1964; 1965); and Weiss, Edwards, Norman, and Sharp (1965). The shales consist primarily of fine- to medium-sized silt which comprises almost 60% of the total shale composition. Clay-sized material constitutes only 38% and sand makes up the remaining 2-3% (Scotford, 1965). The average mineral composition of the Cincinnatian shales, as reported by Scotford (1965), is 47% illite, 24% quartz, 7.7% chlorite, 7% dolomite, 6% calcite, 4.4% mixed-layer illite, and 2% mixed-layer chlorite, with trace amounts of kaolinite, feldspar, and pyrite. Vermiculite also occurs in the Kope and Fairview Formations (Bassarab & Huff, 1969). The texture, mineralogy, and chemistry of the shales are remarkably consistent in both vertical and lateral extent, as noted by Scotford (1965). However, Butler and Scotford (1973) recognized three persistent shale units, one each from the base, middle, and top of the section, that are mineralogically and texturally distinct.
PETROGRAPHY OF THE KOPE FORMATION

Scotford (1965) reported that the Fulton Formation (Kope Formation) revealed much less pronounced variation laterally within the unit than the other lithologies in the study. Only three of twenty-two environmental parameters indicated statistically significant variation, which suggests a high probability of a depositional environment that was constant throughout Cincinnatian time. Vertical uniformity was likewise reported by Scotford. In light of the extensive nature of the previous work done on the shale lithologies, in conjunction with general agreement in the conclusions among the investigators, it was decided to concentrate the focus of this study primarily on the genesis of the limestone beds and, to a lesser extent, the siltstone beds.

Limestone Petrography

The bioclastic limestones of the Kope Formation are readily characterized within the framework of Dunham's (1962) classification. This scheme is selected for its use of textural criteria to distinguish between rock types, and these criteria also reflect the level of water energy in the depositional environment. Two modifications need to be included, however. One involves the addition of two intermediate classifications between packstones and grainstones, and the other provides a common classification for carbonate mud (neomorphic spar) and terrigenous mud.

It is readily apparent that practically all of the Kope limestones
are in the packstone to grainstone classes, however many of the packstones are winnowed to some extent and a number of the grainstones are somewhat muddy. These beds are not readily classified according to the original criteria for the Dunham classification. After some experimentation, criteria were established (Fig. 9) which could consistently be applied to these rocks and which would reveal an accurate pattern of the variations in the texture of the rocks.

The second modification addresses the disparity between the types of sparry calcite which exist in many of the Cincinnatian limestones. One type of spar is that which precipitates out of solution within the pore spaces between grains as primary cement. The other type of spar results from the inversion of microcrystalline calcite (or aragonite) mud to microspar or pseudospar. This type of cement represents an original pore-filling mud matrix, and, as such, may not be included in the same genetic classification with primary pore-filling cement. The former cement type indicates deposition in a more agitated environment than the latter, and this distinction reflects important differences in the environment of deposition. Carbonate mud shares a number of depositional characteristics in common with terrigenous mud, consequently, in this study, they are both classified simply as mud. The problem, however, is in distinguishing the recrystallized carbonate mud (neomorphic spar) in the polished slabs and thin sections from pore-filling primary spar. Because they are similar in appearance, the key is to establish criteria that emphasize genetic and morphologic differences. Folk (1965) and Bathurst (1975) have identified a number of distinguishing
<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grainstone</td>
<td>Grain-supported; contains less than 5% mud, which usually occurs as mud shelters.</td>
</tr>
<tr>
<td>Poorly Washed Grainstone</td>
<td>Grain-supported; contains more than 5% mud, which is subordinate to spar by a ratio of at least 1:2.</td>
</tr>
<tr>
<td>Partially Winnowed Packstone</td>
<td>Grain-supported; contains more than 5% spar, never exceeds a ratio of 2:1 with mud.</td>
</tr>
<tr>
<td>Packstone</td>
<td>Grain-supported in a mud matrix; contains less than 5% spar.</td>
</tr>
<tr>
<td>Wackestone</td>
<td>Mud-supported; contains more than 10% grains.</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Mud-supported; contains less than 10% grains.</td>
</tr>
</tbody>
</table>

Figure 9. Classification of Kope limestones (modified from Dunham, 1962).
characteristics among carbonate mud, microspar, and pseudospar, but, for the purposes of this study, all forms of original carbonate mud were grouped together under one heading, so it became a question of distinguishing primary sparry cement from neomorphic spar and carbonate mud. Figure 10 illustrates the criteria, modified from Folk (1965) and Bathurst (1975), which were used to identify primary calcite, and Figure 11 illustrates the criteria which distinguish neomorphic calcite.

Utilizing the modified classification scheme for the lithologies of the Kope Formation revealed that almost three-quarters (72%) of the samples could be classified as packstones or winnowed packstones. Poorly washed grainstones accounted for another 11%, and grainstones, wackestones, and mudstones together comprised the remaining 17% in approximately equal numbers.

The texture of the rocks is described according to the degree of sorting, bedding characteristics, orientation of grains, and indications of abrasion or compaction-breakage of grains. Sorting is estimated according to the technique proposed by Folk (1974) wherein the coarsest and finest fractions of grain sizes are ignored and a sorting value is assigned to the remainder. The majority of Kope limestones are either very well-sorted or very poorly sorted, which means that their textural classification is usually a straightforward judgment and the use of the modifiers "very well" and "very poorly" often proves to be unnecessary. Predictably, the fine-grained, well-winnowed, sparry grainstones are also the best-sorted rocks among the Kope limestones, and the muddy packstones and wackestones.
Figure 10. Examples of criteria used to identify primary sparry calcite cement.
Figure 11. Examples of criteria used to identify neomorphic (recrystallized) sparry calcite.
with whole or broken fossils are the most poorly sorted.

Numerous examples of bedding lamination and cross bedding are observed in the limestones of the Kope Formation. These are described according to their presence as well as their orientation in the limestones. Cross-bedding is usually noted in the thick-bedded limestones, whereas the more nearly horizontal laminations may be observed in any bed, regardless of thickness. Additional evidence of cross-bedding is observed in a number of limestone beds whose upper surfaces display well preserved ripples (Fig. 12). Limestones display both symmetrical and asymmetrical ripples with an average wavelength of 18 inches (45 cm) and an average amplitude of 3 inches (8 cm). Ripple crests appear to be relatively straight and only somewhat discontinuous; however, the limited extent of most of the rippled surfaces reduces the level of confidence that can be asserted in these observations. The crests of the ripples that were noted and measured were observed to strike between N 10° W and N 8° E. This range was consistent for all 32 measurements taken on nine beds which are exposed predominantly in the lower half of the section. One of these is a series of discontinuous "starved ripples" (Figs. 13 & 14) that probably resulted from an insufficient supply of bioclastic sediment within the ripple-forming flow regime of the bottom currents.

The orientation of individual fossil grains correlates closely with the occurrence of cross-bedding and lamination in the limestone beds. Where bedding is present, most of the grains that comprise the bedding are parallel to it. The presence or absence of bedding, like sorting, usually correlates with the type of bioclastic fabric. Where
Figure 12. Rippled limestone bed in lower section of Kope Formation (RR Section).
Figure 13. Series of starved ripples near Sanfordtown, Ky. (MP Sections).
Figure 14. Close-up of starved ripple.
the absence of bedding in some samples is attributed to bioturbation, a muddy matrix usually predominates in the bioclastic fabric. Grainstones and winnowed packstones reflect the various styles of bedding, whereas the grains of the muddy lithologies are more randomly oriented.

Compaction breakage and transport of grains is described, where observed, according to degree and extent. Abrasion of grains is questionably observed in some instances, although the degree of the possible abrasion is slight. On the other hand, numerous contraindications of extensive grain transport exist in most beds. Typical examples are the presence of the thin, fragile genal spines of *Cryptolithus* and articulated crinoid columnals (Figs. 15 & 16). Breakage due to compaction occurs randomly in all Kope lithologies. Correlation of specific bioclastic fabrics with the occurrence or absence of compaction breakage is less clearly defined than was the case with the sorting and bedding characteristics.

Another important consideration is the relationship of successive or adjacent lithologies that are distinct from each other. This is especially true where these lithologies, or microfacies, occur within a single bed (Fig. 17). Approximately one-half of the limestone beds sampled in this study reflect more than one lithologic type and display differences in texture and/or composition. Each lithologic type is termed a microfacies. Three types of contacts between microfacies are recognized: sharp (change from one microfacies to the next occurs within 1 mm); abrupt (change occurs between 1-3 mm); and gradational (change occurs in more than 3 mm). Changes from one microfacies to another in the same bed are common throughout the Kope
Figure 15. Upper surface of limestone bed with articulated crinoid and Cryptolithus cephalon.
Figure 16. Upper surface of limestone bed with articulated crinoids and calyx.
LIMESTONE SLAB CUT NORMAL TO BEDDING

MICROFACIES "A" THROUGH "E"

Figure 17. Limestone slab with five different microfacies.
limestones but seem to occur more consistently in the thicker (>75 mm) beds. Contacts between limestones, siltstones, and shale are typically characterized as sharp or abrupt.

**Summary of the Bioclastic Fabrics**

Grainstone fabrics in the Kope Formation (Fig. 18) are characterized by fine-grained bioclastic debris in a grain-supported framework held together by pore-filling spar cement. The well-fragmented fossil grains have sharp, distinct edges and angular corners. Apparently these grains have undergone very little mechanical abrasion, such as that associated with long-distance transportation. These rocks are further characterized by an almost total absence of mud, a high degree of sorting, and the presence of cross-bedding or laminations. This well-winnowed fabric represents the most highly agitated environment of deposition for these limestones.

Poorly washed grainstones (Fig. 19) are almost identical to the above, with the exception that a minor amount of mud is allowed if less than or equal to half the amount of spar present. A slight decline in the degree or duration of water agitation is indicated by this fabric.

A further decline in water energy results in the partially winnowed packstone fabric (Fig. 20). The bioclastic grains are somewhat coarser than in grainstones, and this wider range of grain sizes indicates poorer sorting. Mud content also increases to the point where it exceeds that of spar, although the latter is still present in minor amounts.

The packstone fabric (Fig. 21) is characterized by a further
Figure 18. Grainstone fabric in a limestone slab cut normal to bedding.
Figure 19. Poorly-washed grainstone fabric in a limestone slab cut normal to bedding.
Figure 20. Partially-winnowed packstone in a limestone slab cut normal to bedding.
Figure 21. Packstone fabric in a limestone slab cut normal to bedding.
increase in the range of grain sizes, and a corresponding decrease in the degree of sorting. The framework of this rock is one of sub-horizontal to randomly oriented skeletal fragments in contact with each other. Mud fills all pores and voids between the grains as matrix material with no evidence of sparry cement. This fabric represents a low level of water agitation in the depositional environment.

Wackestone fabrics (Fig. 22) consist of whole or broken fossils which are randomly oriented within and supported by a mud matrix. Large, unfragmented, ramose bryozoans or articulated crinoid columns commonly occur in this fabric. Minimal water energy is indicated by the association of these components.

A variety of small-scale patterns may be noted in the upward trend of these fabrics; however, none is consistent for any reasonable distance vertically in the section. Fining- or coarsening-upward tendencies of bioclastic grains are observed in the majority of limestone beds that consist of more than one microfacies. Slightly more than 50% of these beds are characterized by fining-upward trends, and coarsening-upward sequences are observed in just over one-third of the microfacies beds. Another variable that was considered is the increase or decrease in grain size between two successive beds that are separated by a shale interval. Again, no apparent trend is indicated, as the mean grain size increases in approximately one-half of the intervals between limestones, whereas a decrease is noted for the other half. Also, no correlation could be recognized between these variables. The fining- or coarsening-upward sequences in the
Figure 22. Wackestone fabric in limestone slab cut normal to bedding.
microfacies beds are independent of the change in grain size that occurs between the top of one bed and the bottom of the succeeding bed.

One trend, however, is continuous and consistent upward through the section. This correlation exists between successive beds, where both the size of the skeletal fragments and the mud content increase from one bed to the next. Consequently, the coarse-grained limestones also reflect increases in mud content. A decrease in spar content is also observed in these rocks, as might be expected, because an inverse relationship normally exists between mud and sparry calcite.

**Diagenesis**

Primary diagenetic events include the bioerosion and micritization of bioclastic debris and the neomorphric inversion of carbonate mud and aragonite to microspar and pseudospar. Additional evidence of diagenesis is observed in many limestones as the breakage of fossil grains due to compaction of the sediments. Dissemination of pyrite is a feature more common to the mudstone and wackestone fabrics. Intergranular cementation by sparry calcite is common to both the limestones and siltstones.

**Siltstone Petrography**

Siltstones consist of silt-sized angular quartz grains, clay-sized particles, and interstitial calcite crystals. Whole or broken fossils which are randomly oriented in the mudstone are locally observed. The grain size for quartz ranges from 0.01-0.10 mm with a mean grain size of 0.03 mm for all the siltstones. The abundance of quartz ranges from
4-34% of the total composition for any one rock, with a mean abundance of 19%. The mud fraction of the siltstones ranges from 22-53% and has a mean abundance of 45%. Pore-filling calcite cement among siltstone samples ranges from 20-47% with a mean of 30% for all siltstones. This represents a minimal range of values for porosity as the porosity of the original sediment was probably higher before compaction. Also, the presence of numerous calcitic nodules, noted along specific horizons within shale or siltstone intervals (Fig. 8), indicates local concentrations of calcite cement, and this suggests that variations may have existed in these sediments prior to their lithification. Some of these nodules are massive and free of internal structure, and others reveal laminations that continue from the host rocks through the nodules (Fig. 23). Miscellaneous unidentified grains comprise the remaining constituents of the Kope siltstones.

Bioturbation is common in the siltstones and ranges in degree from a few small burrows to extensive disruption of the laminations. Small horizontal burrows that range from 2 or 3 mm up to 15 mm are the most abundant (Fig. 24), but vertical and randomly oriented burrows are also commonly observed. Evidence of compaction is not readily apparent in the burrows. A few of them exhibit slightly elliptical cross-sections or margins that are somewhat flattened, but the majority of the burrows do not appear to have undergone appreciable compaction.

Rippled siltstones exhibit a somewhat different form, in surface expression as well as in cross-section, than the previously described limestones and non-rippled siltstones. They are best described as
Figure 23. Calcitic nodules in upper part of siltstone slab cut normal to bedding.
Figure 24. Numerous burrows in a siltstone slab cut normal to bedding.
undulatory current ripples that form an irregular, wavy surface on the
tops of rippled beds (Fig. 25). The strike of the ripple crests is
difficult to determine because of the variability in orientation caused
by their undulatory nature. As was the case with the limestones,
complete and detailed descriptions were hampered by the limited
exposure of rippled surfaces. In cross-section, these beds exhibit
a variety of structures, from inclined laminations to hummocky cross-
bedding (Harms, 1975) that locally has small truncation contacts
between some of the sets of laminations (Fig. 26).

Another characteristic of some of the siltstones is their occur-
rence in shale intervals as numerous, massive, silty, thin (2-4 cm)
horizons that may be somewhat laminated at the base but then grade
upward into the overlying fissile shale. Silt-sized quartz predom-
inates near the base of these beds and then diminishes upward.

**Distribution of Bioclastic Sediments, Matrix Material and Cement**

Skeletal fragments and whole fossils comprise approximately 60%,
by volume, of the total composition of the Kope limestones. Individ-
ually, they fall into one of five major taxonomic groups, with a sixth
miscellaneous group for the few assorted fauna that do not belong to
one of the preceding groups. Bryozoans are the most numerically
abundant group, comprising a mean of 24% of the total composition of
the limestones, as established by point counting all the constituents
of each slab. The range of abundance of bryozoans in individual
limestone beds is from zero to 73% of the total composition. Crinoids
rank second in abundance with a mean of 16%, and they range from zero
Figure 25. Siltstone with rippled upper surface.
Figure 26. Hummocky cross-bedding in a siltstone slab cut normal to bedding.
to 51% of the total composition of the individual beds. The third most abundant group consists of several genera of brachiopods which comprise 9% of the total rock composition for the limestones. The range in values for individual beds is from 1-52%. The remaining two taxa, mollusks and trilobites, each account for 7% of the total. The range for mollusks is from zero to 33% of the total in individual beds, and the range for trilobites is from zero to 24%. Graptolites and tentaculites are assigned to the miscellaneous group which comprises 5% of the total rock composition of the Kope Formation limestones. It is further noted that more than 60% of the graptolites in these rocks are concentrated in a section of strata 35 feet (10 meters) thick that is located approximately 75 feet (22 meters) above the base datum for the sequence. In two limestone beds, graptolites comprised 10% of the total composition.

Vertical trends in abundance were plotted for each taxonomic group using the percent of each constituent for each successive sample in the stratigraphic section. Comparison of these vertical trends, each with the others, revealed a number of correlations, both positive and negative. In some instances, no correlations between trends were observed.

No apparent relationship between bed thickness and composition exists in these strata. The variation in fossil assemblages as well as grain sizes is independent of the thickness of the respective limestone bed. A relationship does seem to exist wherein rippled or cross-bedded rocks occur more commonly in the fine-grained layers of limestone and siltstone, however there is apparently no correlation between the types
of fossil assemblages and the grain sizes of these rocks. For example, abundant bryozoan debris is nearly as abundant in fine-grained limestones as it is in the coarse-grained rocks. Similarly, crinoid plates and columnals are often as abundant in coarse-grained rocks as in fine-grained samples.

Patterns in the distribution of specific taxa within the limestone beds are apparent for some groups. For example, brachiopod fragments and whole fossils predominate in the upper and lower surfaces of in situ limestone beds as they appear in outcrop. Likewise, they are least abundant in the central portions of the polished slabs. This same general pattern also holds for bryozoans, although they are generally more conspicuous than brachiopods in the central portions of the polished slabs. Crinoid plates and columnals on the other hand are most abundantly represented in the central portion of the in situ limestone beds, as indicated in the polished slabs. They are also observed on the upper surfaces of many of the limestone strata, but occur on very few of the lower bounding surfaces of the rocks.

Some striking correlations appear in the vertical trends of relative abundances for certain faunal constituents in the sequence of limestone beds. Although these trends do not necessarily correlate in exactly the same way from one bed to the next, the overall patterns may still be observed. An inverse relationship exists between the distribution patterns of crinoids and bryozoans. Crinoids generally increase as bryozoans decrease, and vice versa, from one bed to the next. This inverse relationship is illustrated on a log of moving averages to minimize local effects (Fig. 27). A conspicuous difference between
Figure 27. Moving averages of vertical trends in faunal distributions.
these two trends and the trends of other taxa exists, the abundance of bryozoans and crinoids increasing or decreasing much more dramatically than the corresponding decrease or increase of other taxa. In fact, the rate of change in abundance of bryozoans from one bed to the next is greater than for any other taxon in the Kope.

The distribution of bryozoans and brachiopods is also inversely related, however the relationship is not as distinct nor as consistent as that between bryozoans and crinoids. This inverse relationship is best illustrated by a log of moving averages (Fig. 27). The small-scale changes in trends that occur within thicker beds tend to obscure many of the fluctuations between the overall distributions of these two faunal groups. It may be noted that the abundance of brachiopods tends to increase upward to a broad peak in the upper Kope strata and then begins to decline at the contact between the Kope Formation and the overlying Fairview. This peak in the trend of the brachiopods is not reflected in that of the bryozoans.

The vertical trends in the distributions of trilobites and mollusks are not particularly distinctive. They bear very little similarity to the trends of the other taxa except in the most general sense. A possible correlation exists between trilobites and mollusks, although it is vague and discontinuous. This relationship appears to develop vertically, and indeed, trilobite fragments commonly occur with fragments of mollusks on the surfaces of limestone beds and in the cross-sections of polished slabs. Trilobite fragments are also associated with crinoids and brachiopods, although not in abundance. No faunal group appeared to be negatively correlated with trilobites or
mollusks.

Vertical trends were also calculated for such lithologic characteristics as the mean grain size, the percentage of matrix, and the percentage of cement for each successive sample in the stratigraphic section (Fig. 28). Comparison of these vertical trends revealed such predictable correlations as the inverse relationship that commonly exists between sparry calcite cement and matrix material. As the amount of sparry cement increased from one sample to the next, the content of mud matrix usually decreased. Conversely, a decrease in spar content between adjacent samples usually corresponded to an increase in mud. However, trends such as upward increases or decreases in grain size, or mud and spar content, were not apparent over the vertical extent of any single log. Of course, the absence of such trends is noted only for the study area and may not indicate that stratigraphic patterns do not exist elsewhere in the region.
Figure 28. Moving averages of vertical trends in mean grain size, spar and mud content throughout the composite thickness of the Kope Formation.
ENVIRONMENTAL INTERPRETATIONS

The interpretation of recurring associations of fossil assemblages as biological communities has become a common approach for paleontologists and paleoecologists as indicated in current literature. According to Schäfer (1972), a living community is described by first counting and characterizing its members, and then by noting which properties of each member affect other members. Also, the geographic distribution of the individual members is determined. This leads to a description of the interrelationships between the organisms and the surrounding environment.

**Paleoecology of the Kope Fauna**

Consistent and recurrent associations of the members of major faunal groups led Bretsky (1969) to the recognition of three primary communities of Upper Ordovician, central Appalachian fauna. One of these, the *Sowerbyella-Onniella* community, is characterized by an association of fauna that occupies an area extending from eastern Pennsylvania to central Virginia. The same association is characteristic of the fauna of the Kope Formation in southern Ohio and northern Kentucky (Table 2). The other two communities, *Orthorrhynchula-Ambonychia*, and *Zygospira-Hebertella*, are also similar in composition and structure to other assemblages of fossils found in the Upper Cincinnatian Series of southern Ohio and northern Kentucky.

Bretsky suggests that the environmental setting of the central Appalachian *Sowerbyella-Onniella* community was along the outer shelf,
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bryozoa</td>
<td>Hallopora</td>
<td>Hallopora</td>
</tr>
<tr>
<td></td>
<td>Batostoma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dekayia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bythopora</td>
<td></td>
</tr>
<tr>
<td>Brachiopoda</td>
<td>Sowerbyella Rafinesquina</td>
<td>Sowerbyella Rafinesquina</td>
</tr>
<tr>
<td></td>
<td>Onniella</td>
<td>Onniella</td>
</tr>
<tr>
<td></td>
<td>Zygospira</td>
<td>Zygospira</td>
</tr>
<tr>
<td>Mollusca</td>
<td>Sinuopea</td>
<td>Sinuites</td>
</tr>
<tr>
<td></td>
<td>Lophospira</td>
<td>Lophospira</td>
</tr>
<tr>
<td></td>
<td>Ruedemannia</td>
<td>Holopea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ambonychia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pterinea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modiolopsis</td>
</tr>
<tr>
<td>Arthropoda</td>
<td>Isotelus Flexicalymene</td>
<td>Isotelus</td>
</tr>
<tr>
<td></td>
<td>Calymene</td>
<td>Flexicalymene</td>
</tr>
<tr>
<td></td>
<td>Cryptolithus</td>
<td>Cryptolithus</td>
</tr>
<tr>
<td></td>
<td>&quot;Ostracodes&quot;</td>
<td></td>
</tr>
<tr>
<td>Echinodermata</td>
<td>Unidentified Columnals</td>
<td>Heterocrinus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ectenocrinus</td>
</tr>
</tbody>
</table>

Table 2. Comparative lists of Upper Ordovician fauna after Bretsky (1969) and Caster, Dalvé & Pope (1955; 1961).
just seaward and to the west and southwest of the Late Ordovician
deltaic complex that was receiving clastic detritus from the rising
Appalachian orogen (Fig. 29). He further proposed that the fauna was
completely normal marine and that the predominant type of substrate
was fine- to medium-sized muddy silt.

MacDaniel (1976) characterized an Onniella-Sowerbyella community
in the Ordovician rocks of southern Ohio and northern Kentucky as an
association of fossils consisting of two species of brachiopods, three
species of trilobites, and several species each of bryozoans and
crinoids that lived in an offshore, muddy environment. It is impor­tant to note that these two communities represent spatial distributions
based solely on the association and recurrence of fossil species. They
are not represented herein as reconstructions of communities which were
discrete entities in this region during the Upper Ordovician. The
relationships that existed between communities will be considered
later in this section.

Communities develop and evolve as a consequence of the ability
of the individual members to adapt to the unique conditions that exist
in the environment. As these conditions changed, or as the environ­
ment migrated, the organisms adapted to the changing conditions, moved
with the migrating environment, or perished.

According to Richards (1972), Sowerbyella and the less abundant
Rafinesquina alternata apparently adapted to living in the soft, muddy
substrate by the concave-convex shape of their valves which allowed
them to lift the commissure above the surface of the mud (Fig. 30).
Richards also suggested that Zygospira lived with its beak oriented
Figure 29. Inferred distributions of abundant faunas in the central Appalachian, Upper Ordovician environments of Brevick, 1969.

APPALACHIAN BASIN

OFFSHORE

SOWERBYELLA ONNIELLA COMMUNITY
Rafinesquina Sowerbyella Lophospira Sinuopea Onniella Zygospera CRINIOIDS Isotelus Flexicalymene Cryptolithus Lyrodesma Praenucula Ctenodonta Ruedemannia Hallopora

LATERAL AND BATHYMETRIC BIOZONES

ORTHORHYNCHULA AMBONYCHIA COMMUNITY

Lingula Tancredliopsis Plectonnotus Bucanlia Ischyrodonta Orthorhynchula Dekayla Ambonychia Modiolopsis

APPALACHIAN OROGEN

ONSHORE

APPALACHIAN BASIN

OFFSHORE
Figure 30. Adaptations of Edenian-type brachiopods to soft substrates.
downward toward the object to which it was attached by a medium-sized pedicle. Although he recognized that this small brachiopod probably attached to the shells of other living or dead brachiopods and bryozoans, he noted that it may also have been able to attach to a fragmented bioclastic pavement or even to a firm substrate (Fig. 30).

Other suspension feeders in the community were several genera of bryozoans, such as Hallopora, Dekayia, and Bythopora, and the crinoids Heterocrinus and Ectenocrinus (Caster, Dalvè, and Pope, 1961). One genus of bryozoan, Eridotrypa, was observed by Anstey and Perry (1972). They suggest that during the early Edenian, colonies of these bryozoans were probably attached to the substrate by means of an uncalcified, flexible joint at the base of a downward-tapered zoarium. This attachment allowed them to exist in somewhat turbulent water conditions, where depths were less than 35 meters. The appearance of rigid zoaria after the early Edenian indicates decreasing water agitation and increasing depth (Anstey and Perry, 1972).

Halleck (1973) observed conspicuous differences among crinoid roots from the Silurian, apparently in response to the type of substrate to which they were attached. In a sequence of the Silurian Waldron Shale, small roots were found attached to shell material, but larger root systems were also noted which had overgrown the original shell substrates and deeply penetrated the mud around the shell. According to Halleck (1973), although they were originally adapted to a hard substrate (shell fragments), these roots apparently became secondarily adapted to mud during growth (Fig. 31).

Ambonychia and Modiolopsis were the only bivalve suspension
Figure 31. Adaptations of crinoids to variable substrates (modified from Halleck, 1973).
feeders that were even moderately abundant in the offshore community (MacDaniel, 1976). Although suspension feeders were certainly the dominant organisms, infaunal and epifaunal deposit feeders also existed (MacDaniel, 1976). Of these organisms, the trilobites Cryptolithus and Flexicalymene were the dominant genera. The gastropods Lophospira and Cyclonema were also probably deposit feeders (MacDaniel, 1976).

The boundaries between marine benthic communities and environments are usually gradational compared to the well-defined limits of some terrestrial environments, or such marine habitats as coral reefs (Johnson, 1972). The communities of benthic organisms that occupy clastic environments, which range from offshore mud to nearshore silt and sand, tend to be laterally continuous and intergrading (Fig. 29). Many investigators tend to explain the intergradation of communities as a consequence of post-mortem transportation of skeletal remains (Johnson, 1972). Schäfer (1972) noted that a variety of skeletal parts, such as echinoderm debris, gastropod shells, and lamellibranch valves, are destroyed after being transported a very limited distance. This is especially true where numerous skeletal parts are transported together by bottom currents. Breakage and abrasion reduce the skeletal remains to unrecognizable constituents of fine-grained sediment, commonly within several kilometers of the original habitat (Schäfer, 1972). Of course, this explanation doesn't hold for very small, lightweight, hard parts that may be drawn up into suspension and carried great distances with little or no abrasion.

MacDaniel (1976) determined that the degree of post-mortem
transport of skeletal material during Cincinnatian time must have been minimal. He noted that even the shoal sequences contained well-preserved fossils, and argillaceous biosparrudites throughout the section revealed numerous articulated fossils and in situ assemblages. These were used to reconstruct the original dimensions of the various environments, which indicated that belts a few tens of kilometers wide were characteristic of the distributions of these communities.

Diversity trends among the fauna of the Cincinnatian communities varied according to the environment in which they occurred, and they are based on outcrop data from a wide area wherein fossils are identified mostly to genus or species. The Rafinesquina-Zygospira community was the least diverse and occurred in the turbulent shoal environment. The diversity increased offshore in the Onniella-Sowerbyella community and to a somewhat lesser extent in the Platystrophia-Hebertella community, which was not a Kope community, but which occurred behind the shoal environment. In the Cincinnatian Series, this community occurs in the Fairview Formation, which immediately overlies the Kope Formation. MacDaniel recognized the emergence of two different communities in the onshore (lagoonal) and shoal environments during the Richmondian regressive cycle, both of which were much more diverse than their first-cycle counterparts. The offshore Onniella-Sowerbyella community became somewhat more diverse in numbers of different fauna, but otherwise remained largely unchanged during this Late Cincinnatian rise in sea level.

The petrographic fossil diversity is determined from fossils that are identified to any of several different and usually broad taxonomic
levels, and it parallels the simple species diversity of the paleontologist. Petrographic fossil diversity in the Kope Formation ranges from 2-11 taxa per microfacies, with a mean value of 6 taxa. This figure is somewhat low as compared to that for the nearly identical Onniella-Sowerbyella community of MacDaniel (1976). He noted a range of 7-11 taxa per sample, with a mean value of 9 for the Onniella-Sowerbyella community. This discrepancy between the ranges of diversity may be explained in several ways. MacDaniel may have included counts of fossil grains from local, unusually fossiliferous zones. Conversely, the counts generated in this study may have included zones that were relatively free of fossils.

Diversity trends are indicated by the range of values for the total number of taxa within and between single limestone beds in the Kope. It is noted that the lowest microfacies in some limestone beds contain only two or three taxa, and these are most often brachiopods or bryozoans (Fig. 32). Commonly, these microfacies are succeeded upwards by other microfacies containing six or eight taxa, which reflects an abrupt increase upward in diversity (Fig. 33). This upward increase may occur within the same bed or the next one above it.

Harris and Martin (1979) noted that there were similarities in diversity patterns among some Upper Cincinnatian limestones and that these diversity patterns correlated with Walker's and Alberstadt's (1975) concept of short-term succession of fauna. Short-term succession, as defined by Walker and Alberstadt, occurs in unstable environments wherein periodic catastrophic events destroy existing communities and rebuilding of the communities involves a rapid, biologically induced
Figure 32. Variety of brachiopods succeeded upwards by bryozoans.
Figure 33. Brachiopods and bryozoans in the lower part of a limestone slab and which are succeeded upwards by crinoids, trilobites, and mollusks.
process of faunal succession from the pioneer stage to the mature community stage. These short-term successions occur rapidly and are recorded in thin, stratigraphic units, and it is the rapid nature of the successional sequence that characterizes the fossil record of these rocks.

Harris and Martin (1979) suggest that the increase in faunal diversity toward the centers of some Upper Cincinnatian limestone beds indicates rapid community succession. They also noted that a decrease in diversity toward the tops of the beds probably represents community degradation resulting from an influx of terrigenous sediment. These authors propose a model wherein the soft, muddy substrate of a subtidal marine environment was colonized by thin, flat brachiopods during Cincinnatian time. The shells of these organisms accumulated through time until a firm pavement was created upon which erect bryozoans could grow. Continued stabilization of the substrate allowed crinoids, mollusks, and trilobites to become established. The community spread laterally as bioclastic debris was swept out to the flanks of the community where the peripheral muds of the substrate were continually stabilized. This process ceased as the fine-grained muddy sediment was thrown into suspension under storm conditions, then settled out to smother the community.

The patterns of diversity and the types of fauna in a number of the limestone beds from the Kope Formation bear a strong resemblance to those described by Harris and Martin (1979). It is suggested that the substrate of soft, terrigenous mud that comprised the Early Cincinnatian sea floor was initially colonized by small, thin, flat
brachiopods such as *Onniella* and *Sowerbyella* (Fig. 34). These brachiopods stabilized the substrate and provided a pavement upon which erect trepostome bryozoans, such as *Hallopora*, *Dekayia*, and *Bythopora*, could attach and grow into dense thickets (Fig. 35). Further stabilization of the substrate through the accumulation of skeletal debris allowed the crinoids *Ectenocrinus* and *Heterocrinus* to become established. These, along with the trilobites *Cryptolithus*, *Flexicalymene*, and *Isotelus*; the gastropods *Lophospira* and *Sinuites*; and the bivalves *Modiolopsis* and *Ambonychia* comprised the preservable members of the mature community (Fig. 36).

Many limestone beds in the Kope Formation, however, do not fit this model. For instance, the diversity in some limestone beds does not appear to increase upward and, in fact, several are noted to decrease upward. Another notable difference is the absence of the lowermost horizon of pioneer organisms, such as brachiopods and bryozoans, that was observed in the short-term successional limestones.

One explanation for the differences in these otherwise similar rocks is that they represent accumulations of transported debris which have become sorted and graded as a result of the action of the transporting mechanism. This is a plausible explanation which probably explains the occurrence of some of these beds. However, many of the Kope limestone beds do not fit the criteria for deposition in high-energy environments, which is discussed in the next section, and therefore another explanation is proposed. The short-term successional model proposed by Walker and Alberstadt, and supported by Harris and Martin, presumes a soft initial substrate which is stabilized by the
Figure 34. Pioneer brachiopods colonizing the soft muddy substrate.
Figure 35. Succession by bryozoans on a stabilized substrate paved by brachiopod shells.
Figure 36. Mature community develops on the remains of pioneer and successional organisms.
shells of the pioneer organisms. Subsequent organisms develop the climax community by succeeding the original colonizers on the newly created firm substrate. However, following disruption of the climax community by a high-energy storm event, the bioclastic debris that is spread over the sea floor creates a firm substrate, such that the short-term successional cycle need not be repeated from the pioneer stage (Mahan and Harrison, 1980). Instead, successional and climax organisms may develop directly on the remains of the previous community. Consequently, diversity trends would not necessarily exhibit an upward increase in these rocks, and if the community degraded and died out, the diversity trend would likely decrease upward. It is therefore suggested that most Kope limestone beds represent the in situ accumulation of bioclastic debris from either the short-term succession communities of Walker and Alberstadt or communities representing secondary succession that bypass the pioneer stage, or else they represent the accumulation of redistributed debris from disrupted communities.

The diversity trends that are described in this study are relative. Climax communities are more diverse than pioneer communities, but they can hardly be described as highly diverse faunal assemblages because they seldom exceed 12 to 15 taxa.

Environment of Deposition

Generalized Setting

According to Heckel (1972), modern shallow marine environments are composed of a wide variety of physical conditions and biological
inhabitants that extend generally from the shoreline seaward to the position of the shelf break, which usually occurs at a depth of 600 feet (180 meters). Furthermore, Heckel suggests that recognition of ancient marine subenvironments is accomplished through comparisons with modern sediments of known depositional environments, but, where the distinctions between subenvironments are vague, other factors must be considered. Heckel proposes that ecologic considerations of fossil assemblages may help to distinguish between environmental conditions, such as clear water from turbid water, or soft substrate from hard substrate in the environment. He also notes that environmental inferences may be made from petrographic considerations. For example, calcilutite indicates a quiet water environment that was either protected or one that occurred in relatively deep water, whereas a calcarenite composed of well-sorted fossil fragments indicates a more turbulent environment that is usually associated with shallow water.

Modern shallow marine environments occur most often as shelf seas, whereas broad epicontinental seas were more common in the geologic past (Shaw, 1964). Epicontinental seas are characterized as an expanse of water that extended over the craton for perhaps 1000 to 2000 miles (1600 to 3200 km). Shaw (1964) suggests that depths of 600 feet (180 meters) were probably rare and in reality may not have exceeded 100 feet (30 meters). Bottom slopes would therefore have been less than 1 foot per mile (0.2 meters per kilometer) compared with the slopes of modern shelf seas which range from 2 to 10 feet per mile (0.4 to 2 meters per kilometer).

Although some aspects of the tolerance of organisms to
environmental stress certainly changed through geologic time, the fundamental aspects probably have not. An understanding of the relationships between modern organisms and their environments permits such factors as salinity variations, type of substrate, and turbidity of water to be inferred from the fossil record (Heckel, 1972). Organisms typical of the Edenian fossil assemblage are distributed according to the salinity of the environment as illustrated in Figure 37a. These characteristics, combined with the taxonomic distribution of Kope fauna relative to substrate type and water turbidity (Figs. 37b & 37c), indicate that the Kope sediments were deposited in an open, normal marine, subtidal environment that was below normal wave base in a broad, shallow, epeiric sea.

Deposition of Clay-Sized Clastic Sediment

The rate of deposition of fine-grained clastic sediment in the Appalachian Basin is not easily reduced to a concise value. Kay (1955) noted that an important difference exists between rates of deposition and rates of subsidence. Deposition is controlled at least partially by subsidence as the total thickness of sediments cannot exceed subsidence by any significant amount prior to or during deposition. Other variables include distance from shore, type of shoreline, climate, and water depth. However, in spite of these various influences, accurate rates of deposition may still be calculated. Benedict and Walker (1978) stressed the importance of paleobathymetric analyses combined with determination of cumulative sediment thickness to accurately depict significant, short-term rates in subsidence history.
Figure 37. Modern distribution of major fossilizable invertebrates similar to the Kope fauna (modified from Heckel, 1972).
They used these methods to analyze Middle Ordovician shelf and basin deposits of the Sevier Basin in eastern Tennessee. The results of their observations and calculations yielded a maximum rate of shelf subsidence of 5 cm per 1000 years and maximum basin subsidence rates in excess of 40 cm per 1000 years. Briggs and Roeder (1975) calculated an average subsidence rate for the entire Paleozoic in eastern Tennessee of approximately 2 cm per 1000 years based on subsidence and sedimentation data.

Heezen and Hollister (1971) noted that the rate of accumulation of hemipelagic clay on the continental margin of the eastern United States generally ranges from 5-10 cm per 1000 years. Their observations were based on core studies of rocks from the continental margin that date back through the last 10,000 years.

Based on calculations of present-day rates of erosion, Broecker (1974) calculated that the total accumulation rate of aluminosilicate detritus in the world ocean is 8 cm per 1000 years. He determined that only about 6% of the debris disgorged by rivers reaches the deep sea, so that the remaining 94% must be deposited in small ocean basins, on continental shelves, and elsewhere.

According to calculations produced in this study, a value of approximately 2 cm per 1000 years is suggested for an accumulation rate of the terrigenous clastics in the section. This figure is based on the total thickness of the section combined with some general assumptions concerning the span of time necessary for the deposition of the Kope sediments and the amount of compaction that occurred. The duration of sedimentation is arbitrarily set at six million years, or
approximately one-third of the Cincinnatian Epoch, which itself is assumed to represent approximately one-third of the Ordovician Period. Compaction values are generalized from those of Shelton (1962) which were determined by palinspastically straightening out contorted sandstone dikes that originally extended vertically into shale beds from sandstone laminae. It is assumed that the dikes became contorted solely from compaction of the shale so that a ratio of the present length of the dike to its original length reveals a value for the amount of compaction that the shale has undergone. Shelton arrived at an average value for the original thickness of the shales that was 2.6 times the present thickness.

A sedimentation rate of 2 cm per 1000 years seems to compare well with other observations which also suggest a low rate of sedimentation. For example, the numerous suspension-feeders that are present as fossils in these rocks could not have adapted to an environment that was characterized by rapid deposition of fine-grained sediment out of suspension (Heckel, 1972). Also, if the assumption of a terrigenous source area gradually rising in the southeast is correct, the amount of fine-grained sediment that was available for deposition in the basin would have to be small. Therefore, although a definitive value for the rate of sedimentation in the Kope sea remains in question, it can be demonstrated that the deposition of sediment in this basin was a very slow process that probably continued at a more or less constant rate.

Weiss, Edwards, Norman, and Sharp (1965) noted that local, short-term disturbances in sedimentation on the Cincinnatian sea floor
appeared as changes in texture or as the presence of mud clasts at the base of shale intervals or siltstone beds. In the course of this investigation, a number of massive, silty, shale horizons were observed to grade upward into fine-grained, fissile shale, and these small-scale (10 to 20 cm thick), fining-upward sequences may be interpreted as the diastems noted by Weiss et al. (1965). After periods of non-deposition, the character of sedimentation might have changed because of variations in the amount or type of sediment that was available, or because of variations in the flow regime. The rippled upper surfaces of siltstone and limestone beds may also be interpreted as diastems.

Dunbar and Rodgers (1957) explain the origin of diastems in the following sequence of events. A storm passing over the surface of a shallow sea stirs the surface layer of sediment on the sea floor and sets it moving for a period of time, only to come to rest in a new place. Over a longer span of time the same grains of sediment will be moved so far in one direction by one storm and in a different direction for some distance by the next. It will be shifted about many times before final deposition. The net result is that very little or no deposition takes place most of the time. Fine sediment in suspension may settle in a wide pattern during fair weather, but is lifted and moved periodically during stormy weather.

One of the consequences of slow rates of sedimentation is the prolonged contact of the sediments of the substrate with any benthic organisms that are present. These organisms plow through the substrate ingesting the sediments to extract organic nutrients and
redepositing the "processed" sediment as excrement (Twenhofel, 1942). This process would effectively homogenize the sediment and erase the bedding. The preservation of original depositional structures, such as lamination or cross-bedding in the sediment would imply the lack of an extensive infaunal biota (Byers, 1974). Byers also suggests that normal marine mudrocks should be characterized by a lack of fissility due to the random orientation of particles produced by the bioturbation, whereas a fissile shale should imply abiotic conditions in the original environment of deposition. His viewpoints apparently contrast with the observations noted in this investigation because fissile shales comprise the majority of the rocks in this formation and yet the interbedded, richly fossiliferous limestones indicate an abundant biota that was contemporaneous with the shales.

One explanation for this inconsistency is that the physical conditions necessary for the existence of burrowing and deposit-feeding organisms were lacking. This might indicate spatial or temporal variations in temperature, salinity, light, etc., which might be a difficult proposition to support given a shallow epicontinental sea in a subtropic climate. Another possibility is that the fine-grained clastic sediment was deposited so rapidly that the infaunal biota did not have time to rework it. However this would also suggest that the environment might be too turbid for suspension-feeding organisms such as brachiopods, bryozoans, and crinoids to exist.

A third explanation is suggested in the findings of Blatt, Middleton, and Murray (1972), and proposes that small particles of sediment do not adopt a particular orientation during settling. These
authors suggest that the fissility of shales is a result of reorientation of particles during compaction rather than a function of primary deposition. Meade (1966) suggested that the amount of water held in the clay during the earliest stages of compaction might be the most critical factor determining the degree to which particles might reorient. If enough interstitial water is present, the particles may slip past each other into efficiently packed arrangements. Therefore, sediment with a high fluid content would not readily permit the preservation of burrow texture, so that even if the sediments have been bioturbated, that distinctive texture may be obliterated by the subsequent reorientation of particles. Rhoads (1970) noted that burrowing of surface muds by deposit-feeders increased the water content and reduced compaction in the burrowed zone, such that resuspension of these sediments was readily effected and the margins around burrows became indistinct.

Evidence of bioturbation is noted locally in some siltstone and limestone beds of the Kope Formation. This would suggest that the nature of these sediments encouraged the burrowing activities of an infaunal biota, or at least allowed for the preservation of their burrows. The water content of these sediments would be expected to be less than in the shales, given the coarser grain size and lower clay content of the siltstones and limestones. Additionally, in the limestone beds, the abundance of organic detritus necessary to support deposit-feeders probably far exceeded that which occurred in the shale beds.

Apparently the question of the presence or absence of burrowed
sediments in the beds of the Kope Formation is not one that is easily resolved. Where bioturbation is observed, it may be assumed that the conditions were suitable for the existence of an infaunal biota. However, where bioturbation is not evident, it is important to consider also whether the conditions were suitable for the preservation of the burrows. Therefore, the question of bioturbation is not simply whether it occurred, but also whether it was preserved.

Early compaction of fine-grained sediments is influenced by factors other than the water content of the clays. Meade (1966) indicated that the grain size, clay mineralogy, and geochemistry of the sediments are of particular importance. Depth of burial is also important but probably exerts less influence during the early stages of compaction. Meade observed that fine clays have a higher initial porosity and compact more readily than do silty clays. This phenomenon might account for the early introduction of aqueous solutions into the limestone beds of the Kope Formation. As compaction and dewatering occurred in the supersaturated, muddy sediments, pore fluids which may have had increased concentrations of dissolved salts were expelled (Rieke & Chilingarian, 1974). These solutions were then available to infiltrate the buried limestone beds of the Kope, and probably enhanced the subsequent cementation and recrystallization of the limestones. These solutions were also probably responsible for cementation of the siltstones.

Deposition of Silt-Sized Clastic Sediment

The siltstones and massively bedded shales that occur in such
abundance throughout the Kope Formation probably represent pulses of terrigenous sediment that resulted from onshore storms and floods which occurred in a low-lying source area. The muddy run-off was deposited at the distal end of deltaic systems (King, 1977). As subsequent major storms approached from the offshore direction, the silty sediment was resuspended and, after passage of the storm, a seaward-flowing density current was generated which carried the sediment offshore to be redistributed as a thin but extensive blanket of mud. Such an event would probably involve an erosional current which would explain the flute and groove casts that are often noted on the bottom surfaces of many Kope siltstone beds.

Walker (1979) suggests that where a high-energy wave base extends to a depth below that of the sea floor, waves will affect the bottom, and as deposition from a density current takes place, hummocky cross-stratification develops. Where the depth of the wave base is above that of the sea floor, turbidites with classic Bouma sequences may be produced. The presence of hummocky cross-bedding, such as that noted in the Kope siltstones, without the adjacent, basinward turbidite facies, can be expected if the storm wave base consistently extends to a greater depth than that of the sea floor. Also, the amount of sediment that was available for deposition in the Kope environment was reduced, as was the average grain size of the sediment because the distance from the source area to the site of deposition was so great (600-800 km). These factors probably prevented the development of the turbidite facies as well as reducing the overall size of the bed forms that are characteristic of Kope siltstones. Walker measured hummocky
bed forms in Canada that averaged 75 cm thick and had wavelengths of 1-5 meters. These are in contrast to the bed forms of the Kope siltstones which have an average thickness of less than 10 cm and wavelengths of less than 50 cm.

The variety of bed forms observed in the Kope siltstones and limestones is probably best explained by a depth/velocity/grain-size relationship. These three parameters vary independently to result in a given bed form. If one variable is held constant (e.g. water depth), then flow velocity and sediment grain size may be plotted against each other (Fig. 38). Although flume data are derived from hydraulic measurements in very shallow water, they may be useful when extrapolated for the greater depths of natural marine environments. Figure 39 illustrates the relationship between depth and flow velocity.

As the flow velocity is increased for silt-sized sediment, Southard (1975) noted that the sequence of bed forms that develops at a constant depth ranges from no movement on a flat bed, upward through ripples, and finally to horizontal upper flat bed (Fig. 38). Large-scale features do not develop in sediments in this size range. For medium sand-sized sediments, the sequence of bed forms extends from no movement on a flat bed to ripples, sand waves, dunes, and finally to upper flat bed (Southard, 1975). The relationship between flow velocity and water depth is proportional. As depth increases, velocity must increase to produce a given bed configuration (Fig. 39). Therefore, the style of bed form that is produced on the substrate will vary as the grain size of the sediment, the flow velocity, and the water depth.

Compaction appears to have had little effect on these sediments,
Figure 38. Size-velocity diagram for a flow depth of 20 cm, derived from depth-velocity sections using flume data (Southard, 1975, after Barton & Lin, 1955; Costello, 1974; Guy et al., 1966; Hill et al., 1969; Pratt & Smith, 1972; Pratt, 1973; Southard & Harms, 1972; Stein, 1965; Williams, 1967, 1970; and Willis et al., 1972).
Figure 39. Depth-velocity diagram based on observations of flow velocity and flow depth associated with intertidal estuarine bed configurations (Southard, 1975, after Boothroyd and Hubbard, 1972).
as there is little or no deformation noted in the shape of the burrows or in their cross-sections. The presence of distinct, horizontal burrows in many siltstone beds suggests that the silty sediments were somewhat consolidated prior to their being burrowed.

Storm-Generated Depositional Events

Storms, including hurricanes, have been common occurrences throughout geologic time (Ball, Shinn, & Stockman, 1967). Eight of the storms affecting south Florida in the last fifty years have been of hurricane intensity according to the weather bureau. Assuming a steady-state relationship, 160 such storms would be expected every 1000 years. Although observations and data concerning shallow marine process/response relationships are usually developed from modern, continental shelf environments, it is assumed that similar processes must also have operated within ancient epicontinental seas. Specht and Brenner (1979) proposed a model which characterized bioclastic limestones in the Jurassic Redwater Shale member as responses to a series of marine processes. A number of these same processes may also have operated in the epeiric Kope sea.

Both the Jurassic Redwater sea and the Ordovician Kope sea were characterized by subtropical, fair-weather conditions. Fine-grained, terrigenous detritus carried in suspension from a distant submarine source area or an exposed region of low relief settled out of suspension to the slightly irregular sea floor where various bottom currents redistributed the sediment laterally. The muddy substrate was somewhat below effective wave base, therefore the environment was
one that was characterized by low levels of mechanical energy.

Some organisms thrived in the soft substrate that developed, but many more survived only in accordance with a sequence of events that followed a successional pattern, as suggested earlier in this study. The success or failure of a given community may have depended largely on the specific location where the pioneer organisms settled relative to the prevailing current patterns which provided circulation and nutrient supply. The general setting, therefore, was characterized by many discrete communities in various stages of development that existed more or less side by side (Fig. 40).

Periodic, high-wind, storm conditions produced unusually high-amplitude waves which depressed the effective wave base allowing it to approach or even intersect the substrate. Where wave base intersected the substrate, mud was stripped away and suspended, and bioclasts were entrained or swept across the sea floor into bioclastic shoals. As the storm subsided, the entrained bioclasts settled out first, followed by progressively finer material, all of which resulted in the conventional fining-upward sequence (Fig. 41). However, according to Specht and Brenner (1979), where the effective wave base only approached the substrate, winnowing of mud and in-place settling of bioclasts occurred without erosion or entrainment (Fig. 42). Therefore the specific Dunham rock types that were produced, from wackestone to grainstone, were the result of the proximity of effective wave base to the sea floor.

A return to fair-weather conditions re-established pre-storm bottom currents which began to rework and redistribute the sediments
Figure 40. Isolated benthic communities at various stages of successional development.
Figure 41. Fining-upward sequence of bioclastic debris and mud after passage of storm.
Figure 42. Shallow disruption of substrate following less intense storm activity.
on the newly-formed surface of the substrate into a variety of bed forms (Fig. 43). Where insufficient bioclastic material existed, rippled bed forms developed such that the troughs of the ripples intersected the underlying beds, producing starved or discontinuous ripples. As previously suggested in this study, new communities consisting of organisms which represented secondary stages of succession were able to attach and develop directly on the newly formed, firm substrate of fragmented bioclastic debris (Fig. 44). Therefore, the dependence of communities on pioneer species to colonize unstable substrates was effectively diminished.

Specht and Brenner (1979) suggest that an idealized sequence from undisturbed muds to well-winnowed grainstone fabrics would be best characterized by fining-upward grading of bioclastic grains, a general upward trend of increasing grain support, and an upward reduction in mud matrix (Fig. 45). The predominant fabric control in this model was the relationship between the position of the substrate and its proximity to effective wave base. Near the margins of the storm path, effective wave base probably did not extend to the depth that it might have near the center of the storm path. Consequently, an interwoven complex of bioclastic fabrics was produced, and these in turn overlapped the patterns developed as subsequent storms approached the region along different paths and at different times. Grainstone fabrics (Fig. 46) resulted where water turbulence either entrained bioclasts or caused thorough flushing of mud from near-surface sediments on the sea floor (Specht & Brenner, 1979). Packstone and wackestone fabrics (Figs. 47 & 48) formed at greater
Figure 43. Bioclastic storm debris reworked into ripples on the newly-formed substrate.
Figure 44. Successional organisms form communities on stabilized substrate resulting from the storm debris from previous communities.
LIMESTONE SLAB
CUT NORMAL TO BEDDING

Figure 45. Sequence of bioclastic fabrics.
Figure 46. Grainstone fabric formed near the zone of maximum water turbulence.
Figure 47. Packstone fabric of *in situ* bryozoans located at a distance from the zone of maximum water turbulence.
Figure 48. Packstone fabric which formed at some distance from the zone of maximum water turbulence. Note mud shelters.
distances from the zone of maximum water turbulence because the less-completely winnowed sediments were produced by the influence of increased water depth or diminished storm intensities.

The intermittent pulses of silt-sized sediment described earlier, that originated from nearshore deltaic deposits, were another process that enhanced the variable nature of the depositional environment. These rapidly deposited sheets of silty mud were probably responsible for smothering a number of living communities in the Kope environment. This is interpreted from limestone beds of in situ organisms that are overlain by a silty shale interval.
SUMMARY AND CONCLUSIONS

The model proposed in this study emphasizes variations in lithologies, or microfacies, that exist vertically in a composite section of the Lower Cincinnatian (Edenian) Kope Formation located in northern Kentucky. The development of the discontinuous interbedded shales, siltstones, and limestones in the Kope environment cannot be adequately characterized by one simple model. The textural and compositional features of these rocks are so variable, horizontally as well as vertically, and even between individual beds of the same lithology, that no single mode of deposition will explain all features of all of the rock types. Therefore, a model is proposed featuring multiple modes of deposition that may function together or independently, temporally as well as spatially (Fig. 49).

Typical sedimentation probably occurred at a very slow but steady rate as fine-grained terrigenous material was shed from a source in the rising Taconic highland to the southeast. The initial erosion was probably submarine as the sea floor began rising and approached wave base and the surf zone. As uplifting continued, subaerial erosion became dominant. Bottom currents redistributed the slowly accumulating muds over the Kope sea floor.

Rapidly deposited pulses of silty mud probably account for the siltstones and silty shales. These are interpreted as short-term events, possibly resulting when onshore storms in the source area to the southeast flooded sediment into the sea and storm-wave and tidal bottom currents transported it out into the basin in broad sheets.
III PIONEER ORGANISMS COLONIZE SOFT, UNSTABLE SUBSTRATES

II OCCASIONAL PULSES OF SILT-SIZE SEDIMENTS FROM NEAR SHORE

I CLAY-SIZE SEDIMENT SETTLES OUT OF SUSPENSION

VII WAVE BASE APPROACHES SEA FLOOR AND SPREADS A BLANKET OF BIOCLASTIC SEDIMENT

VI WAVE BASE INTERSECTS SEA FLOOR AND A GRADED SEQUENCE FORMS

V REDISTRIBUTION AND REWORKING BY BOTTOM CURRENTS

IV SUCCESSIONAL ORGANISMS BECOME ESTABLISHED

V MATURE COMMUNITY DEVELOPS ON REMAINS OF PREVIOUS ORGANISMS

PERIODIC HIGH ENERGY STORM EVENTS

Figure 49. Integrated model featuring multiple modes of deposition.
Many limestone beds contain a varying faunal composition such that small brachiopods occur on the bottom surface of individual beds and are succeeded upward through the unit by bryozoans, crinoids, gastropods, and trilobites, all in a matrix of carbonate mud. These relationships suggest an undisturbed, \textit{in situ} community that evolved through short-term community succession. Apparently, thin, flat brachiopods were able to adapt to the soft, muddy substrate of the Kope environment, so that after they died their shells paved the substrate and created a more stable surface. This provided a suitable pavement upon which small, erect bryozoans could attach and grow, developing into dense thickets. As stabilization continued, crinoids and bivalves became established, along with various deposit-feeders, such as trilobites and gastropods. Another type of limestone reveals a modification of this pattern such that all species of fossil organisms are dispersed randomly throughout the matrix and notably fewer brachiopods are present. The reduction in the number of pioneer brachiopods, combined with the random occurrence of other fossils, suggests evolution other than through short-term community succession. This type of limestone is interpreted as an \textit{in situ} community that developed on a stable substrate, perhaps the disrupted remains of a previous community. It did not evolve by succession from colonizing pioneer organisms, but instead by reoccupation of the substrate by organisms from later stages in the successional sequence. Both types of communities were probably terminated by degradation due to age or by burial under rapidly deposited sediments from a recent storm.

Although community succession, or the general development of
communities of organisms, are processes not usually considered as modes of sedimentation, for the purposes of this study they represent a source of various sizes of sediment, and it is this influence that is considered a depositional feature.

A third type of limestone is characterized by finely fragmented, well-winnowed bioclasts that occur in thinly bedded grainstones. Community patterns are notably lacking, or at least obscured, in these beds. The bioclastic grains are not extensively abraded, so the mechanical processes of long-distance transport are discounted. More probably, these grains resulted from the biological breakdown of the hard parts of dead individuals by predators and boring organisms. This organic detritus was subsequently swept from atop the living community to accumulate along the flanks, ultimately to be redistributed by bottom currents into thin shoals and lenses.

It is suggested that the grainstone, packstone, and wackestone fabrics noted in the bioclastic limestones resulted where turbulent, high wind conditions produced greater than normal magnitude waves which lowered effective wave base to a depth where it approached or intersected the sediment surface. Temporary entrainment of bioclasts and suspension of mud occurred where wave base intersected the sediment surface and formed a graded sequence in the sediments. However, where the sea floor was still below effective wave base, winnowing of mud occurred without erosion or entrainment of grains. The degree of winnowing that occurred varied with the depth of the water and the intensity of the storm at that particular location. The textural features noted in these rocks range from large, unabraded,
unwinnowed, skeletal fragments supported by a matrix of mud, to finely
fragmented, unabraded, well-winnowed skeletal debris that is free of
mud and grain-supported. Mud-sheltered areas and intact, fragile
fossils are common in some limestones and suggest incomplete winnowing
of these sediments.

Application of the model in Figure 49 is demonstrated by relating
the various modes of deposition to each of the individual beds com­
prising the Kope Formation. Correlation between each bed and its mode
of deposition is detailed in the Appendix. Furthermore, the percentage
of the total beds resulting from each depositional mode was calculated
for each measured section (Table 3). Comparison of the values for
each section according to depositional mode revealed some differences
in the environments of deposition for each section. The most obvious
difference between the sections is revealed where a greater number of
beds of in situ fossil organisms are present in the stratigraphically
lower RR Section, whereas reworked beds of storm debris are more
abundant in the higher BRC Section. This suggests that the early Kope
environment was one of relatively low energy, well below normal wave
base, where communities of organisms flourished and survived all but
the most intense storms. As the depositional basin began to fill with
sediment and the sea began to recede, a shoaling environment developed
where more frequent high-energy storms repeatedly disrupted the sub­
strate and destroyed the communities of organisms, thus producing beds
of redistributed storm debris.

Because of the difference between the stratigraphic intervals of
the two sections it is assumed that the changes in depositional style
<table>
<thead>
<tr>
<th>MODES OF DEPOSITION FROM INTEGRATED MODEL</th>
<th>PERCENT MICROFACIES FROM KOPE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RR SECTION</td>
</tr>
<tr>
<td>I  SETTLING OF CLAY-SIZED SEDIMENT OUT OF SUSPENSION</td>
<td>ALL SHALE LITHOLOGIES</td>
</tr>
<tr>
<td>II PERIODIC INFLUX OF SILT-SIZED SEDIMENT</td>
<td>6.4</td>
</tr>
<tr>
<td>III COLONIZATION OF SUBSTRATE BY PIONEER ORGANISMS</td>
<td>1.4</td>
</tr>
<tr>
<td>IV SUCCESSION BY ORGANISMS LATER IN THE COMMUNITY SEQUENCE</td>
<td>9.2</td>
</tr>
<tr>
<td>V DEVELOPMENT OF MATURE COMMUNITY</td>
<td>36.2</td>
</tr>
<tr>
<td>VI STORM EVENT WHERE WAVE BASE INTERSECTS THE SUBSTRATE</td>
<td>20.6</td>
</tr>
<tr>
<td>VII STORM EVENT WHERE WAVE BASE APPROACHES THE SUBSTRATE</td>
<td>17.0</td>
</tr>
<tr>
<td>VIII REWORKING AND REDISTRIBUTION OF SEDIMENTS BY BOTTOM CURRENTS</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Table 3. Percent microfacies from composite section of Kope Formation according to mode of deposition.
between the sections are related to environmental changes through geologic time. It is important to emphasize that these percentages are valid only for the present study and may vary in other locations as a result of differences in sampling technique or local variations in the original depositional environment.

The relationships that exist among these various modes of sedimentation result in a complex sequence of interfingering, overlapping strata which have variable lithologies, fabrics, and textures, all of which characterize the Kope Formation. It is for this reason that a multifaceted depositional model is suggested.
APPENDIX

DETAILED STRATIGRAPHIC COLUMN OF THE KOPE FORMATION FROM THE RIVER ROAD (RR) AND BRIDGE ROAD CUT (BRC) SECTIONS, NEAR FORT THOMAS, KENTUCKY.

EXPLANATION

VERTICAL SCALE

1" = 1'

DEPOSITIONAL EVENT ACCORDING TO INTEGRATED MODEL (FIG. 49),

DESCRIPTION OF SHALE LITHOLOGIES AND FAUNAL CONTENT.

LITHOLOGIC LOG

SAMPLE NO., AND DESCRIPTION OF LIMESTONE AND SILTSTONE LITHOLOGIES

SHALE
LIMESTONE
SILTSTONE
BRACHIOPODS
BRYOZOA
CRINOID

127
NUMEROUS LENSES OF FOSSIL HASH.
RR008A

25 M SW OF RR008

GRAY FISSILE SHALE WITH SCATTERED BROKEN FOSSILS

GRAY FISSILE SHALE

GRAY FISSILE SHALE

MASSIVE SILTY SHALE WITH SCATTERED FOSSILS GRADING DOWNWARD TO FISSILE SHALE.

ALTITUDE 505'
GRAY FISSILE SHALE GRADING UPWARD TO MASSIVE SILTY SHALE SCATTERED FOSSILS

GRAY FISSILE SHALE, SCATTERED WHOLE FOSSILS

GRAY FISSILE SHALE WITH LENSES OF FOSSIL HASH

RR008 5 TO 8 CM IRREGULAR LIMESTONE WITH SHALE PARTING IN THE MIDDLE

RR007 3 CM SILTSTONE

RR006 2 TO 5 CM SILTSTONE PINCHES AND SWELLS

RR005 3 CM LIMESTONE

RR004 10 TO 15 CM IRREGULAR LIMESTONE

RR003 2 CM SILTSTONE

RR002 2 TO 5 CM SILTSTONE

RR001 2 TO 5 CM SILTSTONE
GRADING DOWNWARD TO MASSIVE SILTY SHALE BED.

THIN GRAY FISSILE SHALE BEDS.

GRAY MASSIVE SILTY SHALE HORIZON IN FISSILE SHALE WITH LENSES OF FOSSILS AND FOSSIL HASH.

GRAY FISSILE SHALE GRADING DOWNWARD TO MASSIVE, SILTY SHALE, SCATTERED FOSSILS.

GRAY FISSILE SHALE, SCATTERED FOSSILS.

GRAY FISSILE SHALE WITH NUMEROUS LENSES OF CEMENTED FOSSILS AND SCATTERED FOSSILS AND FOSSIL HASH.

GRAY, MASSIVE, SILTY SHALE.

GRAY, FISSILE SHALE WITH SCATTERED BRACHIOPODS AND BRYOZOA.
GRAY, FISSILE SHALE.

GRAY, FISSILE SHALE.

GRAY, FISSILE SHALE.
GRAY, FISSILE TO MASSIVE, SILTY SHALE WITH NUMEROUS LENSES OF CEMENTED FOSSILS IN A MATRIX. SOME SILTSTONES, SCATTERED FOSSILS ALSO.

GRAY, FISSILE SHALE GRADING DOWNWARD TO MASSIVE, SILTY SHALE.

GRAY, FISSILE SHALE WITH SCATTERED BRACHIOPODS AND BRYOZOA.

GRAY, FISSILE SHALE.
FISSILE SHALE PARTING.
GRAY, FISSILE SHALE WITH SCATTERED FOSSILS.

GRAY, FISSILE SHALE WITH NUMEROUS LENSES OF FOSSILS.
GRAY, FISSILE SHALE INTERBEDS.

ALTITUDE 545'

RR102

3 TO 5 CM SILTSTONE.

GRAY, FISSILE SHALE WITH HORIZONS OF MASSIVE SILTY SHALE, SCATTERED BRACHIOPODS AND BRYOZOA.

COVERED INTERVAL

GRAY, FISSILE SHALE WITH HORIZONS OF MASSIVE SILTY SHALE, SCATTERED BRACHIOPODS, BRYOZOA AND CRINOID.

COVERED

GRAY, FISSILE SHALE WITH HORIZONS OF MASSIVE SILTY SHALE, NUMEROUS LENSES OF CEMENTED FOSSILS IN A MATRIX AND SILTSTONES, SCATTERED BRACHIOPODS AND BRYOZOA.

RR104

5 TO 8 CM IRREGULAR LIMESTONE

RR103

5 TO 8 CM SILTSTONE, PINCHES AND SWELLS, FOSSIL HASH ON BOTTOM.

RR39

3 CM SILTSTONE, CRINOID HASH ON BOTTOM.

RR 38

8 CM SILTSTONE.
FISSILE SHALE.
GRAY, FISSILE SHALE WITH HORIZONS OF SILTY SHALE.

GRAY SHALE PARTING.
GRAY, FISSILE SHALE WITH SCATTERED BRACHIOPODS AND BRYOZOA.
GRAY, FISSILE SHALE.
GRAY, FISSILE SHALE.
GRAY, FISSILE SHALE.
GRAY, FISSILE SHALE WITH SOME BRACHIOPODS AND BRYOZOA.
GRAY, MASSIVE, SILTY SHALE WITH HORIZONS OF FISSILE SHALE.
SHALE INTERBEDS.
GRAY FISSILE SHALE.

CRESTS N 40 W TO N 60 W.

RR121
3 TO 8 CM LIMESTONE.
V
RIPPLED.
RR120
3 TO 5 CM IRREGULAR LIMESTONE.
VIII
RR119
8 TO 15 CM LIMESTONE, PINCHES AND SWELLS.
VI
RR118
3 CM LIMESTONE.
V
RR117
5 TO 10 CM LIMESTONE, RIPPLED.
VII
RR116
5 TO 8 CM SILTSTONE.
II
BURROWS ON UPPER SURFACE.
RR115
8 TO 10 CM SILTSTONE.
V
RR114
3 TO 8 CM SILTSTONE.
RR113
3 TO 8 CM SILTSTONE.
RR112
15 CM SILTSTONE.
RR111
II
RR110
2 TO 5 CM SILTSTONE.
RR109
MISSING
V
RR108
5 TO 15 CM LIMESTONE, PINCHES AND SWELLS.
VI
RR107
5 TO 8 CM SILTSTONE.
RR106
5 CM LIMESTONE LINEAR CAST (?).
VIII
RR105
5 TO 15 CM RIPPLED LIMESTONE.
SCATTERED BRACHIOPODS AND BRYOZOA.

GRAY, FISSILE SHALE WITH LENSES OF Siltstone AND FOSSIL HASH. SCATTERED FOSSILS ALSO NOTED.

FISSILE SHALE WITH LENSES OF Siltstone AND FOSSIL HASH. SOME SCATTERED BRACHIOPODS AND BRYOZOA.

GRAY FISSILE SHALE.

GRAY, FISSILE SHALE, WITH LENSES OF Siltstone AND FOSSIL HASH.

GRAY, FISSILE SHALE.

20 TO 25 CM LIMESTONE WITH Siltstone LAMINA ON TOP, FOSSIL HASH ON Siltstone.

3 TO 8 CM LIMESTONE.
RIPPLES STRIKE N 8 W.
GRAY, FISSILE SHALE.
GRAY, FISSILE SHALE.
GRAY, FISSILE TO MASSIVE SHALE.
GRAY, FISSILE TO MASSIVE, SILTY SHALE WITH SEVERAL LENSES OF SILTSTONE AND FOSSIL HASH.
FISSILE SHALE INTERBEDS.
BROWN, SILTY SHALE.
GRAY, FISSILE SHALE.
GRAY, FISSILE SHALE WITH LENSES OF SILTSTONE AND FOSSIL HASH.
GRAY, FISSILE TO MASSIVE, SILTY SHALE.
THIN-BEDDED FISSILE SHALE LAYERS BETWEEN SILTSTONES.

ALTITUDE 590'

FISSILE SHALE.

MASSIVE SILTY SHALE TO FISSILE SHALE WITH SCATTERED BRACHIOPODS AND BRYOZOANS.

FISSILE SHALE.

GRAY FISSILE SHALE.

GRAY FISSILE SHALE WITH NUMEROUS LENSES OF FOSSIL HASH.

GRAY FISSILE SHALE WITH NUMEROUS LENSES OF FOSSIL HASH.

GRAY FISSILE SHALE WITH NUMEROUS LENSES OF FOSSIL HASH.

GRAY FISSILE SHALE WITH NUMEROUS LENSES OF FOSSIL HASH.

COVERED INTERVAL

RR203
RR202
3 CM SILTSTONE.
FESTOONS.
RR201
5 CM SILTSTONE.
FESTOONS.
RR150
3 TO 5 CM LIMESTONE.
RR149
3 CM SILTSTONE.

RR148
3 TO 5 CM LIMESTONE.
RR147
3 TO 5 CM SILTSTONE.
RR146
3 TO 5 CM LIMESTONE.
RR145 5 CM

RR144
5 CM SILTSTONE
MASSIVE SILTY SHALE TO FISSILE SHALE WITH LENSES OF CEMENTED FOSSILS.

FISSILE SHALE WITH LENSES OF FOSSIL HASH.

RR211A 2ND SAMPLE. LENS OF FOSSIL HASH AT BASE OF SILTSTONE.

FISSILE SHALE WITH LENSES OF FOSSIL HASH.

LENS OF IN SITU BRYOZOANS, MOSTLY WHOLE OR BROKEN IN PLACE.

SILTY SHALE.

SILTY SHALE TO FISSILE SHALE WITH LENSES OF FOSSIL HASH.

FISSILE SHALE WITH LENSES OF SILTSTONE AND FOSSIL HASH.

RR204 MUDSTONE NODULES.

RR216 1 TO 8 CM LIMESTONE, RIPPLED.

RR215 1 TO 3 CM LIMESTONE, PINCHES AND SWELLS.

RR214 2 TO 8 CM LIMESTONE, PINCHES AND SWELLS.

RR213 3 TO 5 CM LIMESTONE, RIPPLED.

RR212 3 TO 5 CM SILTSTONE, CROSS-BEDDED.

RR211 1 TO 3 CM LIMESTONE WITH LARGE BRYOZOANS.

RR209, RR210 2 TO 3 CM LIMESTONE LENS, FOSSIL HASH ON BOTTOM.

RR208 5 TO 10 CM LIMESTONE WITH WHOLE ONNIELLA, SOWERBYELLA AND BRYOZOANS.

RR207 1 TO 3 CM MUDSTONE, LARGE BRYOZOANS.

RR206 1 CM THIN-BEDDED FOSSIL HASH.

RR205 15 TO 25 CM LIMESTONE, MUDCLASTS IN LOWER HALF.
FISSILE SHALE WITH LENSES OF SILTSTONE, SCATTERED BRACHIOPODS AND CRINOIDs, MASSIVE SHALE.

GRAY, FISSILE SHALE WITH LENSES OF SILTSTONE AND FOSSIL HASH.

COVERED AND WEATHERED INTERVAL

FR220
3 TO 5 CM LIMESTONE.

RR219
3 CM LIMESTONE WITH SILTSTONE ON TOP, 20 M LONG, RIGHT TO LEFT.

RR218
1 TO 3 CM SILTSTONE LENS.

RR217
3 CM SILTSTONE, ORANGE-STAINED.
ALTITUDE 615'

GRAY FISSILE SHALE WITH SCATTERED BRACHIOPODS AND BRYOZOANS.

FISSILE SHALE INTERBEDS

GRAY FISSILE SHALE WITH LENSES OF FOSSIL HASH. MORE NUMEROUS NEAR RR251.

RIPPLE CRESTS STRIKE N 60 W.

GRAY FISSILE TO MASSIVE SILTY SHALE WITH LENSES OF FOSSIL HASH, SCATTERED BRACHIOPODS AND BRYOZOANS.

FISSILE SHALE PARTING.

FISSILE SHALE.

RR254
RR253
RR252
RR251
3 TO 10 CM LIMESTONES.

RR250
3 TO 8 CM LIMESTONE, RIPPLED.

RR249
5 TO 8 CM LIMESTONE, NUMEROUS BRYOZOANS.
VARIABLE, BROWN TO GRAY SHALE WITH FOSSIL LENSES AND SCATTERED FOSSILS

GRAY, FISSILE SHALE WITH SCATTERED BRYOZOA, BRACHIOPOD AND TRILOBITES

GRAY SHALE WITH BRYOZOA

ALTITUDE 605'

BRACHIOPOD FRAGMENTS

BRC 5
2 TO 5 CM SILTSTONE

BRC 4
15 CM LIMESTONE CONTINUOUS ACROSS SECTION

BRC 3
3 TO 9 CM SILTSTONE, RIPPLED

BRC 2
3 CM LIMESTONE WITH SHELL FRAGMENTS

BRC 1
7 CM LIMESTONE, CONTINUOUS FOR 100 YDS
VARIABLE, GRAY TO BROWN FISSILE SHALE WITH NUMEROUS LENSES OF SILTSTONE.

GRAY SHALE, FISSILE TO MASSIVE UPWARD.

GRAY, FISSILE SHALE WITH FOSSIL LENS.

GRAY, FISSILE SHALE WITH SEVERAL LENSES OF FOSSILS.

BROWN TO GRAY, FISSILE SHALE, BECOMES SILTIER UPWARD.

BRC 14
8 CM SILTSTONE.
BRC 13
5 CM SILTSTONE.

BRC 12
5 CM LIMESTONE, LATERALLY CONTINUOUS.

BRC 11
2 LIMESTONE BEDS, 3 TO 5 CM THICK.

BRC 10
7 TO 12 CM LIMESTONE, FOSSIL HASH ON TOP.

BRC 9
3 TO 5 CM LIMESTONE.

BRC 8
3 TO 7 CM LIMESTONE VARIABLE THICKNESS.

BRC 7
5 TO 7 CM LIMESTONE.

BRC 6
3 CM LIMESTONE.
GRAY TO BROWN, FISSILE TO SILTY SHALE WITH LENSES OF FOSSILS, SOME SCATTERED FOSSILS.

GRAY TO BROWN, FISSILE SHALE, BECOMES MORE SILTY UPWARD

BRC 16
2 CM LIMESTONE, ABUNDANT FOSSIL FRAGMENTS.

BRC 15
8 TO 15 CM LIMESTONE, ABUNDANT FOSSIL FRAGMENTS.
Silty to fissile, gray shale with numerous siltstone lenses.

Fissile, gray shale with lenses of fossil hash.

Gray to brown, fissile shale with numerous lenses of fossil hash.

Gray, fissile shale with several lenses of fossil hash.

Thin beds of gray, fissile shale.

BRC 22
10 to 15 cm rippled limestone.

BRC 21
15 to 20 cm limestone, some bedding.

BRC 20
5 to 8 cm, irregular limestone, overlying siltstone bed.

BRC 19
5 to 8 cm limestone.

BRC 18
3 to 5 cm limestone.

BRC 17
2 cm limestone with siltstone lamination.
GRAY, FISSILE SHALE WITH LENSES OF FOSSILS.

BROWN, FISSILE SHALE.

BROWN, FISSILE SHALE. BROWN SHALE PARTINGS.

BROWN SHALE.

GRAY, FISSILE SHALE WITH SEVERAL LENSES OF FOSSIL DEBRIS.

BROWN, SILTY SHALE.

GRAY, FISSILE SHALE, BECOMES SILTIER TOWARD THE TOP.

NUMEROUS LENSES OF SILTSTONE AND FOSSILE HASH.

BROWN, SILTY SHALE WITH NUMEROUS LENSES OF FOSSIL HASH.

BRC 28
5 CM LIMESTONE, REGULAR, EVEN BEDDED.

BRC 27
BRC 26
BRC 25
THREE LIMESTONE BEDS, 2 CM THICK.

BRC 24
8 CM LIMESTONE WITH THIN (<2CM) LAYER OF VARIOUS FOSSILS.

BRC 23
5 TO 20 CM, RIPPLED, LIMESTONE.
GRAY, FISSILE SHALE WITH LENSES OF FOSSILS AND FOSSIL HASH.

BROWN, SILTY SHALE.

BROWN, SILTY SHALE WITH SEVERAL LENSES OF FOSSILS.

SHALE PARTING.

GRAY, FISSILE SHALE, WITH NUMEROUS LENSES OF SILTSTONE AND FOSSIL HASH.

GRAY, FISSILE SHALE WITH SILTSTONE LENSES.

BRC 34
2 TO 5 CM LIMESTONE.

BRC 33
2 CM LIMESTONE, PINCHES AND SWELLS.

BRC 32
5 TO 12 CM LIMESTONE

BRC 31
5 TO 8 CM LIMESTONE

BRC 30
2 CM, GRAY, FLATTENED, SILTSTONE NODULES.

BRC 29
2 CM SILTSTONE.

TOP OF SECOND BENCH.
BROWN, FISSILE SHALE, WITH THIN (< 2CM) LIMESTONE LENS.

GRAY, FISSILE SHALE, WITH LENS OF COARSE BRYOZOAN DEBRIS.

GRAY, FISSILE SHALE, WITH NUMEROUS LENSES OF FOSSILS AND FOSSIL DEBRIS.

BROWN, FISSILE SHALE.

BROWN, SILTY SHALE.

GRAY, FISSILE SHALE, WITH LENSES OF FOSSIL HASH.

BROWN, MASSIVE SHALE, WITH LENSES OF FOSSILS.

BRC 41
5 CM LIMESTONE, COARESNS UPWARD.

BRC 40
7 TO 10 CM, RIPPLED LIMESTONE WITH COARSE BRYOZOAN DEBRIS ON BOTTOM.

BRC 39
SILTSTONE NODULES.

BRC 38
3 CM, IRREGULAR LIMESTONE.

BRC 37
5 TO 15 CM IRREGULAR LIMESTONE, BRYOZOAN DEBRIS ON BOTTOM.

BRC 36
2 CM LIMESTONE, BRYOZOAN DEBRIS.

BRC 35
8 TO 25 CM LIMESTONE, VARIABLE THICKNESS.
BROWN, SILTY SHALE, WITH FOSSIL LENSES.

GRAY, FISSILE SHALE.

BROWN, FISSILE SHALE.

BROWN, SILTY SHALE, WITH SEVERAL LENSES OF SILTSTONE.

BROWN, SILTY SHALE.

GRAY, FISSILE, SHALE, WITH THIN LENSES OF SILTSTONE AND FOSSILS.

GRAY, FISSILE, SHALE, WITH NUMEROUS LENSES OF FOSSIL SHALE.

BROWN, SILTY SHALE, WITH FOSSIL LENSES.

BROWN, SILTY SHALE WITH THIN SILTSTONE BED.

GRAY, FISSILE SHALE.

BROWN, SILTY SHALE, WITH FOSSIL LENS.

BROWN, FISSILE SHALE PARTING, SHALE PARTING.

BRC 63
3 CM LIMESTONE.
TOP OF THIRD BENCH

BRC 62
3 TO 5 CM LIMESTONE, WITH NUMEROUS BRACHIOPODS.

BRC 61
5 TO 8 CM LIMESTONE, BRYOZOA ON BOTTOM SURFACE.

BRC 60
2 CM LIMESTONE, PINCHES OUT TO LOOSE BRYOZOA IN SHALE.

BRC 59
2 CM LIMESTONE.

BRC 58
2 CM LIMESTONE.

BRC 57
2 CM LIMESTONE.

BRC 56
10 TO 15 CM LIMESTONE, FOSSILS ON TOP.

BRC 55
7 TO 12 CM LIMESTONE.

BRC 54
10 TO 15 CM LIMESTONE WITH IRREGULAR UPPER SURFACE.
BROWN, SILTY SHALE, WITH SEVERAL SILTSTONES, SCATTERED FOSSILS.

BROWN, SILTY SHALE, WITH SEVERAL THIN (<2 CM) LIMESTONE BEDS, NUMEROUS LENSES OF FOSSIL DEBRIS AND WHOLE FOSSILS.

THIN (<2 CM) SILTSTONE.

BROWN, SILTY SHALE WITH THIN (<2 CM) LIMESTONE BED GRADING INTO LOOSE FOSSILS.

ALTITUDE 695'

BROWN, SILTY SHALE, WITH BEDS OF FOSSIL DEBRIS.
BROWN, SILTY SHALE, WITH SEVERAL LENSES OF FOSSIL HASH.
BROWN, SILTY SHALE, WITH BEDS OF FOSSIL HASH.
GRAY, FISSILE SHALE.

BRC 67
25 CM LIMESTONE, CROSS-BEDDED NEAR BOTTOM, WITH SEVERAL BRYOZOA BEDS.

BRC 66
3 TO 5 CM RIPPLED LIMESTONE.

BRC 65
3 CM LIMESTONE.

BRC 64
2 CM LIMESTONE, WITH VERY COARSE BRACHIOPOD DEBRIS.

BRC 69
3 CM LIMESTONE, VARIABLE THICKNESS.

BRC 68
8 CM SILTSTONE, SEPARATES ALONG BEDDING PLANES.
GRAY, FISSILE SHALE.

BROWN, SILTY SHALE, WITH SEVERAL LENSES OF COARSE BRYOZOA DEBRIS.

SHALE PARTINGS BETWEEN LIMESTONE BEDS.

BROWN, FISSILE SHALE, WITH SCATTERED FOSSILS AND THIN (< 2 CM) LIMESTONE LENSES.

SHALE PARTING.

BROWN, SILTY SHALE.

GRAY, FISSILE SHALE, WITH SILTY BED AND SCATTERED FOSSILS.

BRC 79
5 CM SILTSTONE.

BRC 78

BRC 77

BRC 76

BRC 75

BRC 74
FIVE, 5 TO 8 CM LIMESTONE BEDS
BRC 73
5 CM SILTSTONE SCOUR FILLING, N 8 E.

BRC 72
2 CM LIMESTONE.

BRC 71
5 CM SILTSTONE, WITH BRACHIOPOD DEBRIS ON BOTTOM.

BRC 70
5 CM LIMESTONE
ALTITUDE 705'

GRAY, FISSILE SHALE.

GRAY, FISSILE SHALE, WITH SCATTERED FOSSILS AND A THIN (<2 CM) LIMESTONE LENS.

GRAY, FISSILE SHALE, WITH SCATTERED FOSSILS AND THIN (<2 CM) SILTSTONE BEDS.

BRC 84
10 TO 20 CM LIMESTONE

BRC 83
3 CM SILTSTONE NODULE.

BRC 82
5 CM SILTSTONE.

BRC 81
3 TO 5 CM RIPPLED SILTSTONE.

BRC 80
3 TO 5 CM RIPPLED SILTSTONE, WITH HUMMOCKY CROSS-BEDDING.
BIBLIOGRAPHY


Richards, R. Autecology of Richmondian brachiopods (Late Ordovician

Rieke, H.H. III., & Chilingarian, G.V. Compaction of argillaceous

Rodgers, J. The Taconic orogeny. *American Association of Petroleum

Schäfer, W. [Ecology and paleoecology of marine environments.]. Edin­
burgh: Oliver and Boyd, 1972.

Scotford, D.M. The Cincinnati Arch: mineralogic - statistical
evidence of a post-Ordovician origin. *American Association of

Scotford, D.M. Petrology of the Cincinnatian Series shales and envi­
1965, 76, 193-222.


Shelton, J.W. Shale compaction in a section of Cretaceous Dakota
Sandstone, northwestern North Dakota. *Journal of Sedimentary

Smosna, R., & Warshauer, S. Fossil diversity in thin section. *Journal

Southard, J.B. Bed configurations. In J.C. Harms, J.B. Southard,
D.R. Spearing, and R.G. Walker (Eds.), Depositional environments
as interpreted from primary sedimentary structures and stratifica­
tion sequences (Short Course No. 2). Tulsa, Oklahoma: Society of

Specht, R.W., & Brenner, R.L. Storm-wave genesis of bioclastic car­onates in Upper Jurassic epicontinental mudstones, east-central

Sweet, W.C., & Bergström, S.M. The American Upper Ordovician Standard:
XIII. A revised time-stratigraphic classification of North American
Upper-Middle and Upper Ordovician rocks. *Geological Society of

Twenhofel, W.H. The rate of deposition of sediments: a major factor
connected with alteration of sediments after deposition. *Journal

models (Reprint Series 1). Toronto: Geological Association of


