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A MODEL FOR CYCLIC DEPOSITION IN THE CINCINNATIAN SERIES OF SOUTHWESTERN OHIO, NORTHERN KENTUCKY, AND SOUTHEASTERN INDIANA

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A MODEL FOR CYCLIC DEPOSITION IN THE CINCINNATIAN SERIES OF SOUTHWESTERN OHIO, NORTHERN KENTUCKY, AND SOUTHEASTERN INDIANA

A dissertation submitted to the

Division of Graduate Education and Research
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in the Department of Geology
of the College of Arts and Sciences

1982

by

Rick C. Tobin

M.S., University of Cincinnati, 1980

B.S., Madison College, 1977

UNIVERSITY OF CINCINNATI

November 3 **19** 82

I hereby recommend that the thesis prepared under my supervision by Rick C. Tobin

entitled A MODEL FOR CYCLIC DEPOSITION IN THE CINCINNATIAN SERIES OF SOUTHWESTERN OHIO, NORTHERN KENTUCKY, AND SOUTHEASTERN INDIANA

be accepted as fulfilling this part of the requirements for the degree of DOCTOR OF PHILOSOPHY

Approved by:

Wayne A. Pryor

[signature]

David L. Meyer

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (concluded)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (concluded)

LIST OF APPENDICES

ABSTRACT

The Upper Ordovician Cincinnatian Series is an undeformed 800-foot-thick (244 m) sequence of interbedded carbonates and shales that are exposed in southern Indiana, southwestern Ohio, and northern Kentucky. Although some carbonates are restricted to individual facies (e.g., dolomites), eight varieties of carbonate rocks are repeatedly encountered throughout the Cincinnatian Series, including packstones, wackestones, micstones, siltstones, poorly washed grainstones, coarse grainstones, fine grainstones, and calcisiltites. Cincinnatian shales are olive gray in color, unfossiliferous, unlaminated, and dolomitic. Most shales are unburrowed and occur as thin, graded "packages."

Cincinnatian sediments were deposited on the inner part of a gently sloping, storm-dominated, shallow-marine carbonate ramp, in subenvironments ranging from the offshore zone to the supratidal zone. Sedimentation on this ramp was discontinuous. Periods of quiet-water, *in situ* accumulation of carbonate sediments (represented by packstones and wackestones) were frequently interrupted by storm events (represented by erosional surfaces, shales, grainstones, and siltstones). Tropical storms had four major effects on sedimentation: (1) submarine erosion, (2) upslope transportation and deposition of argillaceous muds, (3) winnowing, transportation, and redistribution of carbonates, and (4) generation of downslope gravity flows. Frequent storms also affected benthic ecology in three ways: (1) by mixing benthic fauna from different communities, (2) by periodically interrupting the process of community succession, and (3) by creating favorable conditions for the evolution and success of opportunistic species.

Cincinnatian strata are arranged in a cyclic pattern. Three levels of cyclicity are represented: (1) *storm cycles* (thin, graded sequences deposited from suspension by storms), (2) *megacycles* (moderately thin sequences having a carbonate hemicycle overlain by a shale hemicycle, and representing the fluctuation of terrigenous sediment supply), and (3) *shoaling-upward shelf cycles* (thick sequences that grade upward from shale-rich facies to shale-poor facies and represent the lateral progradation of consanguineous environments, ranging from offshore shelf to supratidal).

Previous lithostratigraphic revisions of the Cincinnatian Series were made without strict adherence to the rules of priority established by the Code of Stratigraphic Nomenclature, and without due consideration of the facies concept. As a result, numerous problems of correlation, mapping, and interpretation have arisen. Accordingly, a new stratigraphic classification is proposed for use in Ohio, Indiana, and northern Kentucky which will eliminate most of these problems. New stratigraphic units include the Corryville, Mt. Auburn, Sunset, Oregonia, Waynesville, and Liberty formations. These names have priority, are well known, and represent genetically related rock facies, and thus are quite useful for interpretive purposes.

INTRODUCTION

Previous Work

The fossiliferous limestones and shales of the Upper Ordovician Cincinnatian Series have been the object of geologic research for nearly 150 years (see Weiss and Norman, 1960). The earliest workers, before the advent of modern sedimentology and paleoecology, were attracted to the abundant and well-preserved fossils that could be found in outcrop. Hence, most of the research generated before the turn of the century was taxonomic and biostratigraphic in nature. From 1902 to 1960, geologists directed their attention to subdividing the Cincinnatian Series into "formations" and "members," based largely on fossil zones. Over the years those zones became more and more refined, culminating in the classification of Caster, Dalvé, and Pope (1961).

The period from 1960 to the mid-1970's can be thought of as a "renaissance" in the study of the Cincinnatian Series. Two factors contributed to this great outpouring of research: (1) improvements in the study of carbonate petrography (e.g., Folk, 1959 and 1962; Dunham, 1962), and (2) the appearance of the Code of Stratigraphic Nomenclature (1961). Both factors provided the impetus for research in two major areas: (1) the petrography of Cincinnatian limestones (e.g., Weiss and Norman, 1960b; Wetzel, 1968; Farber, 1968), and (2) the lithostratigraphic reclassification of Upper Ordovician strata (e.g., Weiss and Sweet, 1964; Brown and Lineback, 1966; Peck, 1966; Ford, 1967). Other new areas of interest included trace fossils (Osgood, 1970), paleocurrents (Hoffman, 1966a), X-ray diffraction study of shales (e.g., Scotford and Smoot, 1962; Scotford, 1965; Bassarab and Huff, 1968), benthic community analysis (Lorenz, 1973), and SEM study of limestones (Lobo and Osborne, 1973).

Since the mid-1970's, the dominant trend in Cincinnatian geologic research has been in the field of paleoecology. Geologists have studied paleocommunity sturcture and community succession (e.g., Oldroyd, 1978; Harris and Martin, 1979), the autecology of selected Cincinnatian fossils (e.g., Richards, 1972; Alexander, 1975; Frey, 1980), and biostratinomy (e.g., Brandt, 1980; Krumpolz, 1980; Meyer et al., 1981). Other workers have studied the relationship between paleoecology and depositional environments (e.g., Mahan and Harrison, 1980; Hinterlong, 1981; Meyer et al., 1981; Schumacher, in progress). Other areas of interest include biostratigraphy and lithostratigraphy (e.g., Hay, 1975 and 1981; Frey, 1976; Pope and Martin, 1977; Hay et al., 1981), limestone petrology (Martin, 1975), hardground formation and submarine cementation (Rassman, 1981), trace fossils (Norrish, in progress), and sedimentology (Tobin, 1980).

Purpose and Objectives

The preceding section outlines the abundant and diversified literature on the geology of the Cincinnatian Series. Given this plethora of information, one may legitimately ask: "Is there anything *new* that can be discovered about the geology of the Cincinnatian Series?" Logical reasoning would suggest that only the smaller details or gaps in our understanding remain to be studied. However, I believe that the reverse is true--that the broad concepts of depositional environments, modes of sedimentation, diagenesis, and paleoecology have not yet been fully developed. I recognize that each new generation of geologists has the advantage of new research tools and information that were unavailable to their predecessors. Yet, with 150 years of study and re-evaluation of data, a comprehensive sedimentologic, paleoecologic, and diagenetic model for the entire Cincinnatian Series has not yet appeared.

Three basic factors are responsible for this lack of information: (1) Key areas of research have been studied superficially or ignored altogether. For example, even though the significance of Walther's Law and the vertical sequence has been known to North American geologists for more than 40 years, it has never been applied to the Cincinnatian Series. Another key area of research that has been overlooked is the study of shales. Shales comprise approximately 58 percent of the total thickness of the Cincinnatian Series. Even so, with the exception of Scotford (1965) and Tobin (1980), shale petrology has been ignored. (2) Most researchers have failed to incorporate into their studies the wide variety of information available to them in the literature. For example, much is known about the taxonomy and ecology of Cincinnatian trace fossils (see Osgood, 1970). However, very few workers have attempted to *use* this data for interpretive purposes. (3) With a few exceptions (Caster, Dalvé and Pope, 1961; Martin, 1975; Hay, 1981), past research has focused on thin stratigraphic units (formations or members) rather than on the entire Cincinnatian Series. In some cases, this trend has had no effect on the validity of interpretations. In other cases, particularly those in which the reconstruction of depositional environments was at stake, the isolated study of one or two formations greatly weakened their results (see "Cyclic Sedimentation and the Vertical Sequence").

Thus, the purpose of this study is to describe the sedimentology of the Cincinnatian Series by utilizing modern research tools and ideas, by using the valuable legacy of information generated by earlier workers, and by avoiding the three pitfalls mentioned above. The specific objectives of this study are: (1) to re-evaluate the current lithostratigraphy of the Cincinnatian Series, and to propose any changes necessary for producing a more appropriate and useful classification scheme; (2) to develop a model which best explains the sedimentary processes and depositional environments of the Cincinnati Arch region during Late Ordovician time; and (3) to provide a plan for future research on the Cincinnatian Series which will test the validity of the model proposed herein, and generate new ideas and information which may enhance the model. It is my sincere hope that this plan may help to avoid the random, unrelated studies of the Cincinnatian Series that have been so characteristic of the past. This study should serve as a framework upon which future generations will be able to integrate depositional models with paleoecology and diagenesis.

Methods Used

My first task was to locate and describe outcrops of Cincinnatian Age strata in the field area. Because most of the available outcrops exposed only one or two contiguous formations, it was necessary to piece together a composite section of the entire Cincinnatian Series. Hence, outcrops were selected as close together as possible to minimize the lateral distance between adjacent formations. This insured that the possibility of lateral facies change did not interfere with the results.

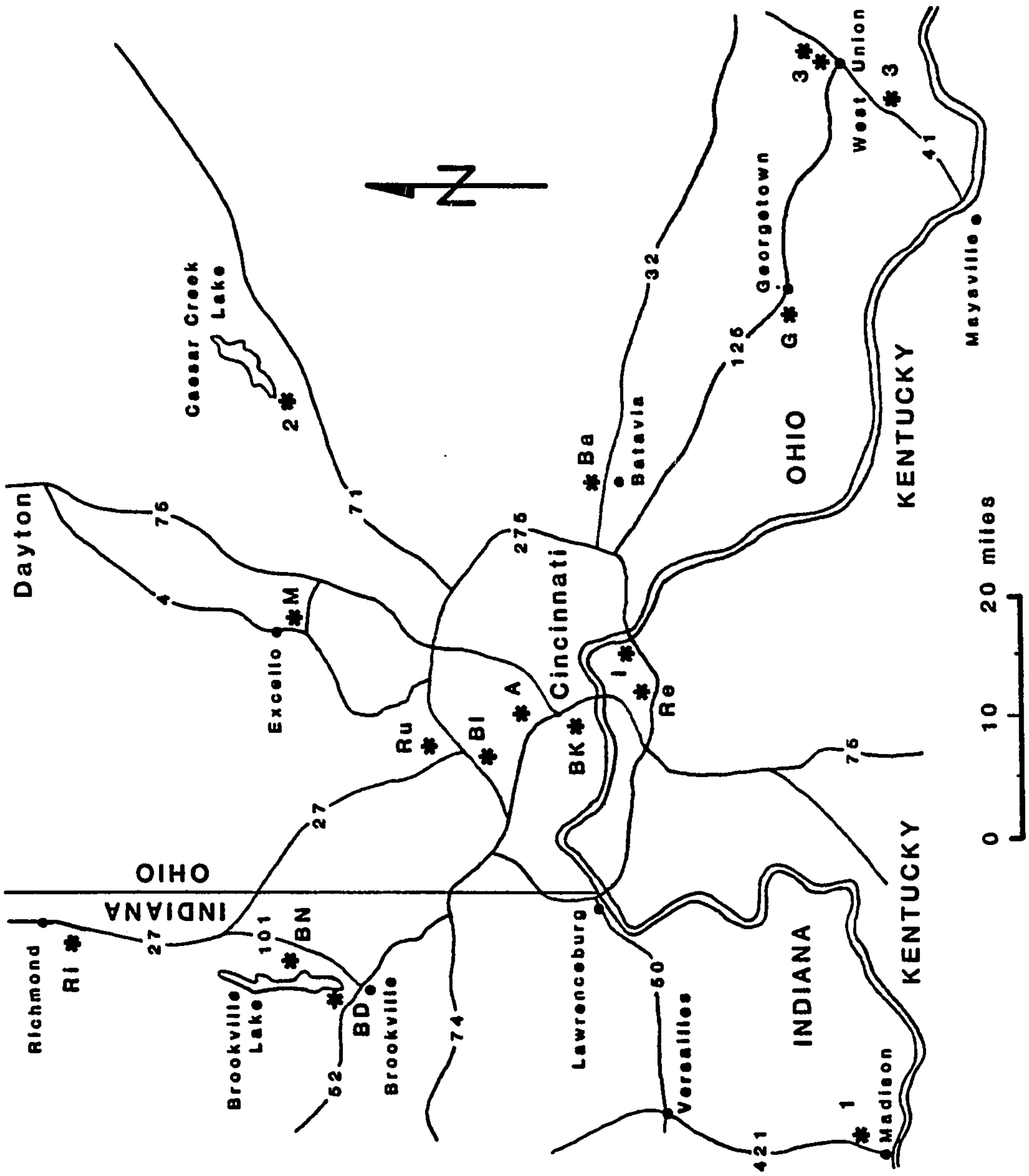
After it had been determined that the Cincinnatian Series contained three distinct lithogenetic sequences, additional outcrops were selected and described so that each sequence could be compared regionally.

Twelve outcrop sections were measured and described in southwestern Ohio, northern Kentucky, and southeastern Indiana (see Figure 1). A total of 348 meters (1,142 feet) of section was described and sampled. The thickness of measured vertical sections and formation designations for each of the 12 localities are given in Appendix 1, and exact locations are given in Appendix 2. The thickness of each outcrop was initially measured using a Jacob's staff and a Brunton compass, and one-meter intervals were marked off with paint. The following properties were then described for each meter of section: formational contacts, bedding type and thickness, lateral continuity of beds, rock types, characteristic fauna, sedimentary structures, bioturbation, shale percent, color, and weathering characteristics. Every bed thicker than 1 cm was described. Strata thinner than 1 cm were noted and described, but were not drafted onto the outcrop log sheets. The detailed descriptions of all 12 outcrop sections are given in Appendix 3. Three additional outcrop sections and one core were described with less detail for various reasons. The results of those descriptions are discussed within the text, and do not appear in Appendix 3. However, all four locations are plotted on Figure 1.

Over 800 rock samples were collected from outcrops in the field area. Samples were not collected at regular intervals. Instead, sampling was done at very irregular intervals with four purposes in mind: (1) to compare and interpret the wide variety of rock types present; (2) to compare carbonates and shales stratigraphically; (3) to collect from all parts of

<u>Figure 1</u>: Outcrop locations in study area.

A = Aiken High School
BK = Bald Knob Hill
Ba = Batavia
Bl = Blue Rock Road
BD = Brookville Dam
BN = Brookville North
G = Georgetown
I = I-275 East/KY 445 composite
M = Middletown
Re = Reidlin Road
Ri = Richmond
Ru = Rumpke Landfill
1 = Saluda outcrop near Madison
2 = Richmondian outcrops at Caesar Creek Dam
3 = Drakes outcrops in Adams County


Dayton
Caesar Creek Lake
2
75
71
4
M
Excello
Ru
Bl
A
275
Cincinnati
Ba
Batavia
32
125
Georgetown
G
OHIO
KENTUCKY
3
West Union
3
41
Maysville
0
10
20 miles
I
Re
BK
75
27
OHIO
INDIANA
Richmond
Ri
27
101
BN
Brookville Lake
BD
Brookville
52
74
Lawrenceburg
50
Versailles
INDIANA
KENTUCKY
421
1
Madison

"megacycles" and "storm cycles" (to be discussed in a later section); and (4) for miscellaneous reasons (e.g., unusual rock types, fossil orientations, trace fossils, sedimentary structures, important guide fossils, etc.). Carbonates were described using the classification of Dunham (1962), and shales were classified following the scheme of Potter, Maynard and Pryor (1980). The vertical positions of samples collected from each of the 12 outcrops are shown in Appendix 3.

Hand specimen samples were then returned to the laboratory and described in more detail with the aid of a binocular (reflected light) microscope. The following properties were described: rock name, fossil types, genera, generic diversity, fossil orientation, degree of fossil breakage and abrasion, sorting, grain size, bioturbation, lamination, and accessory diagenetic minerals. Hand specimen descriptions are given in Appendix 4. In addition, approximately 25 polished slabs were made for additional textural analysis or for the analysis of vertical changes in lithology that occur within the thickness of a single bed.

Of the 800 hand specimen samples described, 128 were selected for thin-section analysis (86 carbonates and 42 shales). All thin sections were cut normal to bedding, polished to a final thickness of 25 microns (10 to 15 microns for shales), and then stained using a combination of Alizarin Red S and potassium ferricyanide. Composition of all samples was determined by point-counting 200 grains each for shales, and 300 each for carbonates. Textures and bioturbation were also described in thin section. Wilson's petrographic checklist was used to enhance carbonate descriptions (Wilson, 1975, pp. 60-63). The results of this petrographic analysis are given in Appendices 5 and 6. In addition, 10 shale samples were examined texturally with the aid of a Scanning Electron Microscope (SEM).

S T R A T I G R A P H Y

Historical Development

The supposedly "monotonous" interbedding of limestone and shale in the Cincinnatian Series, combined with an abundant and well-preserved fauna, led early stratigraphers to believe that stratigraphic subdivisions of these rocks should be based mostly on faunal rather than lithologic characteristics. Moreover, they were largely stratigraphic "lumpers." Riddell's "Blue Miami Limestone" (1837), Briggs' "Great Limestone Deposite" (1838), and Orton's stratigraphic subdivision of "River Quarry Beds," "Middle Eden Shales," "Hill Quarry Beds," and "Lebanon Beds" (1873) are all examples of the tendency to define broad, undifferentiated stratigraphic units. With time, additional faunal subdivisions were described and refined. The development of this subdivision took place mainly between 1902 and 1940, and can be credited to the poineering efforts of J. M. Nickles, A. F. Foerste, R. S. Bassler, E. R. Cumings, E. O. Ulrich, and many others. The most recent compilation of this largely biostratigraphic classification is that of Caster, Dalvé and Pope (1961), who described eight "formations" and fourteen "members." Excellent summaries of the development of Cincinnatian stratigraphy are given by Cumings (1922), Gutstadt (1958), and Weiss and Norman (1960).

Perhaps the first worker to recognize the need for lithologically defined Cincinnatian stratigraphy was Gutstadt (1958). His study was published just three years prior to the Code of the American Commission on Stratigraphic Nomenclature, which recommended that rock stratigraphic units be defined on the basis of lithologic characteristics. The Code provided the impetus for a number of lithostratigraphic studies of the Cincinnatian, starting in 1964. Table 1 summarizes the development of Cincinnatian lithostratigraphic classifications, and Figure 2 compares some of them graphically. The most recent study of Cincinnatian lithostratigraphy is that of Hay (1981), who proposed new stratigraphic units based largely on her study of outcrops in southeastern Indiana (see Figure 3).

Assessment of Cincinnatian Lithostratigraphy

Three observations are readily apparent from the preceding discussion: (1) A great deal of confusion concerning the vertical and lateral relationships of these newly defined rock units has created problems with mapping and correlating geologic formations in the Cincinnati Arch region. (2) Because of this confusion, some geologists working on non-stratigraphic geologic problems in the Cincinnati area have resorted to the use of informal stratigraphic names (e.g., Meyer et al., 1981; Rassman, 1981). (3) The "new wave" of lithostratigraphers have tended to lump, as did the earliest stratigraphers, thick sequences of Cincinnatian rocks into formations (e.g., Peck's "Bull Fork Formation" and Brown and Lineback's "Dillsboro Formation"), disregarding numerous facies changes previously described by biostratigraphers.

Lithostratigraphers have repeatedly disregarded the traditional stratigraphic divisions of the Cincinnatian Series (see Caster, Dalve and Pope, 1961) on the grounds that they were entirely biostratigraphic in nature. Krumpolz (1980) pointed out that lithostratigraphers based

Table 1: Summary of Lithostratigraphic Studies of the Cincinnatian.

Author and Publication Date	Summary of Article
Weiss and Sweet (1964)	Defined the Kope Formation of Ohio and Kentucky.
Weir, Greene and Simmons (1965)	Defined the Calloway Creek Limestone, the Ashlock Formation, and the Drakes Formation for southcentral Kentucky.
Brown and Lineback (1966)	Defined the Dillsboro Formation, the Saluda Formation, and the Whitewater Formation of southeastern Indiana. Also used the term "Kope Formation."
Peck (1966)	Defined the Grant Lake Limestone and the Bull Fork Formation for the Maysville, Kentucky, area. Also used the terms "Kope," "Fairview," and "Drakes" Formations.
Ford (1965, 1967)	Defined the Fairview Formation, the Miamitown Shale, and the Bellevue Limestone for the Cincinnati area. Also used the term "Kope Formation."
Hatfield (1968)	Defined the Tanner's Creek and Whitewater Formations, and redefined the Saluda Formation for southeastern Indiana and northcentral Kentucky.
Lee (1974)	Used the terms "Kope," "Fairview," "Grant Lake," and "Bull Fork" for the area between Dayton, Ohio, and Maysville, Kentucky. Proposed the names Waynesville Formation and Whitewater Formation be used for two intertonguing units in the Bull Fork.
Hay (1981)	Defined the Brookville Formation, with five members. Used the terms "Whitewater," "Saluda," and "Elkhorn." Also used Ford's (1967) classification.

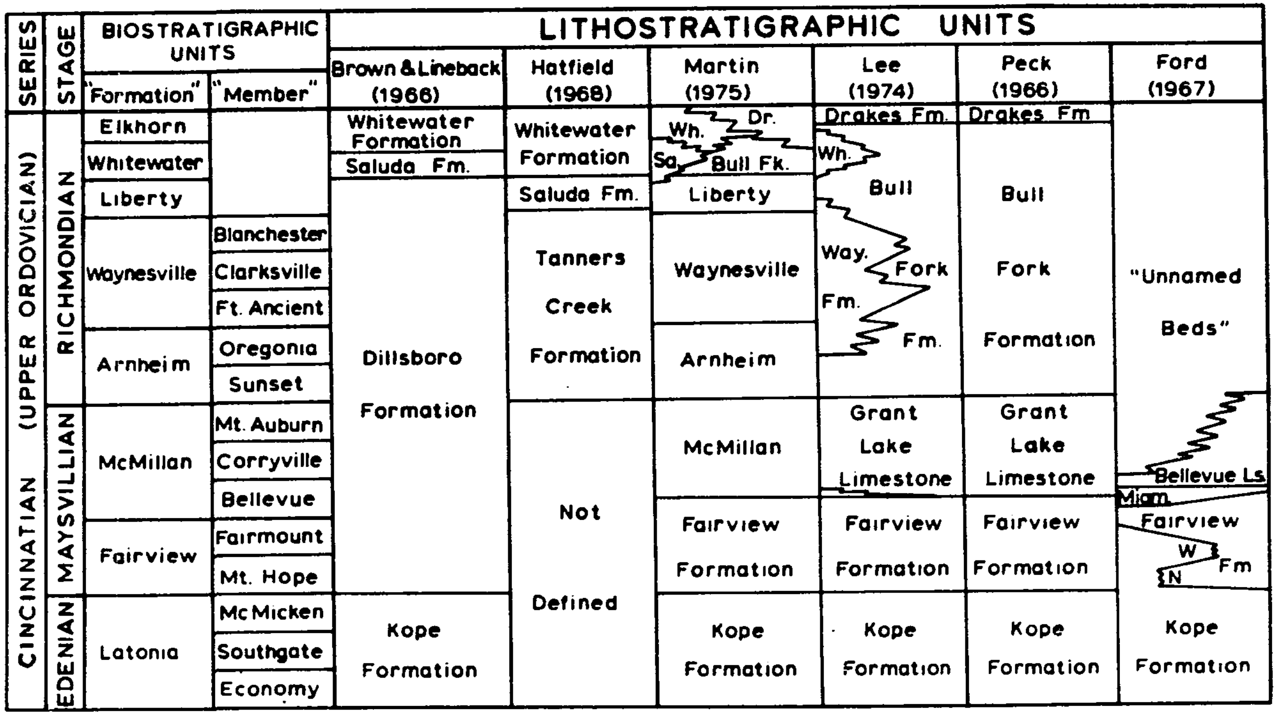


Figure 2: Comparison of Cincinnatian stratigraphic nomenclature.

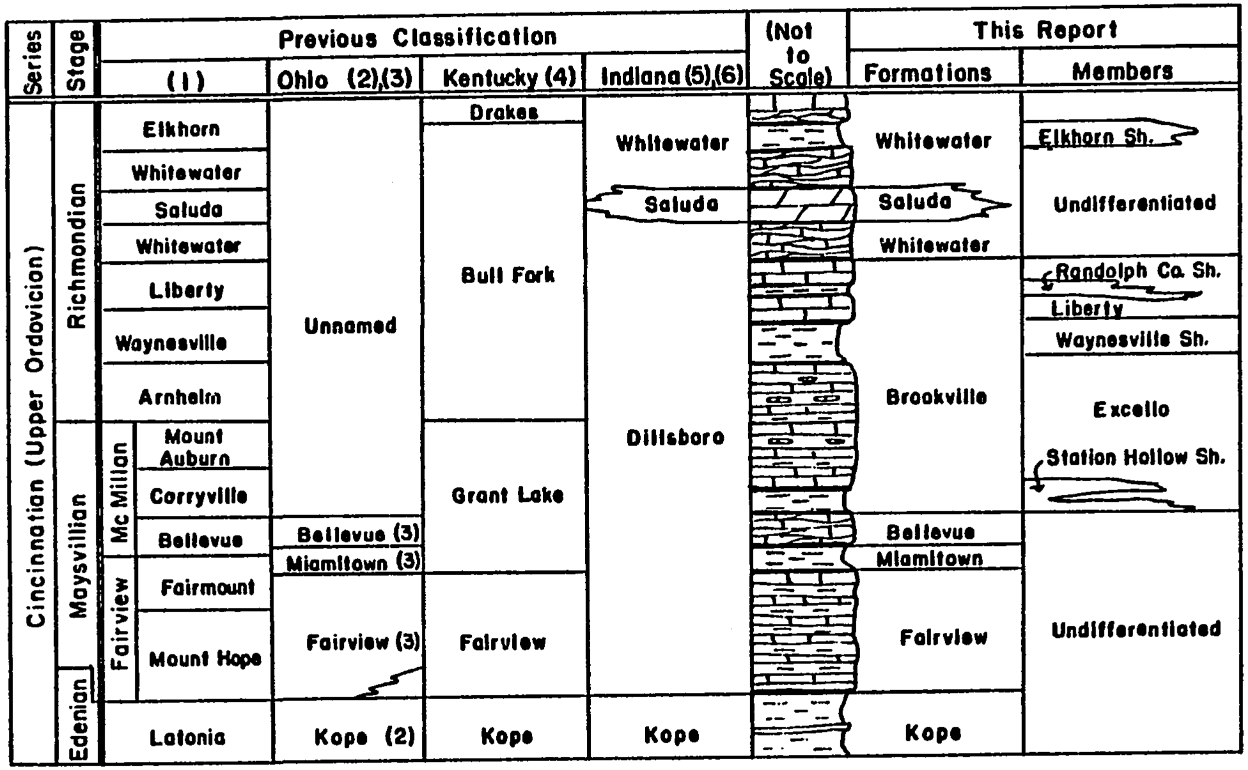


Figure 3: Lithostratigraphic Nomenclature (from Hay, 1981).

this conclusion largely on quotations from summary articles such as Cumings (1922) and Gutstadt (1958), without consulting the original references (e.g., Nickles, 1902 and 1903; Foerste, 1903 and 1910b; Bassler, 1906; Cumings, 1908). Krumpolz noted that many of the traditional biostratigraphic units ". . . were *originally* defined as units with a distinct lithologic, as well as paleontologic identity . . . ." And therefore ". . . should be considered as lithostratigraphic units" (1980, p. 115). Krumpolz cited the Mt. Auburn strata (Nickles, 1902) as an example of a stratigraphic unit originally defined on the basis of its paleontologic *and lithologic* characteristics, noting, however, that its upper and lower boundaries were defined faunally.

I agree with the conclusions of Krumpolz (1980). Field and laboratory observations prove that many of the traditional "biostratigraphic" units do indeed possess distinctive lithologic characteristics which can be correlated laterally, and recognized in the original descriptions. Because previous lithostratigraphers ignored those original descriptions, I propose that a new stratigraphic classification scheme, which reinstates these "traditional" units be adopted for use in southwestern Ohio, southeastern Indiana, and northern Kentucky (see Figure 4). Although the original lithologic descriptions of these units are unsophisticated, I can easily recognize their occurrence in the field, and will update those descriptions using modern terminology. Furthermore, upper and lower boundaries will be redefined lithologically to conform to the rules of the Code of Stratigraphic Nomenclature (Article 5). The results of this stratigraphic revision will be presented in detail in the section entitled "Lithogenetic Sequences." However, additional work will be necessary to

SOUTHEASTERN INDIANA	CINCINNATI AREA	MAYSVILLE, KY to DAYTON, OH
Saluda Formation	Elkhorn Formation?	Drakes Formation (Preachersville Member)?
Whitewater Formation	Whitewater Formation	Whitewater Formation
Liberty Formation	Liberty Formation	Liberty Formation
Waynesville Formation	Waynesville Formation	Waynesville Formation
Oregonia Formation	Oregonia Formation	Oregonia Formation
Sunset Formation	Sunset Formation	Sunset Formation
	Mt. Auburn Formation	Mt. Auburn Formation
Corryville Formation	Corryville Formation	Corryville Formation
Bellevue Limestone	Bellevue Limestone	Bellevue Limestone
	Miamitown Shale	Miamitown Shale
Fairview Formation	Fairview Formation	Fairview Formation
Kope Formation	Kope Formation	Kope Formation

Figure 4: Proposed reclassification of Cincinnatian Series Stratigraphy.

determine if this classification is applicable to equivalent strata in central Kentucky.

Not only is there a "legal" reason for reviving the traditional stratigraphic terminology (i.e., "priority," Article 11 of the Code), but more importantly there is an idealistic reason. Some of the new lithostratigraphic units (e.g., "Bull Fork Formation," "Dillsboro Formation," etc.) include several rock facies within their boundaries, some of which are time-equivalent (isochronous facies) and some of which are not (heterochronous facies). In other words, some of these formations represent parts of two lithogenetic sequences or "facies tracts" (i.e., isochronous, heteropic facies--see discussion of the facies concept and Walther's Law in Krumbein and Sloss, 1963, and in Middleton, 1973). It is my belief that stratigraphic nomenclature should conform to the facies concept as originally defined by Gressly (1838) and discussed by Walther (1894), rather than the reverse. That is, one should base interpretations of rock strata on *sequences of genetically related rock facies*, and then name those facies by using appropriate stratigraphic procedures. Unfortunately, previous workers have studied the Cincinnatian Series in the reverse order. They have first given strata formational names, and then interpreted those formations as isolated units in time and space. This "taxonomic approach" to stratigraphy has been criticized by G. V. Middleton, who stated ". . . only knowledge of facies relationships drawn from the study of modern environments can save us from the barren cataloging of rock and fossil sequences that sometimes passes for stratigraphy" (1973, p. 983).

Although the earliest Cincinnatian biostratigraphers did not have a Stratigraphic Code to follow and were unfamiliar with the facies concept, their methodical and thorough investigations accurately uncovered the numerous rock facies that exist in the Cincinnatian Series. Each formation proposed in this study represents a true rock facies (i.e., rocks having a distinct lithologic and paleontologic character, representing an area of uniform environmental and depositional conditions). I believe that this method of naming rock units will greatly enhance our understanding of Late Ordovician environments and modes of deposition, and will end the "taxonomic" approach to Cincinnatian Series lithostratigraphy that has occurred in the past.

REGIONAL PALEOGEOGRAPHY

The sedimentologic interpretation of Cincinnatian Age strata is complex, requiring the discussion of such interrelated topics as stratigraphy, petrology, autecology, facies analysis, and vertical sequences. Of primary importance is the geologic setting, or paleogeography, of the eastern United States (central Appalachians). Without a working knowledge of the regional distribution of major depositional environments, interpretations are limited to the specific processes and sub-environments at a given locality, and are made without understanding the influence of the basin as a whole.

During Late Ordovician time, the Cincinnati Arch region was located in the tropical southern hemisphere at least 15° south of the equator, and rotated approximately 45° clockwise from its present orientation (see Figure 5). A more recent reconstruction of Ordovician paleogeography by Bambach et al. (1980) places the region even further south, and indicates continued southward drift through the Middle Silurian. Bambach et al. (1980, fig. 6) and Scotese et al. (1979, fig. 8) indicate that a very wide ocean basin lay to the east of the North American Plate during Middle Ordovician time. Major paleo-oceanic circulation patterns and probable storm paths have been reconstructed for this part of the world. Their influence on sedimentation in the Cincinnati Arch region is important, and will be discussed in the section entitled "Storm Cycles."

The Cincinnati Arch region is part of an elongate, northeast-southwest trending carbonate sheet extending from the Great Lakes region to southern Tennessee (Figure 5). This sheet is composed of interbedded

UPPER ORDOVICIAN LITHOFACIES

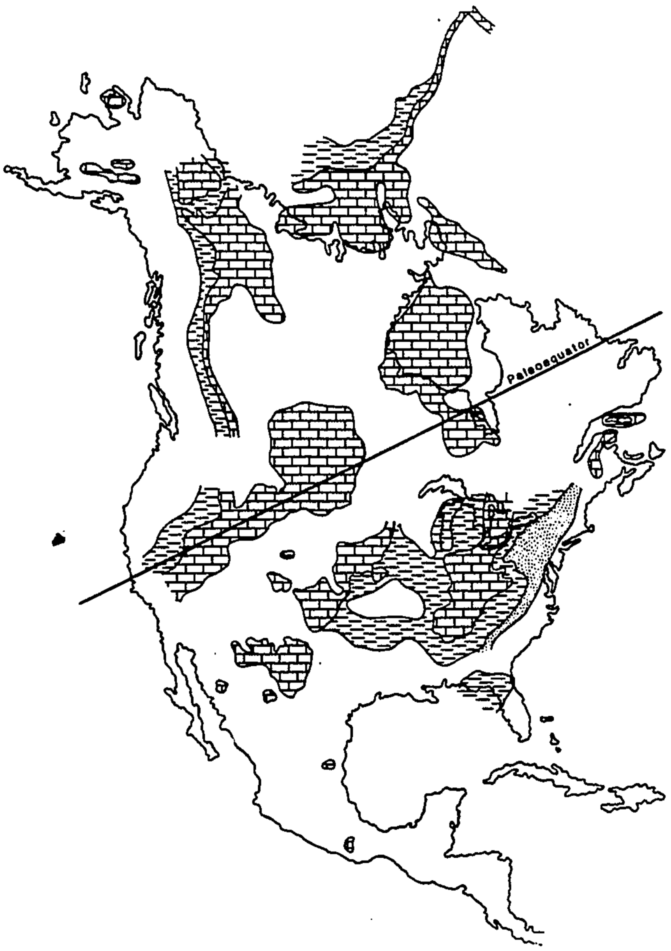


Figure 5: Distribution of carbonate, shale, and sandstone lithofacies during Cincinnatian time in North America. Compiled from various sources (Dott and Batten, 1971, fig. 10.19; Shell Oil Company, 1975; Dennison, 1976, fig. 2; Ross, 1976, fig. 10; Elias, 1979, fig. 2; Stearn et al., 1979, fig. 11-14).

limestones and shales, dolomites, and dolomitic limestones, and represents a carbonate ramp (as defined by Ahr, 1973). Inferred paleoenvironments on this ramp range from offshore shelf to supratidal, but are mostly open-marine, inner shelf. This carbonate sheet is bounded to the west, south, and east by thick, wedge-shaped shale bodies (Figure 5) representing outer shelf, slope, and deep basin paleoenvironments. The Upper Ordovician shales to the east of the Cincinnati Arch region (e.g., Martinsburg Shale, Reedsville Shale; see Twenhofel, 1954, for correlation of these and other Ordovician formations) grade eastward into shallow-marine and fluvial sandstones (e.g., Oswego Sandstone, Juniata Sandstone). These sandstones and shales migrated westward, toward the Cincinnati Arch region, as a consequence of the progressive uplift of the Taconic highlands to the east. The Taconics were a chain of mountains that extended from southeastern Canada to Georgia in a gently curving belt. The westward progradation of sandstones and shales supplied by the Taconics disrupted carbonate sedimentation which had prevailed during Early and Middle Ordovician time, and eventually filled up the Appalachian Basin (see Figures 6 and 7).

Bretsky (1970) has reconstructed the paleogeography of the Central Appalachian region, based on stratigraphic and sedimentologic evidence. Figure 8 (Bretsky, 1970, fig. 12) is a paleogeographic map of Late Ordovician depositional environments in this region, and Figures 9 and 10 (Bretsky, 1970, figs. 10 and 11) are idealized cross sections of the area. Figure 11 is a modification of Bretsky's paleogeographic map, which takes into account additional information from Woodward (1951), McBride (1962), Gray (1972), Kreisa (1981), and from data obtained in this study.

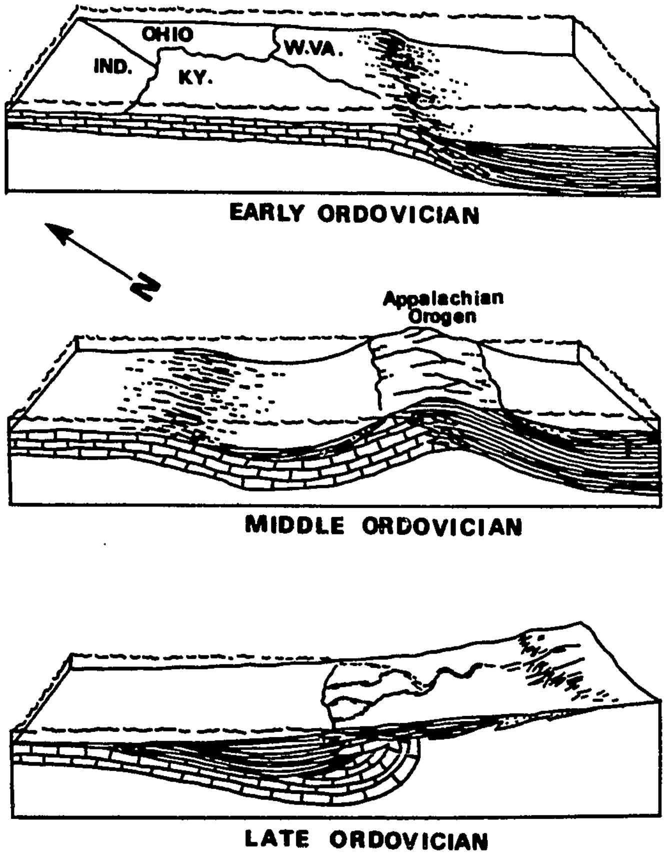


Figure 6: Tectonic evolution of the continental margin of North America during Ordovician time (modified from Bird and Dewey, 1970, fig. 7).

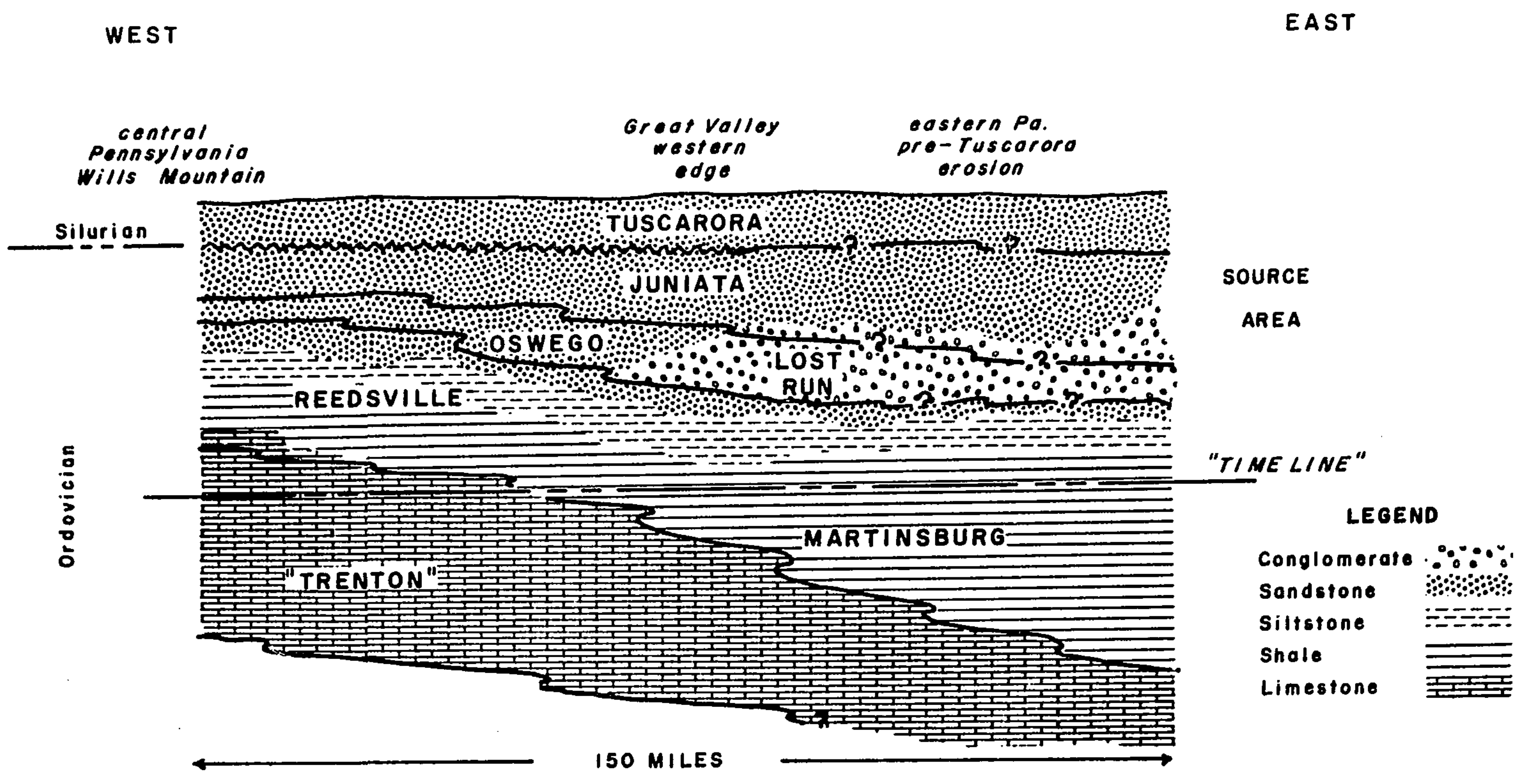


Figure 7: Reconstruction of a probable east to west migration of the Upper Ordovician formations in Pennsylvania and northern Virginia (from Bretsky, 1970, fig. 9).

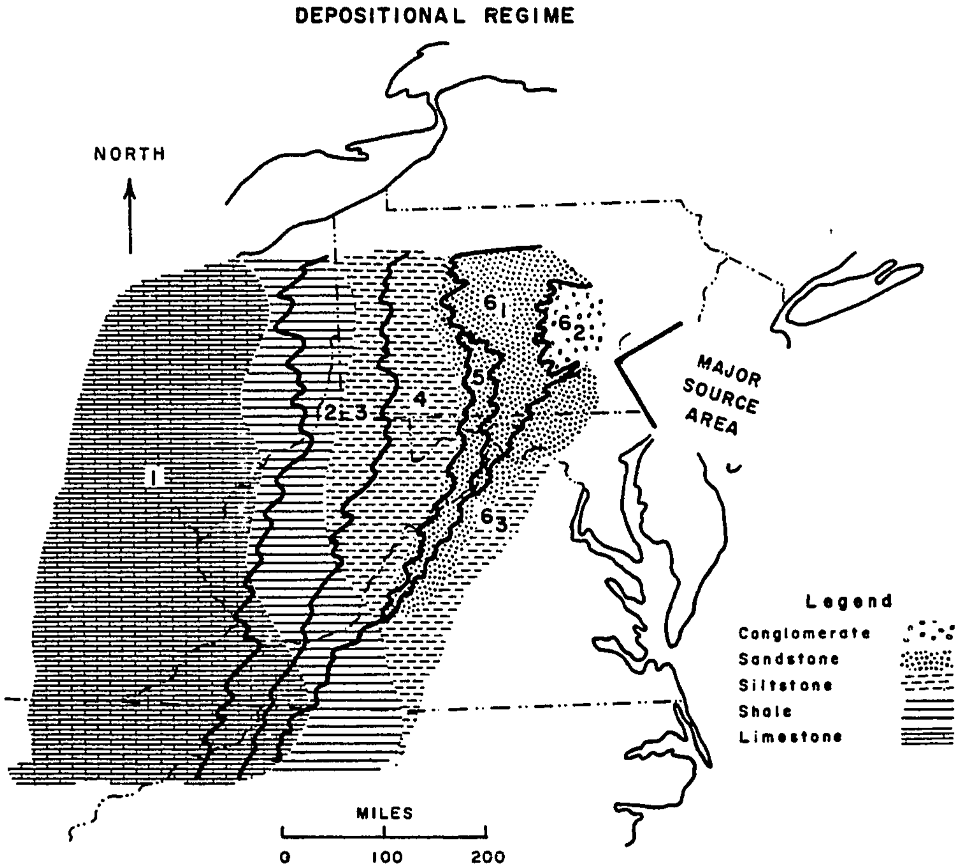


Figure 8: Reconstruction of the depositional environments during the Late Ordovician in the central Appalachians (from Bretsky, 1970, fig. 12).

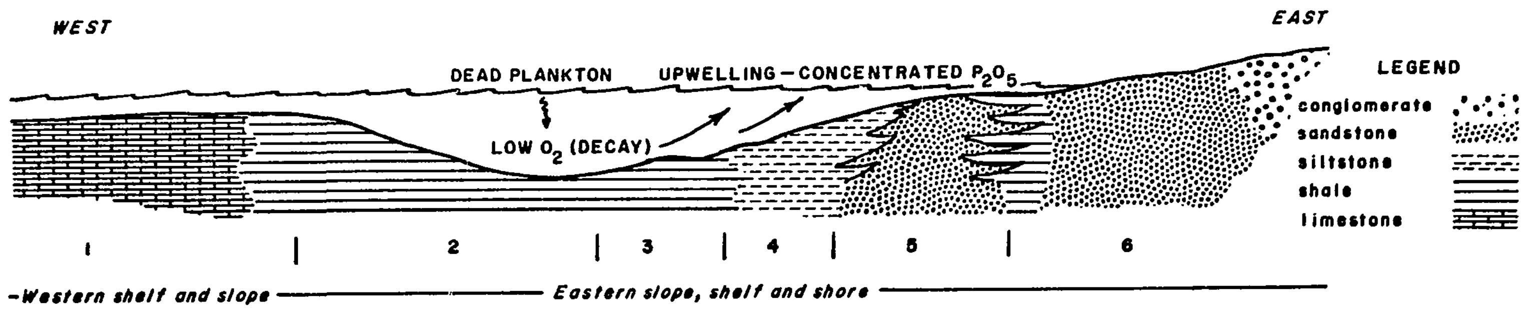


Figure 9: Reconstruction of the onshore to offshore profile (east-west) during the Late Ordovician in the north-central Appalachians (from Bretsky, 1970, fig. 10).

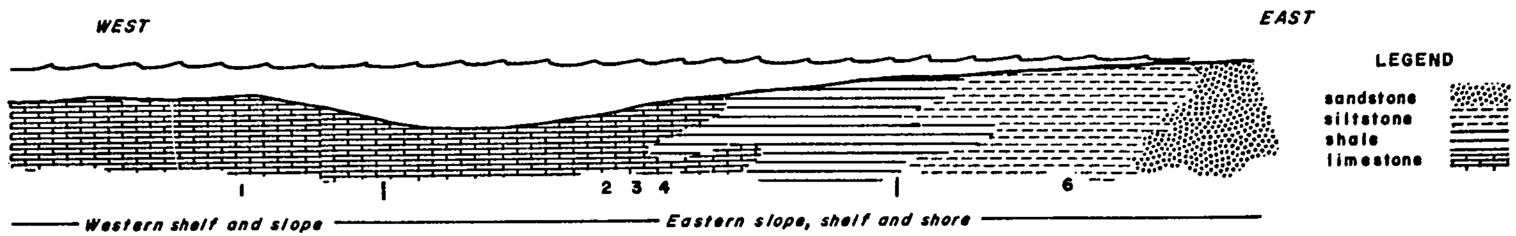


Figure 10: Reconstruction of the onshore to offshore profile (east-west) during the Late Ordovician in southwestern Virginia and northern Tennessee (from Bretsky, 1970, fig. 11).

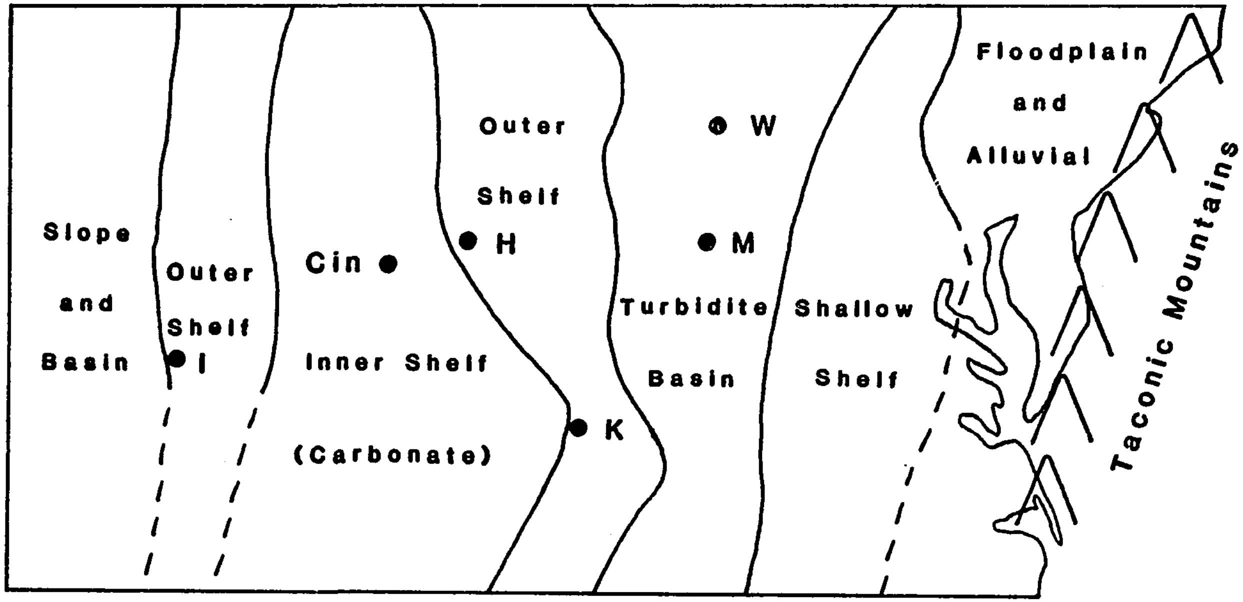


Figure 11: Idealized Paleogeography of the Central Appalachian Region, Eastern U.S. (modified from Bretsky, 1970, fig. 12).
CIN = Cincinnati area (inner shelf)
H = Highland County Core (outer shelf shales--see "Kope to Bellevue Sequence" for discussion)
K = Southwestern Virginia, Kreisa (1980) field area (outer shelf)
M = McBride (1962) description of thick turbidites of the Martinsburg Formation in Central Virginia northward to New York
W = Thickest accumulation of flysch sediments--deepest part of basin (from Woodward, 1951)
I = Deeper water basin in southwestern Indiana--Maquoketa Shale (from Gray, 1972)

PETROLOGY OF CINCINNATIAN CARBONATE ROCKS

Previous Work

Prior to 1960, the sedimentary petrology of Cincinnatian Age carbonate rocks received little attention. Descriptive terms such as "limestone," "fossiliferous limestone," and Grabau's (1904) "calcirudite," "calcarenite," and "calcilutite" were often used. In 1960, Weiss and Norman developed a more detailed classification of Cincinnatian limestones, based on the degree of fossil breakage, fossil orientation, and amount of insoluble residue. However, Weiss and Norman's (1960b) classification scheme is difficult to use (especially in the field), offers little interpretive value, and is unknown to most geologists. Nonetheless, subsequent geologists utilized this classification scheme, at least in part, well into the late 1970's (e.g., Weiss et al., 1965; Ford, 1967; Osborne, 1971, 1972, 1973; Lorenz, 1973; Martin, 1975).

The appearance of Folk's (1959, 1962) limestone classification inspired numerous petrographic studies of Cincinnatian Age limestones during the 1960's. The majority of these studies were M.S. theses (all from Miami University, Oxford, Ohio) on the petrography of selected Cincinnatian formations. These studies emphasized the use of Folk's classification, and were largely descriptive, rather than interpretive in content (e.g., McCormick, 1960; Kuder, 1964; Bayha, 1965; Farber, 1968; Wetzel, 1968). Folk's classification scheme, a modern innovation in its time, is now rarely used because it is complex, places less emphasis on the nature of grain support, and is difficult to use in the field.

Conversely, Dunham's (1962) classification is widely accepted and can be easily used in the field.

Unfortunately, carbonate petrographic research on the Cincinnatian Series during the 1970's followed the same trends of the previous decade. Although more sedimentologically oriented petrographic classification and study procedures had already been introduced in the literature (e.g., Friedman, 1959; Dunham, 1962; Milliman, 1974; Bathurst, 1975; Wilson, 1975), petrologists continued to place heavy emphasis on outdated classifications (i.e., Folk, 1959, 1962; Weiss and Norman, 1960b), outdated descriptive terminology (e.g., "coquinoid limestone," "rubbly bedded limestone," etc.), and insoluble residue analysis (an anachronism of the 1930's). Examples of this type of research include: Booth and Osborne (1971), Hay (1975), Martin (1975, 1977), and Harris (1977). The only exception to this trend was Lobo and Osborne (1973) who studied the origin of micrite in Cincinnatian limestones using Scanning Electron Microscopy (SEM). The first sedimentologically oriented studies of limestones did not appear until the next decade (Mahan and Harrison, 1980; Tobin, 1980; Meyer et al., 1981; Rassman, 1981).

I recognize that Cincinnatian petrographic research in the 1980's should not rely solely on the ideas and procedures of the 1960's, but instead should focus on modern concepts and research tools. In the following section, eight types of carbonate rocks that commonly recur throughout the Cincinnatian Series are described and interpreted using modern techniques and ideas. Diagenesis, although not a primary goal of this dissertation, is also discussed in the section entitled "Carbonate Diagenesis."

Recurrent Carbonate Rock Types

Eight varieties of carbonate rocks are repeatedly encountered throughout the Cincinnatian Series. These rock types are not restricted to any particular facies or geographic location, but occur in most stratigraphic horizons and localities. These "recurrent" rock types include: packstones, wackestones, micstones, siltstones, poorly washed grainstones, coarse grainstones, fine grainstones, and calcisiltites. Table 2 compares the hand-specimen and petrographic characteristics of each rock type, and Figure 12 is a diagrammatic comparison of each. Thin-section photographs of all eight rock types are shown in Figures 13 through 20. These illustrations can be used by subsequent workers to facilitate rock descriptions, both in the laboratory and in the field.

Additional varieties of carbonate rocks exist in the Cincinnatian Series which are not recurrent. These rocks are stratigraphically or geographically restricted, and therefore will be described and interpreted together with the particular stratigraphic unit or geographic location in which they occur (see "Lithogenetic Sequences").

Packstones

Packstones (Dunham, 1962) are grain-supported, matrix-bearing carbonate rocks. As defined in this paper, they contain greater than 45 percent carbonate grains (an average of 57%), and 16 to 55 percent carbonate matrix (an average of 31%). Matrix is interstitial, and in many cases pelletal. Packstones are poorly sorted, coarse grained, and have a moderate-to-low degree of fossil breakage. Fossils are oriented subhorizontally, and both internal and external geopetals are common. As

Table 2: Summary of the Petrology of Recurrent Carbonate Rock Types in the Cincinnatian Series. (Asterisks denote data averaged from thin-section analysis only. Generic diversity is the number of fossil genera observed in hand specimen, and petrographic diversity follows the usage of Smosna and Warshauer, 1978.)

ROCK NAME	PERCENT MATRIX*	PERCENT GRAINS*	SORTING		BREAKAGE		GRAIN ORIENTATION	GRAIN SIZE (mm)		GRADED BEDS*	DOMINANT FOSSILS*	FAUNAL DIVERSITY		PERCENT QUARTZ SILT
			Hand Specimen	Thin Section*	Hand Specimen	Thin Section*		Hand Specimen	Thin Section*			Generic	Petro-graphic*	
Packstone	31	57	mod. to poor	poor	mod. to low	mod. to low	subhorizontal	6.4	2.89	none	Bz = 33% Br = 23% Pe = 18% Cr = 10% Tr = 8% Other = 8%	5.7	7.1	Tr
Wackestone	69	26	mod. to poor	poor	mod. to low	mod. to low	subhorizontal	6.0	2.75	none	same as packstones	4.1	6.5	Tr
Micstone	95	4	N/A	N/A	N/A	very high	N/A	N/A	0.22	none	N/A	N/A	N/A	Tr
Siltstone	0	2	N/A	N/A	N/A	very high	N/A	N/A	0.30	some; hard to detect	N/A	N/A	N/A	55
Poorly Washed Grainstone	8	67	mod.	poor	mod. to high	mod.	subhorizontal	4.3	3.08	none	Bz = 37% Br = 25% Cr = 13% Tr = 8% Pe = 6% Other = 11%	4.9	6.6	Tr
Coarse Grainstone	2	58	mod.	mod. to poor	mod. to high	mod. to high	subhorizontal	4.5	2.36	none	Br = 37% Bz = 24% Cr = 20% Tr = 8% Ga = 4% Other = 7%	5.6	6.3	Tr
Fine Grainstone	Tr	67	well	well	high	high	46% subhoriz. 36% random 18% inclined	1.4	0.90	31% of samples	Cr = 26% Br = 26% Bz = 26% Tr = 8% Ga = 3% Other = 11%	4.7	6.8	1.4
Calcisiltite	0	58	very well	very well	very high	very high	subhorizontal	0.3	0.24	44% of samples	Unk. = 34% Br = 24% Cr = 15% Bz = 14% Tr = 5% Other = 8%	3.0	6.1	11.0

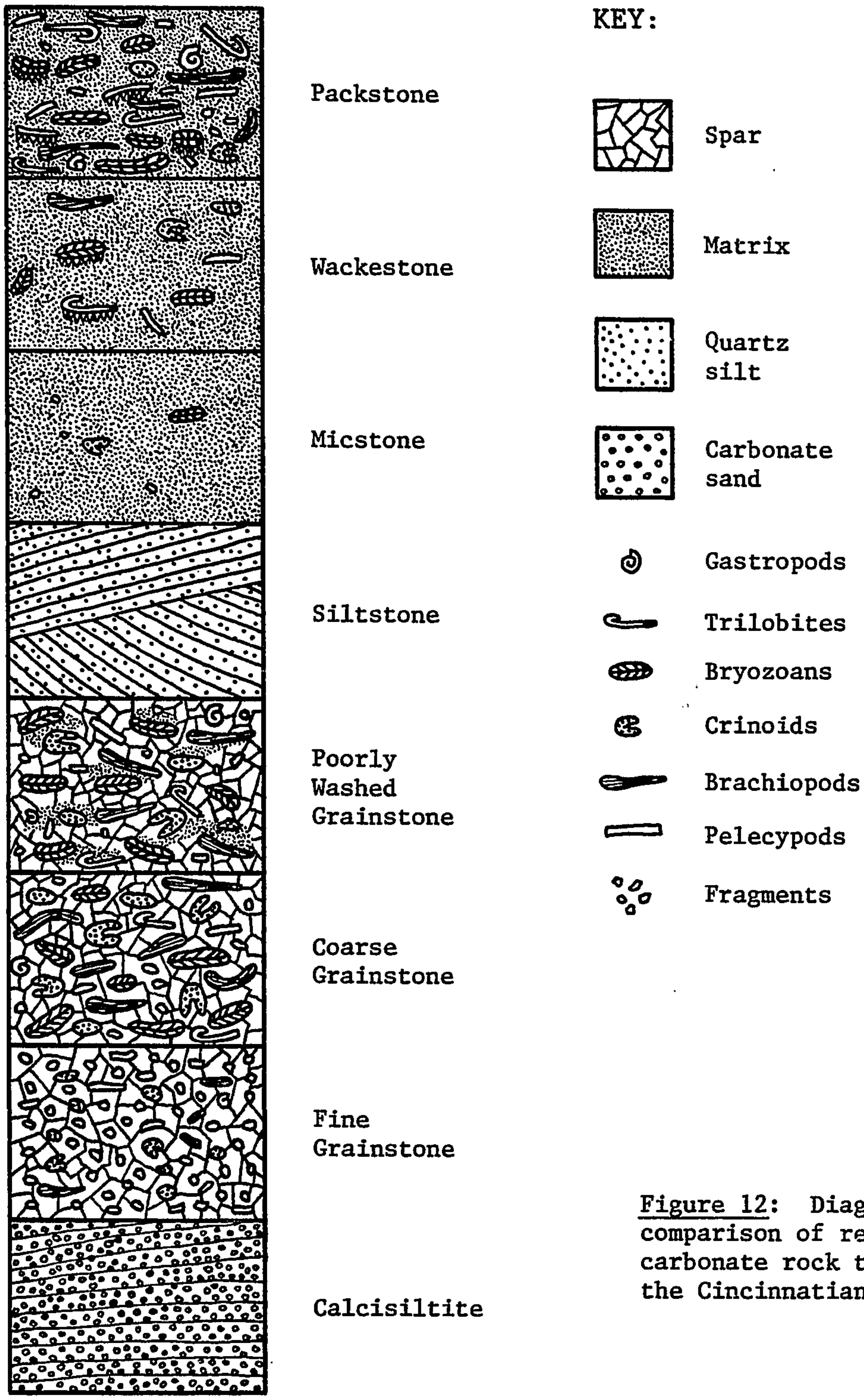


Figure 12: Diagrammatic comparison of recurrent carbonate rock types in the Cincinnatian Series.

Figure 13: Thin-section photograph of a coarse-grained, poorly sorted packstone. Note the diversity of bioclasts and abundance of matrix (scale: 1 cm = 150 microns).

Figure 14: Thin-section photograph of a coarse-grained, poorly sorted wackestone. Note the abundance of matrix (scale: 1 cm = 150 microns).

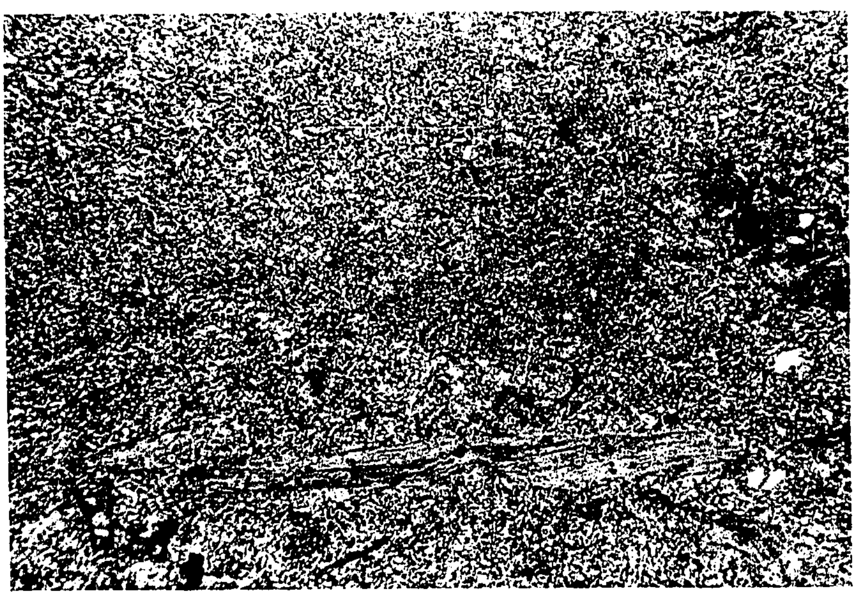
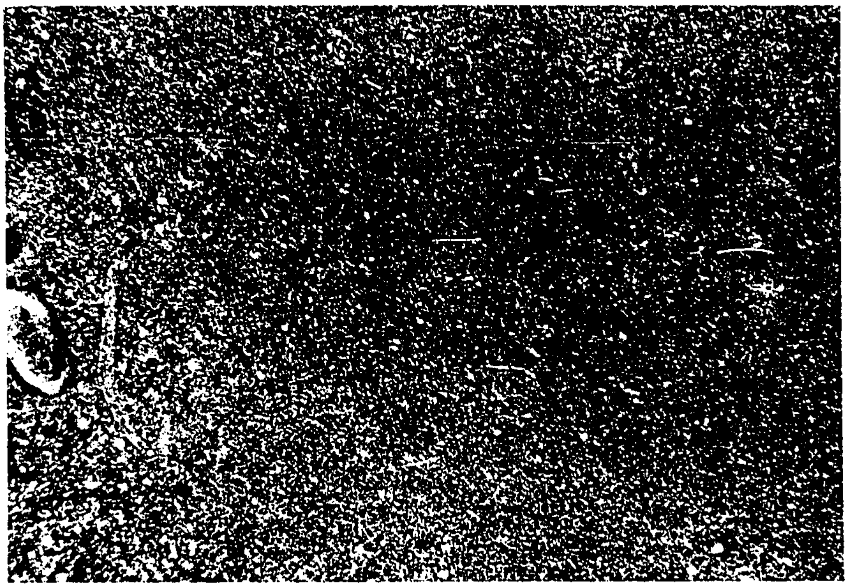


Figure 15: Thin-section photograph of a micstone (scale: 1 cm = 150 microns).

Figure 16: Thin-section photograph of a siltstone. Note the abundance of quartz silt, and occasional feldspar grains (microcline twinning on grain at right). Scale: 1 cm = 40 microns.



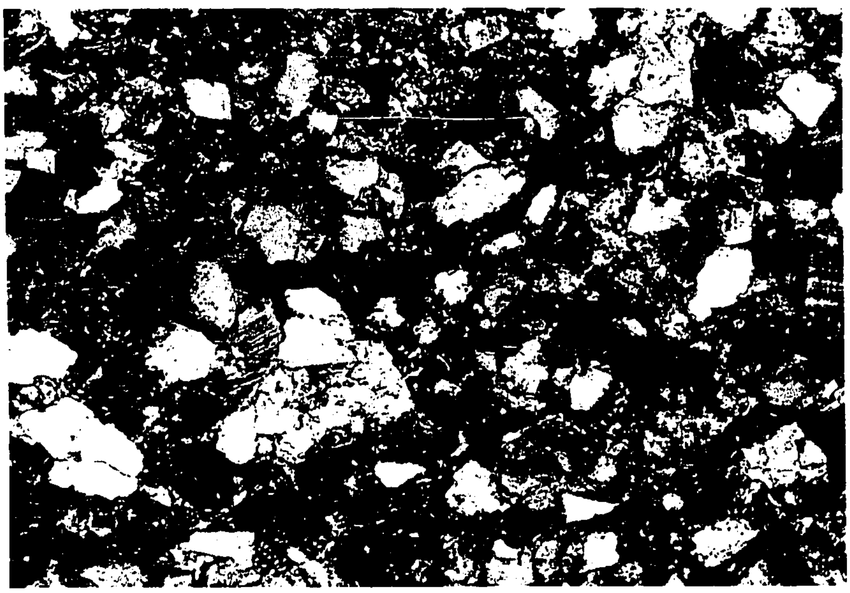
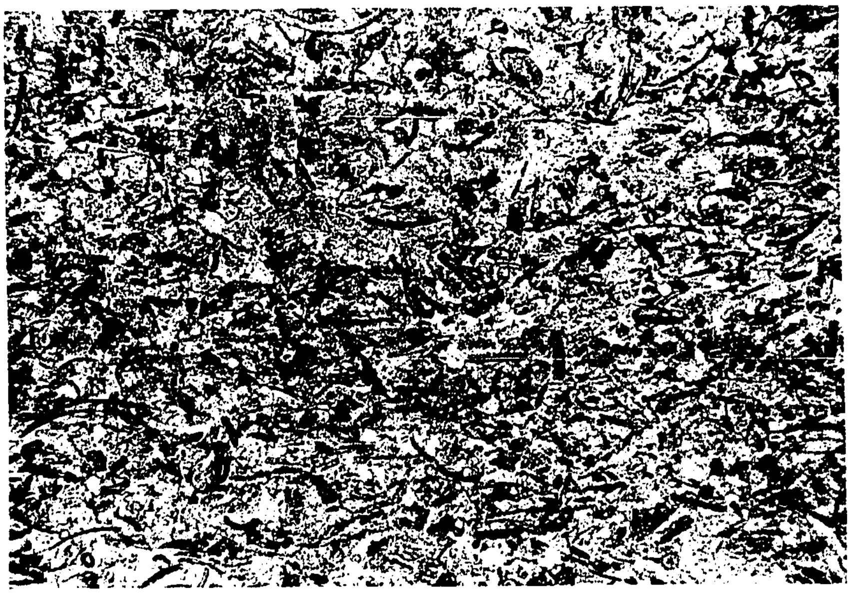


Figure 17: Thin-section photograph of a coarse-grained, poorly sorted "poorly washed grainstone." Note the presence of small amounts of matrix (scale: 1 cm = 150 microns).

Figure 18: Thin-section photograph of a coarse-grained, poorly sorted "coarse grainstone." Note the absence of matrix (scale: 1 cm = 150 microns).

Figure 19: Thin-section photograph of a "fine grainstone." Note the fine grain size (compare with Fig. 18) and good sorting (scale: 1 cm = 150 microns).

Figure 20: Thin-section photograph of a "calcisiltite." Note the very fine grain size and good sorting. Compare this rock type with Figs. 18 and 19 (scale: 1 cm = 150 microns).



a group, packstones exhibit the highest faunal diversity of all eight rock types, and are composed of an open-marine assemblage of bryozoans, brachiopods, pelecypods, crinoids, trilobites, gastropods, and others. Nearly three-fourths of the preserved fauna are bryozoans, brachiopods, and pelecypods.

Although bedding characteristics are variable, packstones dominantly occur in planar, moderately continuous beds having lenticular geometries. Packstone beds are quite variable in thickness, but average 8 cm. The bottoms of packstone beds can be flat, irregular, or wavy, but the tops of most beds are flat. Trace fossils and sedimentary structures are rare.

The abundance of matrix, poor sorting, low degree of breakage, and lack of sedimentary structures indicates that packstones represent the *in situ* accumulation of carbonate debris in non-turbulent environments below wave base. Winnowing and transportation effects were minimal. The abundant and highly diverse fauna suggests that sedimentation occurred in non-turbid, nutrient-rich, open-marine waters having normal salinities and temperatures (Heckel, 1972).

Wackestones

Wackestones (Dunham, 1962) are mud-supported, fossil-bearing carbonate rocks. By definition, they contain from 10 to 45 percent carbonate grains (an average of 26%) and more than 55 percent matrix (an average of 69%). Wackestones exhibit nearly the same fauna, textures, bedding characteristics, and hence, interpretations as packstones; therefore, this information will not be repeated here. However, wackestones possess a slightly higher degree of bioturbation than packstones. Trace fossils include *Phycodes*, *Chondrites*, *Paleophycus*, and *Trichophycus* (all horizontal feeding or locomotion traces). Because of the lower percentage of fossil grains and abundance of carbonate mud, wackestone sediments were more attractive to burrowing organisms, particularly soft-bodied ones. Because of this higher degree of bioturbation, wackestone substrates may have been less cohesive than packstone substrates, and thus, more susceptible to erosion (see Rhoads, 1972). This may explain why wackestone beds are the least abundant rock type in most stratigraphic units (an average of only 6%).

Micstones

The term "micstone" is synonymous with Dunham's "mudstone" (1962), and is preferred in this report to avoid confusion with the shale term "mudstone." Micstones are matrix-rich limestones containing less than 10 percent fossils (an average of 4%). Often these fossils are small, broken fragments. Trace fossils are common, including *Chondrites*, *Trichophycus*, *Paleophycus*, mollusc trails, vertical tubes (escape?), and rare *Phycodes*. Micstone beds are usually thin (averaging 3 cm), wavy to nodular, laterally discontinuous, and occasionally rippled. Micstone sediments are normally thought to accumulate in non-turbulent environments below wave base. However, the wavy-to-nodular bedding and occasional presence of escape structures, ripples, and admixed quartz silt suggests that these carbonate muds were subjected to high-velocity storm transportation (see "Storm Cycles").

Siltstones

Siltstones are defined in this report as any terrigenous rocks of silt size (less than 0.062 mm) regardless of fabric. Thin-section analysis reveals that the average siltstone has the following composition: quartz silt (58%), feldspar (1%), heavy minerals (2%), clays + micas (16%), fossil fragments (2%), calcite cement (7%), dolomite cement (10%), and pyrite (4%). Fossils are usually small, broken fragments less than 0.4 mm in size. Quartz silt averages 0.039 mm in diameter, and reaches a maximum of 0.14 mm (fine sand). In addition, fining upward of the silt fraction is occasionally detected.

Siltstone beds are planar, wavy, or nodular, laterally discontinuous, and thin (averaging 4 cm). Most siltstone beds are laminated or cross-laminated. Three lamination types occur: (1) planar lamination (i.e., horizontally oriented with only minor undulations); (2) wave-ripple cross lamination (i.e., bundled sets of ripple-shaped laminae with erosional contacts between sets); and (3) hummocky cross lamination (i.e., large-scale undulations with gentle dips, high wavelengths, and low amplitudes). The thickness of individual laminae ranges from 0.1 mm to 0.8 mm, averaging 0.34 mm. Laminae are formed by the alternation of quartz-rich and clay-rich layers. Sedimentary structures are common, including symmetric and asymmetric ripples, starved ripples (rare), gutter casts (i.e., elongate, channelized cut and fill structures), tool marks, and flute casts. Of the eight rock types studied, siltstones have the highest degree of bioturbation. More than 90 percent of all taxonomically distinguishable trace fossils occur in siltstones. Trace fossils include *Chondrites* (both horizontal and vertical), *Diplocraterion*, mollusc trails and impressions, *Paleophycus*, *Phycodes*, *Rusophycus*, *Trichophycus*, and vertical tubes (probably escape structures).

Siltstones probably represent the rapid deposition of terrigenous silts and clays from suspension. Two probable depositional mechanisms are high-energy storm events and storm-generated gravity flows (see "Storm Cycles).

Poorly Washed Grainstones

"Grainstones" (Dunham, 1962) are grain-supported rocks which lack carbonate matrix. For interpretive purposes, Cincinnatian grainstones have been subdivided into four categories: "poorly washed grainstones," "coarse grainstones," "fine grainstones," and "calcisiltites." "Poorly washed grainstone" is a term used in this paper to represent those carbonate rocks that contain small amounts of matrix. By definition, a poorly washed grainstone contains more than 45 percent carbonate grains (an average of 67%) and from 6 to 15 percent carbonate matrix (an average of 8%). Matrix, although interstitial, is usually attached to fossil grains. These rocks are moderate-to-poorly sorted, coarse grained, and have a moderate degree of fossil breakage. Fossil orientation is dominantly subhorizontal, although imbricate and low-angle inclined orientations are occasionally found. Faunal diversity is lower than that of packstones, but nearly the same fossil types and abundances can be found.

Poorly washed grainstones usually occur in planar, moderately continuous-to-continuous beds having lenticular geometries. Bedding thickness averages 9 cm. The bottoms of beds are either flat, irregular, or wavy. The tops of most beds are flat, although irregular-to-wavy tops sometimes occur. Sedimentary structures are rare, but include imbricate fossils and ripples. Trace fossils are also rare.

The presence of small amounts of matrix, moderate-to-poor sorting, coarse grain size, and occasional ripples suggests that poorly washed grainstones represent the *in situ* accumulation of carbonate dëbris in slightly turbulent environments at or near wave base. Winnowing was incomplete, and transportation effects were minor. These rocks probably represent the partial winnowing and sorting of originally mud-rich sediments by storm events (see "Storm Cycles"). The abundant and diverse fauna suggests non-turbid, nutrient-rich, open-marine waters having normal salinities and temperatures (Heckel, 1972).

Coarse Grainstones

"Coarse grainstones" are defined as grain-supported carbonate rocks containing more than 45 percent grains (an average of 58%), less than 6 percent matrix (an average of 2%), and having a grain size greater than 2 mm (an average of 4.5 mm in hand specimen). These rocks are moderately sorted and have a moderate-to-high degree of fossil breakage. The dominant fossil orientation is subhorizontal. Faunal diversity is about the same as that of packstones, but crinoids and brachiopods are nearly twice as abundant. Bedding characteristics are the same as those of poorly washed grainstones. Trace fossils are very rare.

The lack of matrix, moderate sorting, moderate-to-high degree of fossil breakage, and bedding features indicate that coarse grainstones represent the *in situ* accumulation of carbonate debris in turbulent environments above wave base. Winnowing was more complete, although transportation effects were moderate to low. These rocks probably represent the winnowing and partial sorting of sediments by high-energy storm events (see "Storm Cycles"). The abundant and diverse fauna suggests non-turbid, nutrient-rich, open-marine waters having normal salinities and temperatures.

Fine Grainstones

"Fine grainstones" are distinguished from "coarse grainstones" by their finer grain size (less than 2 mm by definition), better sorting (well sorted), higher degree of fossil breakage (high breakage), and absence of carbonate matrix. Fossil orientations range from random to inclined, and parallelism of grains is high. Faunal diversity is low, and fossils are dominated by crinoids, brachiopods, and bryozoans. In addition, some beds contain articulated brachiopods or crinoids stems.

Although bedding thickness is variable, fine grainstone beds are the thickest of all eight rock types, averaging 15 cm. These beds are planar and continuous, and have rippled or flat tops and variable bottoms. Graded beds are common. Thirty-one percent of all samples studied fine upward. Sedimentary structures are also abundant, including symmetric, asymmetric and starved ripples, shale clasts (up to 12 cm long), carbonate intraclasts, flute and groove marks, tool marks, gutter casts, imbricated shells, and load structures. Trace fossils are very rare.

The lack of matrix, fossil orientations, textural maturity, and abundance of sedimentary structures indicate that fine grainstones represent sediments that have undergone a high degree of hydraulic sorting, winnowing, and transportation. They were probably deposited rapidly by high-energy processes such as storms or gravity flows (see "Storm Cycles").

Calcisiltites

"Calcisiltite" was originally proposed as a term to describe all silt-size carbonate rocks, regardless of composition (Grabau, 1904). "Calcisiltite" is used in this report to refer to grainstones having a mean grain size less than 0.5 mm. Calcisiltites are very well sorted, and have a very high degree of fossil breakage. Fossils exhibit a high degree of parallelism, and are oriented subhorizontally. Many samples contain articulated brachiopods or crinoid stems (44 percent). Most calcisiltites are silty, containing an average of 11 percent quartz silt. Faunal diversity is the lowest of the eight carbonate rock types. However, this may be a function of grain size because the most abundant fossil types are small, unidentifiable fragments.

Calcisiltite beds are the thinnest of the grainstone group, averaging 6 cm. These beds are moderately continuous, planar to wavy, and often laminated or cross-laminated. Individual laminae are formed by the alternation of coarse and fine layers, by cement-rich and cement-poor layers, or (more rarely) by quartz-rich and quartz-poor layers. Graded beds are very common. Forty-four percent of all beds fine upward. Sedimentary structures are also common, including symmetric, asymmetric, and starved ripples, occasional small shale clasts, intraclasts, sole marks, and load structures. Trace fossils include *Chondrites* (both horizontal and vertical), *Diplocraterion*, *Paleophycus*, *Trichophycus*, and vertical escape tubes. The interpretation of calcisiltites is equivalent to that of fine grainstones.

Carbonate Diagenesis

The effects of diagenesis on Cincinnatian carbonates were not extensively studied in this project. I recognize that the reconstruction of the diagenetic history of these rocks is another thesis in itself, and that to complete such a project would require more than just thin-section analysis. Modern analytical equipment such as the cathode luminoscope, scanning electron microscope, mass spectrometer, and electron microprobe can be used to enhance information gained from stained thin sections, particularly with respect to isotopic and trace element composition of diagenetic minerals. Nevertheless, some valuable information has been compiled from thin-section data in this study, and is summarized in the following subsections.

Matrix

Most of the fine carbonate matrix in Cincinnatian limestones is coarser than the size range specified for "micrite" (i.e., less than 5 microns; Folk, 1959), and therefore would be more precisely named "fine microspar." However, for the purposes of this paper, and to avoid the uncertainty over Folk's concept of "microsparitization," the term "matrix" will be used instead of "micrite," and will refer to very fine carbonate material less than 30 microns in size.

Matrix is unlaminated, sometimes grumelous or pelletal, and composed of platey, irregularly shaped crystals, ranging from 4 to 30 microns in size (an average of 10 microns). Matrix may also contain variable amounts of quartz silt, clays, dolomite, pyrite, hematite, and limonite. Matrix may be interstitial (between grains), attached to grains in the form of irregularly shaped clumps, as "envelopes" which completely surround grains, or as internal pore fillers of some bioclasts.

Matrix is believed to represent carbonate mud which was mechanically deposited from suspension in low-energy environments, or biologically deposited in the form of fecal pellets. The importance of biologic pelletization as a depositional mechanism for fine muds has been outlined by Pryor (1975). The pellet-making capacities of benthic invertebrates are sedimentologically important in this study, and are discussed in the section entitled "Autecological Analysis of Cincinnatian Fossils." There is no evidence to suggest a non-depositional origin for matrix, such as completely micritized grains, or "ghosts" of micritized grains. In addition, much of this matrix may have originated from the comminution of preexisting skeletal material (Lobo and Osborne, 1973).

Dolomite

Ferroan dolomite is a common constituent in many Cincinnatian limestones. Eighty-six percent of all samples studied contain some dolomite. Dolomite content in limestone samples varies from less than 1 percent to 22 percent, and averages 3 percent. However, these values may be underestimated by as much as 5 to 10 percent because, during point counting, points that fell on dolomite rhombs inside of bioclast pores were counted as bioclasts.

Ferroan dolomite occurs as light blue, moderately well-sorted, euhedral-to-subhedral, coarse-grained rhombs (averaging 80 microns and ranging from 30 to 250 microns). In grainstones dolomite usually occurs as an internal pore filler or as isolated clusters, representing the replacement of pellet nests of intraclasts. In packstones dolomite replaces matrix, internal pores of bioclasts, pellets, and more rarely, bioclasts. Matrix and internal pore replacement account for over 90 percent of the dolomite. Although some dolomite is disseminated throughout the matrix, the majority occurs in isolated clusters between, inside, and under shells, especially where geopetal structures are present. In addition, some rhombs are zoned, suggesting at least two stages of crystal growth.

In order to explain the occurrence of ferroan dolomite in Cincinnatian carbonates, the general requirements for non-ferroan dolomitization must first be considered. Deffeyes et al. (1965), Von der Borch (1965a), and others have developed models for dolomitization that require seawater evaporation and high Mg^{++}/Ca^{++} ratios in solution. However, these models do not explain the numerous occurrences of dolomite in rocks that are not associated with sabkha or evaporite deposition. Badiozamani (1973) suggests that a high Mg^{++}/Ca^{++} ratio is not necessary, pointing out that excess magnesium in solution actually inhibits dolomitization, and that the process requires a lower Mg^{++} concentration than is found in seawater. This can be accomplished by mixing groundwater with 5 to 30 percent seawater, provided that the solution is supersaturated with respect to dolomite (i.e., where IAP > K, for the reaction:

$$CaMg(CO_3)_2 \rightleftharpoons Ca^{++} + Mg^{++} + 2CO_3^{--},$$

$$\text{where} \quad K = \frac{[Ca^{++}]\ [Mg^{++}]\ [CO_3^{--}]^2}{[CaMg(CO_3)_2]}$$

$$\text{and} \quad IAP = [Ca^{++}]\ [Mg^{++}]\ [CO_3]^2,$$

and by definition

IAP > K, supersaturated solution

IAP = K, saturated solution

IAP < K, undersaturated solution).

In addition to these generalized requirements for dolomitization, sufficiently high Fe^{++}/Mg^{++} and Fe^{++}/Ca^{++} ratios must exist in solution to produce ferroan dolomite, but the minimum numerical values of these ratios required to produce ferroan dolomite are unknown (Oglesby, 1976; Al-Shaieb and Shelton, 1978). However, the effect of these ratios is very small in comparison to that of the oxidation-reduction potential (Eh) of the solution (Oglesby, 1976). In order for ferrous ions to remain stable, the Eh of the solution must be low enough to offset the elevated pH conditions imposed on the system by the presence of carbonate minerals and by the bacterial reduction of organic matter (Evamy, 1969; Sass and Kolodny, 1972). Thus, Fe^{++} remains in solution and is available for incorporation into dolomite at high pH values only under reducing pore water conditions (Evamy, 1969; Choquette, 1971; Katz, 1971; Oglesby, 1976; Jacka and Brand, 1977; and Al-Shaieb and Shelton, 1978). Figure 21 illustrates this point. Dolomite can only form if the pH is greater than 7.8 (Krumbein and Garrels, 1952, fig. 8). In addition, the bacterial reduction of organic matter in the sediment will drive the pH even higher (greater than 8), producing a zone in which ferroan dolomite can form. Note that this zone falls below the zero Eh line (reducing conditions). Jacka and Brand (1977), and Evamy (1969) suggest that these conditions most likely occur below the water table in the phreatic zone.

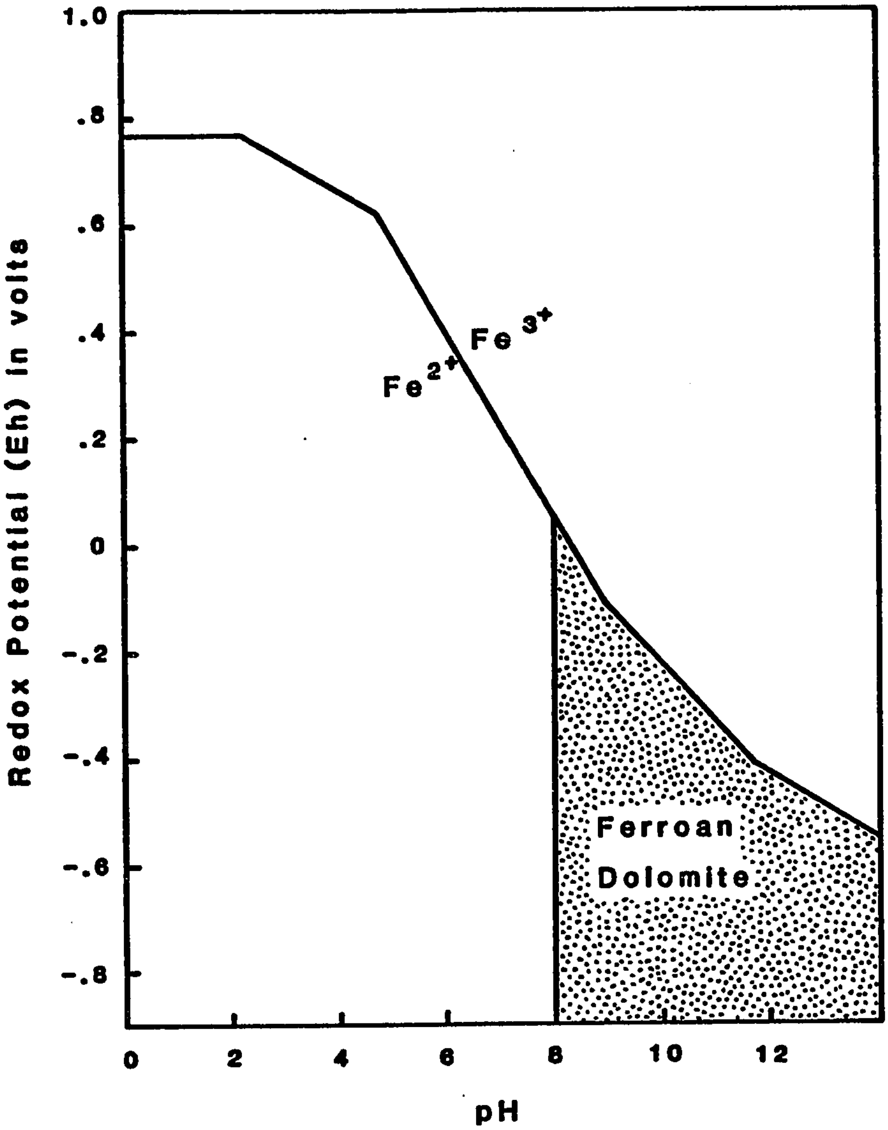


Figure 21: Eh - pH diagram showing the likely stability field of ferroan dolomite (modified from Hem and Cropper, 1959, fig. 6).

The temperature at which ferroan dolomite is formed is another aspect to consider. Choquette's (1971) analysis of ferroan dolomites in the St. Genevieve Formation (Mississippian) indicates that precipitating waters were warm. Rosenburg (1967) has demonstrated that the iron content in artificial dolomites is temperature dependent, reaching a maximum of 36 mole percent $FeCO_3$ at 550°C. Boles (1978, fig. 9) has suggested that as temperature increases, the equilibrium constant, K, also increases for the reaction:

$$4\ CaCO_3 = Fe^{++} + Mg^{++} = 2\ CaFe_{.5}Mg_{.5}(CO_3)_2 + 2\ Ca^{++},$$

$$\text{where}\quad K = \frac{[Ca^{++}]^2\ [\text{ankerite}]^2}{[CaCO_3]^4\ [Fe^{++}]\ [Mg^{++}]},$$

$$\text{and}\quad K = \frac{[Ca^{++}]^2}{[Fe^{++}]\ [Mg^{++}]}.$$

Thus, with increasing temperature (and increasing K) it takes progressively smaller concentrations of Fe^{++} and Mg^{++}, relative to Ca^{++}, to produce ferroan dolomite. Boles also notes that increasing pressure also increases the equilibrium constant, but that the pressure effect is very small in comparison to the temperature effect. However, Boles' assumption that [ankerite] = $[CaCO_3]$ = 1.0 is invalid. Furthermore, the maximum iron content reported in natural, mostly low temperature ferroan dolomite (35 mole percent $FeCO_3$) is very close to that of high-temperature, synthetic dolomite (36 mole percent $FeCO_3$), suggesting that elevated temperatures *may not* be necessary for iron substitution in dolomite, although they may speed it up.

Thus, the presence of ferroan dolomite (in addition to ferroan calcite) in Cincinnatian carbonates indicates that post-depositional pore waters were characterized by: negative Eh conditions (reducing pore waters), sufficiently high concentrations of Fe^{++}, the presence of decomposing organic matter, high pH conditions (greater than 7.8), and mixing of marine and freshwater.

Because dolomite rhombs rarely penetrate grain margins and never penetrate calcite cements, dolomitization may have been an early diagenetic process that occurred before calcite cementation. This idea is supported by the common occurrence of dolomite clusters in close proximity to skeletal grains, which suggests that ferroan dolomite formed at pre-cementation sites of maximum porosity and permeability (for ease of marine and freshwater mixing), or in proximity to bacterial decomposition of organic tissue attached to invertebrate shells (i.e., lowest Eh conditions).

However, if the ferroan dolomite formed during early diagenesis, it must be explained how marine and freshwater mixing could have occurred during Cincinnatian time when the nearest shoreline was more than 400 miles to the east. Other than sporadic periods of subaerial exposure during Richmondian time, a shoreline did not exist in the Cincinnati area until the Middle Silurian.

A more logical conclusion is that the ferroan dolomite is post-cementation, and therefore late diagenetic, possibly forming during Middle Silurian or Early Devonian time. The absence of dolomite in calcite cements or skeletal fragments may instead indicate fabric-controlled dolomitization. In other words, it may be kinetically easier for dolomite to replace micrite because the latter has abundant microporosity and greater surface area (and sites) for dolomite nucleation than skeletal grains and cements.

Sparry Calcite

Three well-known varieties of calcite spar occur in Cincinnatian carbonate rocks: drusy spar, blocky spar, and syntaxial rims. "Drusy spar" is a term which describes fine, elongate crystals which are oriented perpendicular to grain surfaces and point toward the center of pore spaces. These crystals are generally thought to represent true pore-filling cement. Two basic varieties of drusy spar have been identified. Wide, blade-shaped crystals are usually referred to as "bladed spar," "dogtooth spar," or "rhombohedral spar." Thin, elongate, needle-like crystals are usually referred to as "fibrous spar," "acicular spar," or "scalenohedral spar." In Cincinnatian limestones the bladed variety is most common. "Blocky spar" (also known as "equant spar") is a term which describes equant-shaped crystals which are larger than drusy crystals, and commonly fill the centers of pore spaces. Blocky spar can be true pore-filling cement or neomorphic in origin. "Syntaxial rims" (also known as "syntaxial overgrowths") are ovoid-to-equant shaped crystals that completely surround fossil grains and are optically continuous with fossil nuclei. Again, syntaxial spar can be either precipitated cement or neomorphic in origin. This type of spar frequently surrounds crinoid fragments in Cincinnatian limestones.

To facilitate the description of calcite spar in Cincinnatian carbonates, the classification of Orme and Brown (1963) was used (Figure 22). This classification is based on composite spar types and where they occur (i.e., "fabric"), and it distinguishes true pore-filling cement from spar of neomorphic origin. Five varieties of sparry fabrics occur in Cincinnatian limestones: "granular cement," "drusy mosaic," "syntaxial cement rims," "coarse mosaic," and "syntaxial replacement rims."

Most of the spar in Cincinnatian carbonate rocks is true pore-filling cement, having dogtooth spar rims, centripetal enlargement of crystals, three to five generations of cement, and many enfacial junctions. Moreover, rock fabrics suggest that this spar is true cement. The highest percentage of spar occurs in grain-supported rocks containing more than 50 percent fossil fragments. In addition, particles composed of micrite (i.e., pellets and micrite-filled casts) are not converted to spar, no relict structures can be seen, mechanically deposited micrite is present but unaltered (except for some possible microsparitization), contacts between grains and spar are sharp, and geopetal structures are common. More than 90 percent of this spar is ferroan calcite. In some cases, nonferroan dogtooth spar and syntaxial overgrowths enlarge centripetally into blocky ferroan calcite centers, indicating two different chemical environments of cementation.

Neomorphic spar occurs in two forms: "coarse mosaic" and "syntaxial replacement rims" (Orme and Brown, 1963, fig. 1). Some neomorphic spar occurs in almost every sample. However, in samples containing an abundance of neomorphic spar, the rock texture is highly suggestive of recrystallization. These samples exhibit few of the characteristics of

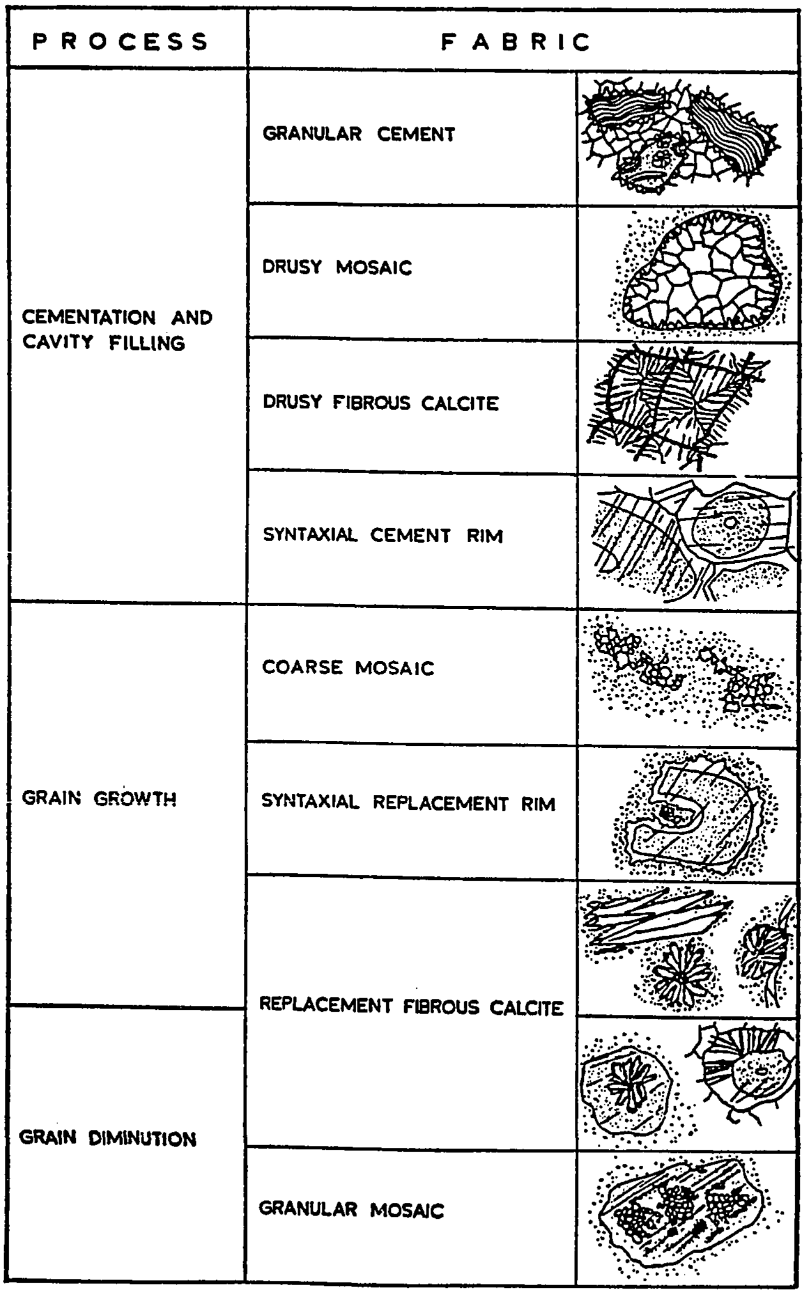


Figure 22: Classification of sparry calcite facrics (from Orme and Brown, 1963, fig. 1).

cement previously mentioned, and are always loosely packed, containing grains that seem to be floating in spar. A comparison of grainstones and packstones reveals that neomorphic spar is most abundant in packstones (Table 3).

The precipitation of ferroan calcite requires nearly the same geochemical conditions as that of ferroan dolomite. Thus, cementation must have taken place in the presence of reducing pore fluids saturated with respect to calcite. These fluids contained high concentrations of Fe^{++}, decomposing organic matter, and had a pH greater than 7.8. Because marine and freshwater mixing is not a requirement for the precipitation of ferroan calcite, and because nonferroan dogtooth rims sometimes occur, cementation may have occurred during early diagenesis, while the rocks were still in the marine environment (i.e., pre-dolomitization). However, additional study will be necessary to prove this idea. Perhaps future workers will be able to enhance our understanding of cementation by investigating topics such as stages of cementation and the related chemistry of enclosing pore fluids, cement stratigraphy, and time of cement emplacement.

Silica

Partial silicification of Cincinnatian carbonate rocks is limited to a narrow zone of Richmondian strata in the Brookville, Indiana, region (upper Liberty Formation, and Saluda Formation). Microcrystalline quartz having a spherulitic or fibrous texture (chalcedony) appears as a replacement feature of individual fossil fragments, matrix, or spar. Silicification does not appear to be fabric controlled. It occurs in a variety

ROCK TYPE	PORE-FILLING CEMENT			NEOMORPHIC SPAR	
	Granular Cement	Drusy Mosaic	Syntaxial Cement Rims	Coarse Mosaic	Syntaxial Replacement Rims
Packstone	21%	36%	0%	20%	23%
Grainstone	75%	3%	20%	2%	0%

<u>Table 3</u>: A Comparison of Sparry Calcite Fabrics in Cincinnatian Packstones and Grainstones (averaged from thin-section data).

of rock types and may replace individual fossils, or parts of fossils, without affecting the surrounding matrix or spar; or it may replace all three. Delicate skeletal structures such as organic lamellae in brachiopods are usually preserved.

The replacement of carbonate material by chalcedony is poorly known and difficult to understand. In general, the chemical conditions necessary for silicification are relatively low pH, low temperature, and saturation of pore fluids with respect to silica (Blatt et al., 1980). In addition, the chalcedony is length-fast (i.e., having its C-axis perpendicular to fibers), suggesting that silicification occurred in a low pH, non-sulphate environment (Folk and Pittman, 1971). The preservation of delicate skeletal structures suggests that this process is one of simultaneous dissolution of calcite and precipitation of chalcedony. The origin of the silica is unknown; however, the rare occurrence of sponge spicules (e.g., sample BN 33.3, lower Saluda Formation) suggests that siliceous sponges could have been a source of dissolved silica.

Phosphate

Minor amounts of phosphate (in the form of amorphous collophane) occur in most Cincinnatian carbonates. Collophane occurs as thin, elongate fragments, sometimes having dentate ridges. Some of these fragments have been positively identified as conodonts (Repetski, pers. comm., 1979). However, some of these structures could also be polychaete bristles (see Schafer, 1972, pp. 176-178). Collophane has also been observed as a pore filler in some bioclasts, especially small gastropods of the genus *Cyclora*, but also in bryozoan zoecia, trilobite spines, and crinoids.

Moreover, collophane content varies stratigraphically, becoming most abundant in limestones of the Mt. Auburn and Oregonia formations, where it reaches a maximum of 52 percent (sample Ru 9.55), and averages 14 percent.

The conditions necessary for phosphatization of carbonate sediments have been recently discussed by Wilson (1975), Baird (1978), and Blatt et al. (1980). In general, collophane can form on very shallow marine shelves adjacent to deep water upwelling zones. Climate must be warm and arid, and clastic sedimentation must be very slow. The process is believed to occur in the follow steps: (1) The process of upwelling transports cold, phosphate-rich waters onto a warm, shallow shelf. (2) Extensive bioturbation facilitates chemical exchanges between the sediment and phosphate-rich marine water. (3) Phosphatization occurs in anoxic, organic-rich bottom sediments which are undergoing bacterial decomposition. These requirements are sedimentologically important and will be discussed in the section entitled "Lithogenetic Sequences."

Pyrite, Limonite, and Hematite

Small amounts of pyrite are present in almost all Cincinnatian limestones (usually less than 5 percent). Pyrite occurs as small, euhedral-to-subhedral crystals (less than 100 microns) that are disseminated in matrix and spar, or as internal pore fillers. In addition, pyrite partially replaces some fossil fragments (particularly trilobites). There does not appear to be any stratigraphic variation in pyrite content, although unusually large crystals (up to 1 cm) are locally found in the Brookville, Indiana, region (Liberty Formation). The presence of pyrite in Cincinnatian limestones indicates that diagenetic pore fluids were reducing (i.e., negative Eh; see Krumbein and Garrels, 1952). According to Berner (1981), the presence of pyrite also indicates anoxic, sulfidic conditions (i.e., $[O_2] < 10^{-6}$ moles/liter, and $[H_2S] > 10^{-6}$ moles/liter).

Hematite is present in very small amounts, usually surrounding pyrite crystals, and therefore is believed to be a modern weathering product of pyrite. Limonite is more abundant, and appears as a yellowish-brown stain on outcrops which have been exposed to weathering for a number of years.

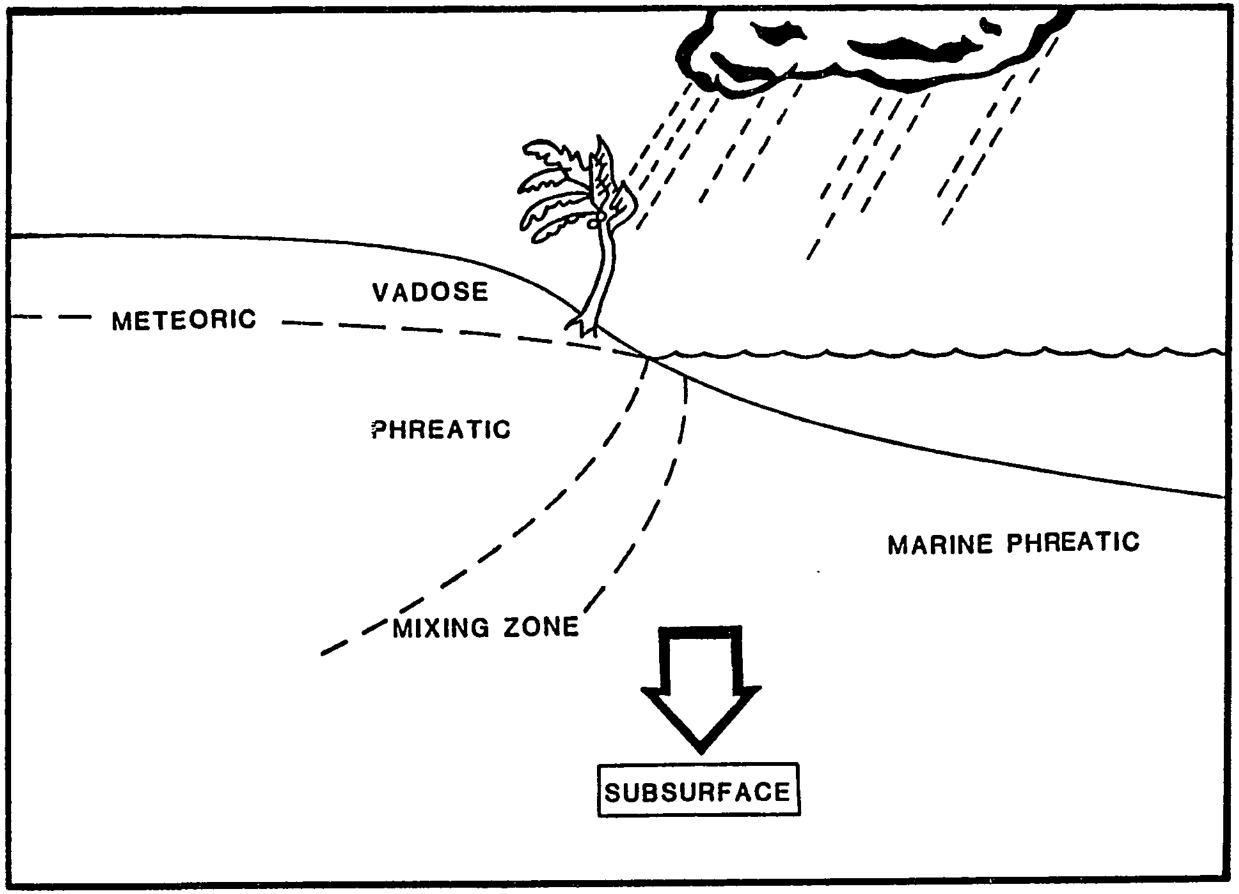
Diagenetic Environments

Diagenetic environments are areas in which similar patterns of diagenesis occur. They are usually defined by pore fluid chemistry and by the distribution of fluids within pore spaces. Diagenetic environments are different from depositional environments because they are mobile and repetitive. The deposition of sediment usually occurs only once in response to the specific processes active within a depositional environment. On the other hand, diagenetic minerals are precipitated in response to the specific diagenetic environment (i.e., pore fluids) which may enter the body of rock at various times. Thus, multiple diagenetic events may occur in a body of rock, each leaving its own "fingerprint" in the form of specific minerals, fabrics, isotopes, and trace elements. Furthermore, the effects of one diagenetic event can erase the imprint of an earlier diagenetic event through dissolution or neomorphism.

The delineation of diagenetic environments and their timing is important in understanding the diagenetic history of the Cincinnatian Series. While I recognize that thin-section analysis alone is insufficient to complete this goal, it is nevertheless possible to perceive the "imprint" of some of these diagenetic environments, even if their timing cannot be determined at present.

Several classifications of carbonate diagenetic environments have appeared in the last decade (e.g., Land, 1970; Folk, 1974; Matthews, 1974; Longman, 1980). Generally, four diagenetic zones are recognized: "marine phreatic," "meteoric phreatic," "mixed marine-meteoric phreatic," and "meteoric vadose." These zones have been recently described by Longman (1980). Hendricks (in progress) has added a fifth diagenetic environment, the "deep subsurface," in his study of the diagenesis of the Brassfield Formation (Silurian) of Ohio. Figure 23 (from Hendricks, in progress) and Table 4 (from Hendricks, in progress) compare the characteristics of these five diagenetic environments.

Diagenetic minerals and textures in Cincinnatian carbonates suggest that these rocks were subjected to at least two of these diagenetic environments. The presence of ferroan dolomite, ferroan calcite (both equant and rhombohedral), syntaxial overgrowths, and silica replacement suggests diagenesis in the "mixing zone." In addition, the occasional presence of nonferroan dogtooth spar indicates that these rocks were temporarily subjected to diagenesis in the "marine phreatic zone."



<u>Figure 23</u>: Coastal profile showing the positions of carbonate diagenetic environments (from Hendricks, in progress).

CRITERIA	DIAGENETIC ENVIRONMENT				
	METEORIC VADOSE	METEORIC PHREATIC	MARINE PHREATIC	MIXING ZONE	DEEP SUBSURFACE
PORE FLUIDS	Air and water Low: Na, Mg, Mn, Fe, Sr	Fresh water Low: Na, Mg, Sr Mod: Mn, Fe	Salt water High: Na, Mg, Sr Low: Fe, Mn	Mixed meteoric and marine water Mod: Na, Mg, Mn, Fe, Sr	Most like meteoric pore fluids Variable High: Fe
PROCESSES	Extensive solution CO_2 degassing Evaporation	Mixing of natural waters Changes in temperature and partial pressure of CO_2	High pore fluid flux CO_2 degassing High organic activity	Mixing of natural waters	Increasing pressure and temperature Variable pore fluid composition
PRODUCTS	Minor cementation Formation of moldic porosity	Extensive cementation and neomorphism Rapid stabilization of Mg-calcite and aragonite	Restricted cementation (reefs and surf zones) Micritization No leaching	Dolomitization Cementation Silicification Stabilization of sedimentary grains	Cementation Pressure-solution features Dolomitization
CEMENTS	Fine equant calcite Miniscus and pendant fabric	Equant calcite Syntaxial overgrowths (crinoids) Isopachous rhombohedral calcite Interlocking crystals coarsen toward pore centers	Micritic Mg-calcite Isopachous rhombohedral to scalenohedral Mg-calcite and aragonite Random aragonite needles	Equant calcite Syntaxial overgrowths Micritic to rhombohedral Mg-calcite	Equant calcite
POROSITY	Preservation of depositional porosity and creation of secondary porosity	Relatively low porosity	Preservation of depositional porosity	Relatively low porosity	Destruction of primary porosity/creation of extensive secondary fracture porosity

Table 4: A comparison of the characteristics of five diagenetic environments (from Hendricks, in progress).

SEDIMENTOLOGY OF CINCINNATIAN SHALES

Previous Work

In the past, shale petrology has been repeatedly neglected by geologists in spite of the fact that shale makes up 58 percent of the total thickness of the Cincinnatian Series. Because shales are fine grained, lack sedimentary structures, and are less productive of fossils than limestones, these geologists have instead preferred to base their studies on interbedded limestones in the section. For example, Martin (1975, p. 911) described the shales in the entire Cincinnatian Series in *one paragraph*, referring to them as "enclosing shales." The attitude that shales are barren rocks with little interpretive value is widespread in the literature. Furthermore, the few studies of Cincinnatian shales that exist are based almost entirely on X-ray diffraction and chemical analyses, rather than on thorough microscopic examinations. Table 5 summarizes this work.

The first petrographic study of Cincinnatian shales was that of Tobin (1980), who utilized stained, ultra thin sections (i.e., 10 to 15 microns thick). In that study, the mineralogy, fabric, grain size, fauna, and trace fossils of Maysvillian-age shales were described. In addition, an original petrographic classification scheme was devised for use with carbonate rich shales. The present study extends that analysis to the entire Cincinnatian Series. Shales are thoroughly described, both in outcrop and in thin section, and interpretations are made about source area, depositional rate, modes of transportation and deposition, depositional environments, and the effect of shale deposition on benthic ecology.

Table 5: Summary of Cincinnatian Shale Studies

Author and Publication Date	Technique Employed and Conclusions
Weidner (1962)	Studied regional and some stratigraphic variation in chemical composition of shales. Used X-ray spectrochemical techniques.
Scotford and Smoot (1962)	Mineralogical study utilizing X-ray and some optical methods. Mineral homogeneity is stressed, suggesting that stratigraphic differentiation should be based on faunal criteria.
Scotford (1965)	Mineralogical, chemical, and textural study. Some vague and poorly written petrography. Made some very interesting environmental and diagenetic conclusions, however. Also suggested that biostratigraphic differentiation is best.
Bassarab and Huff (1968)	Clay mineralogical analysis based on X-ray diffraction, electron-microscopy, cation-exchange, and DTA studies. Reveals a suite of illite and chlorite, and lesser amounts of illite-montmorillonite and vermiculite.
Butler and Scotford (1973)	Applied stepwise discriminant function analysis to data derived from previously described shales (Scotford, 1965). Advocates the use of shale petrology for future stratigraphic work on the Cincinnatian.

Shale Petrology

Outcrop Data

The term "shale" is used in this paper as a field name for ". . . all fine-grained argillaceous sediment, including mud, clay and mudstone . . ." following the usage of the word by Potter, Maynard and Pryor (1980, p. 3). Thus, any argillaceous rocks finer than silt size are referred to as shales, regardless of lamination, parting, composition, or fabric.

Cincinnatian Series shales have the following outcrop characteristics: (1) Color is either gray or brown (mostly "olive gray," 5Y 4/1, and "dark yellowish brown," 10YR 4/2). (2) All are very soft, but indurated. (3) Shales weather more readily than limestones. (4) The majority show parting, ranging from "fissile" to "flaggy" (see Potter, Maynard and Pryor, 1980, table 1.3). (5) Contacts with adjacent limestone or siltstone beds are sharp. (6) Lamination is very rare. (7) Sedimentary structures are absent. (8) Bedding thickness is highly variable, ranging from less than 1 cm to 106 cm. (9) All shales react to 10 percent HCL. (10) All are gritty when chewed. (11) Large, calcareous body fossils are rare, and where present, occur in thin, discontinuous layers. (12) Burrows are extremely rare. Usually, only the tops of shale beds are burrowed (with abundant, horizontally oriented *Chondrites* and some *Paleophycus* and *Trichophycus*). However, horizontal-to-vertical *Chondrites* are sometimes found in thin, discontinuous layers within shale beds.

Shale Classification Scheme

Most shale classification schemes are based on percent silt versus percent clay, and carbonate is regarded as an accessory constituent (e.g., Blatt, Middleton, and Murray, 1980, p. 382; Picard, 1971; Potter, Maynard and Pryor, 1980). Because most of the shales in this study are dolomite rich, these classifications are difficult to use. Accordingly, this study utilizes an original petrographic classification scheme (Figure 24) which recognizes three end members (quartz + feldspar, clays + micas, and calcite + dolomite). The suffixes "-shale" and "-stone," from Potter, Maynard and Pryor (1980), are retained in this scheme, referring to, respectively, laminated and unlaminated rocks. The advantage of this system is its ability to demonstrate subtle compositional changes that occur stratigraphically. Typical Cincinnatian shales are shown in Figure 25.

Thin-Section Data

Thin-section analysis of Cincinnatian shales confirms the presence of the following minerals: quartz, feldspar, clay minerals, calcite, dolomite, pyrite, limonite, hematite, gypsum (very rare), and the heavy minerals chlorite, epidote, garnet, monazite, rutile, tourmaline, and zircon. Scotford (1965) also found apatite, barite, biotite, sphene, spinel, and topaz from his heavy mineral separation study. The composition of the average Cincinnatian shale is QF_{37} CM_{52} CD_{11}, or a dolomitic mudstone. Compositions of shale samples from thin-section study are given in Appendix 6A, and shale fabrics are given in Appendix 6B. Organic matter was not detected in shale thin sections; however, trace amounts could be present in these rocks without being detected optically. Figure 26 illustrates this point. Shale color ranges from 5Y 4/1 (olive gray) to N5 (gray), and thus, organic carbon content could be as high as 0.5 percent.

Fossils in shales are rare, ranging from 0 to 4 percent, and averaging 1 percent. Forty-one percent of all samples studied are completely

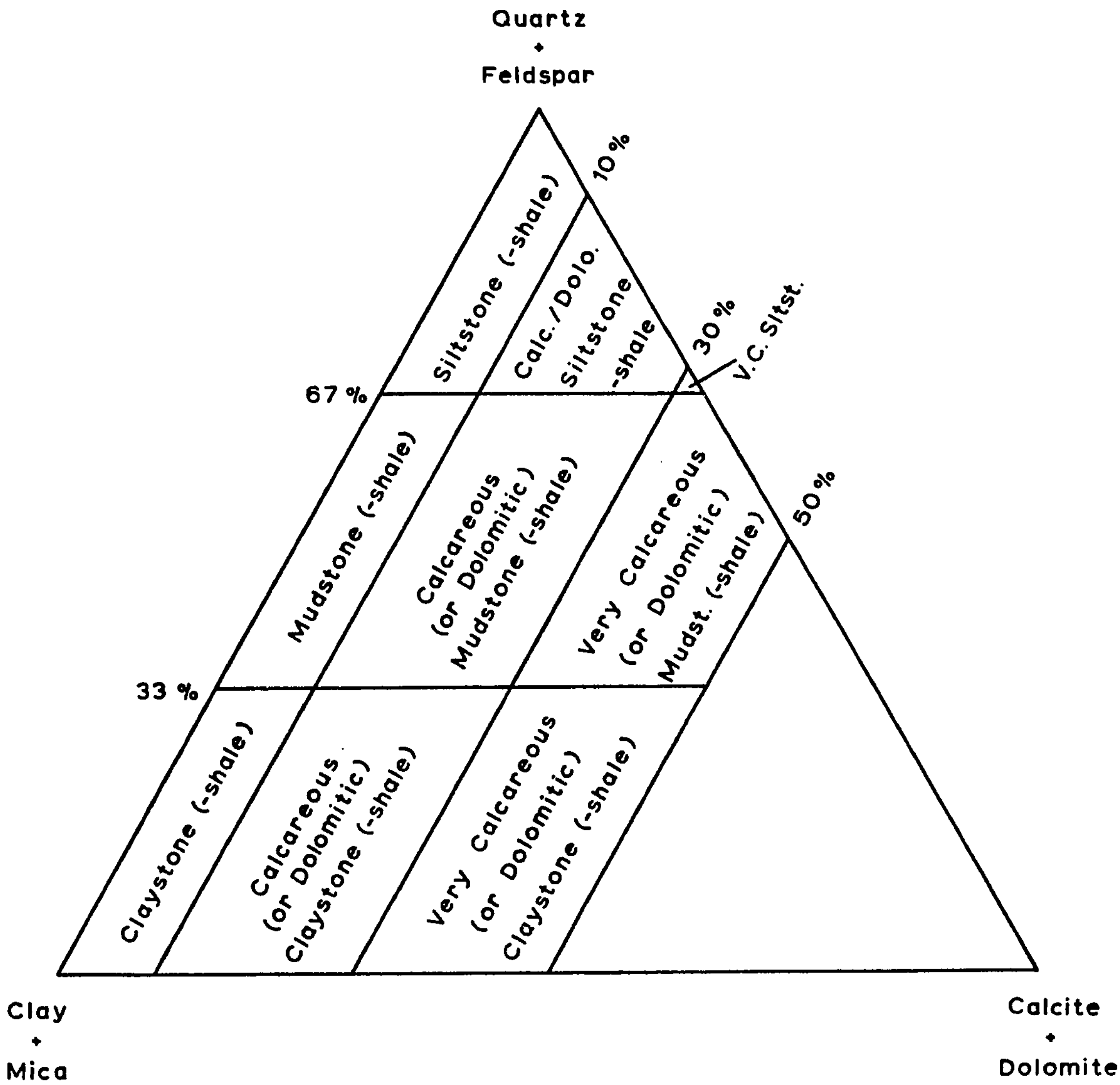
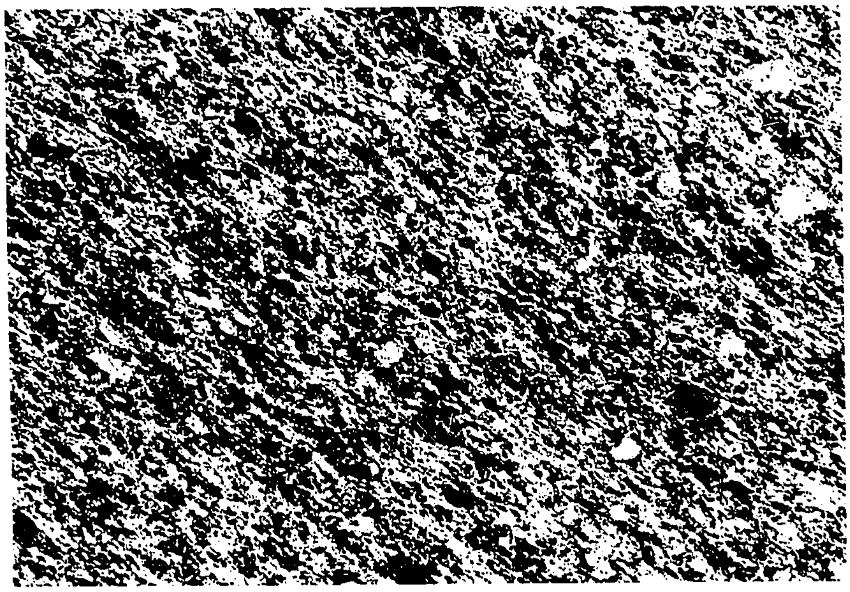
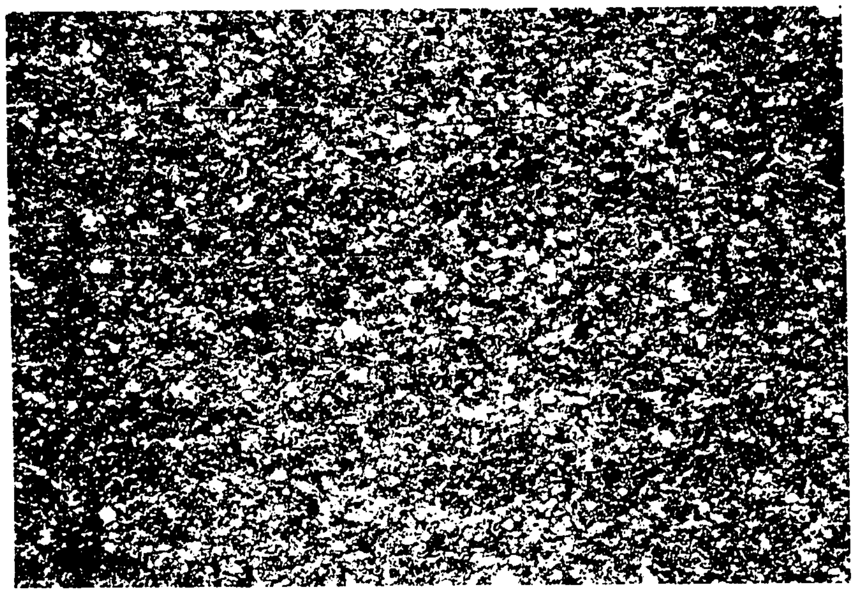


Figure 24: Petrographic classification scheme for carbonate-rich shales.

Figure 25A: Thin-section photograph of a claystone. Note the abundance of clays and the high degree of clay parallelism (bedding is oriented from NW to SE in this photograph. Scale: 1 cm = 40 microns.

Figure 25B: Thin-section photograph of a mudstone. Note the abundance of quartz silt (white grains). Scale: 1 cm = 150 microns.





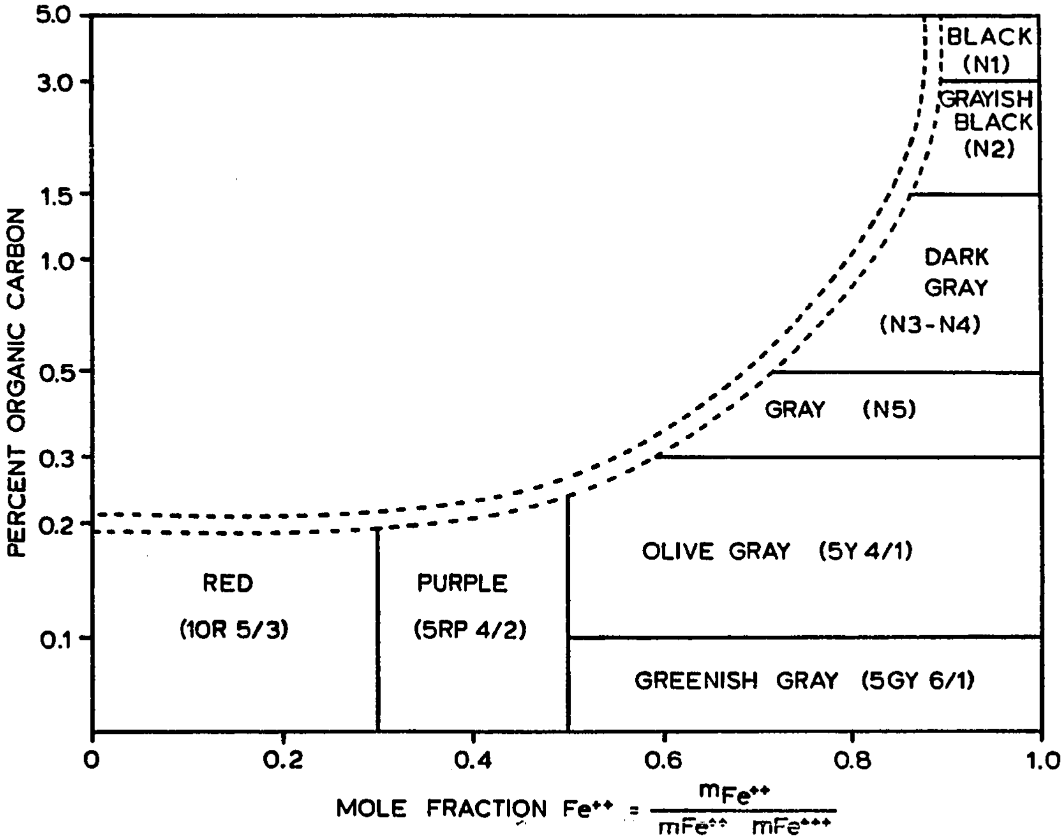
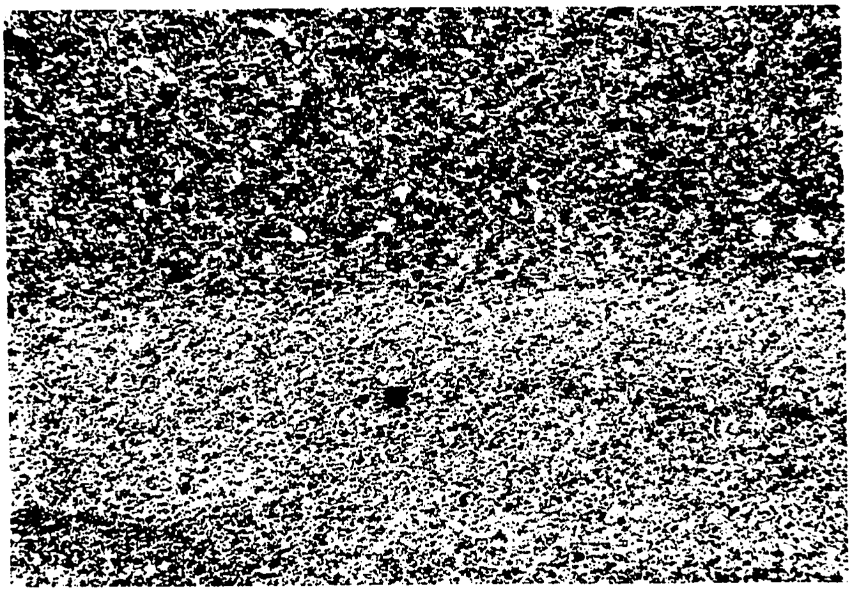


Figure 26: Suggested relationship of shale color to carbon content and oxidation state of iron (from Potter et al., 1980, fig. 1.25).

barren of fossils. However, in some stratigraphic units (e.g., the Bellevue, Mt. Auburn, and Whitewater formations) fossils may occur in greater amounts. In most shales fossils occur as very small, well-sorted, sand-to-silt size fragments, including conodonts, brachiopods, crinoids, unidentified fragments, bryozoans, gastropods, and ostracods (in order of abundance). Whole fossils and large fragments are sometimes found in very thin, discontinuous layers within shale beds. These layers occasionally coincide with *Chondrites*.

The following textural characteristics of the average shale were determined optically: (1) Average grain size of the silt- and sand-size fraction is 26 microns, or "coarse silt." (2) Coarsest grain size (the average of the 10 largest grains in each slide) is 75 microns, or "very fine sand." (3) The ratio of quartz silt to clays and micas (Q/C) is 0.811. (4) Sphericity is low and grain shape is subelongate. (5) Lamination is very rare. (6) Clays and micas exhibit a moderately strong degree of parallelism. (7) The degree of bioturbation is very low, averaging only 1 percent, or "sporadic bioturbation traces" ("grade 1") of Reineck (1963, table 12). Burrows are usually clay rich, silt poor, and darker in color, although a few are filled with coarse silt and calcite, and are lighter in color. All are unlined, have sharp boundaries, and are round to ovoid in shape. Average size is 4 mm long and 2 mm wide. Most are horizontally oriented, although vertical and inclined burrows are also present. (8) The higher the degree of bioturbation in shales, the lower the degree of clay parallelism. (9) Graded "packages" of shale, ranging from several mm to several cm in thickness, sometimes occur (Figure 27). Each "package" has a sharp lower contact and a sharp to



<u>Figure 27</u>: Thin-section photograph of the contact between two graded shale "packages" (crossed nichols). Note the distinct break in lithology; the bottom half of the picture is a claystone and represents the end of a shale-depositing storm event. The upper half is a mudstone which represents the beginning of a second storm event (scale: 1 cm = 150 microns).

gradational upper contact. These layers fine upward from silt-rich mudstone at the base to silt-poor claystone at the top.

Interpretation

Clays, silts, and fine sands deposited in the Cincinnati Arch region during Late Ordovician time were most likely derived from the Taconic highlands to the east. As previously mentioned, this source area was a chain of mountains that extended from southeastern Canada to Georgia in a gently curving belt. The ultimate distance from Cincinnati to the Taconic highlands ranged from less than 350 miles (due east) to over 700 miles (northeast). The transportation of fine-grained sediments across such a wide basin into the Cincinnati area is believed to be the result of two interrelated factors: major oceanic circulation patterns and hurricane events. This process will be discussed in detail in the section entitled "Storm Cycles."

Shale fabric and bioturbation can be used to estimate depositional rate during Cincinnatian time. Bioturbation in shales is very low, averaging only 1 percent, and reaching a maximum of 12 percent. Furthermore, 92 percent of all shales are unburrowed. Where present, traces always consist of a few vertical escape structures in addition to horizontally oriented *Chondrites* that sometimes occur in poorly defined layers. The internal fabric of the average shale shows moderate-to-strong parallelism of clays (Figure 28). Moreover, the degree of clay parallelism is inversely proportional to the amount of bioturbation. If shale depositional rates had been slow, organisms would have had a sufficient amount of time to rework the sediment, leaving behind an abundance of traces and a more disoriented fabric. Because shale fabric is well oriented and bioturbation is low, deposition must have been a fairly rapid process--so rapid that infauna had very little time to churn the sediment, but only enough time to escape or be killed by the rapid influx of clays and silts. Furthermore, the tops of many shale beds are heavily burrowed with horizontal *Chondrites* and *Paleophycus*, suggesting dense recolonization of the surface following rapid deposition (Frey, 1975, pp. 135-136). In addition, the rare occurrence of body fossils in shales, including those of deposit feeders, indicates that depositional rates were fast. Brandt (1980) arrived at a similar conclusion based on taphonomic evidence from the trilobite *Flexicalymene*. Brandt observed unrolled, current-oriented specimens of this trilobite in shale beds, which she attributed to rapid burial. Thus, shales are believed to represent the rapid deposition of muds and silts from suspension via high-energy storm events. The concept of storm deposition will be discussed in the section entitled "Storm Cycles."

The conclusion that shales were rapidly deposited by hurricanes does not imply that each shale bed represents a single hurricane event. To the contrary, many shale beds probably represent the accumulation of mud and silt by multiple depositional events. Breaks in sedimentation (i.e., diastems) are represented by very thin limestone layers, fossil layers, *Chondrites* layers, and contacts between graded shale "packages," all of which occur within individual shale beds. The absolute amount of time loss represented by each diastem is unknown. However, in relative terms, thin limestone layers represent the longest hiatus, followed by thin fossil layers, *Chondrites* layers, and breaks between graded packages of shale.

Thin limestone layers represent recolonization and benthic community development following a shale depositional event. Thin fossil layers probably represent only the initial stage of community development. Thin *Chondrites* layers represent the beginning phase of recolonization. Finally, sharp contacts between graded shale layers represent the shortest hiatus. In this case, two successive depositional events occurred so close together in time that even the initial bioturbation of the newly deposited shale substrate had not yet occurred.

Shale Diagenesis

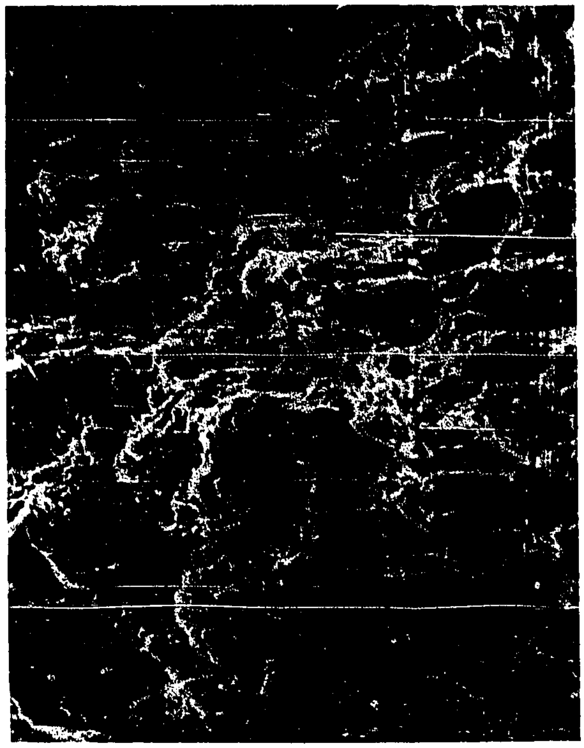
Diagenetic alteration of Cincinnatian-age shales is not extensive. However, four diagenetic processes have occurred, one of which is dolomitization. Most shales contain an abundance of coarse silt-to-fine-sand size, well-sorted, euhedral, ferroan dolomite rhombs (Figure 29). Dolomite is very rare inside burrows, even in dolomite-rich samples. A second diagenetic process is pyritization. Small amounts of anhedral-to-euhedral crystals of pyrite are disseminated throughout most shales (a maximum of 8 percent, and an average of 3 percent). Unlike dolomite, pyrite sometimes occurs inside burrow fillings, and more rarely, replacing fossils. As discussed earlier, the presence of ferroan dolomite indicates reducing pore waters, high pH, the presence of decomposing organic matter, and high concentrations of Fe^{++}, whereas pyrite indicates reducing, sulfidic pore waters (see "Carbonate Diagenesis").

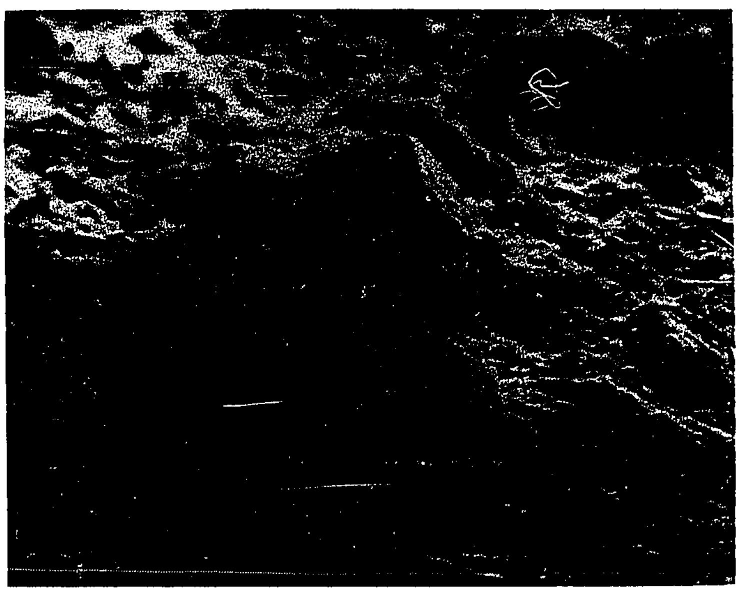
A third diagenetic process is sediment compaction. Compaction was intense enough to flatten burrows into slightly ovoid cross sections, but was not intense enough to destroy burrows, to produce stylolites, or to break delicate fossils, such as the thin-shelled brachiopod, *Onniella*.

The fourth post-depositional process is limonite staining of shales. Limonite occurs as disseminated, anhedral blebs as well as coatings around clays and micas, imparting a brown color to the rock. These brown shales are found only in outcrops that have thick soil covers and have been exposed to weathering for a number of years. This suggests that limonite staining is a recent process.

Figure 28: SEM photograph of a typical Cincinnatian shale (700 x). Note the high degree of clay parallism in this sample (from left to right).

Figure 29: SEM photograph of euhedral dolomite rhombs in a typical Cincinnatian shale (600 x). Note the random orientation of crystals.





AUTECOLOGICAL ANALYSIS OF CINCINNATIAN FOSSILS

Every organism has a specific tolerance to fluctuations in environmental conditions such as salinity, temperature, water depth, substrates, and water clarity. Furthermore, an organism cannot survive in its environment even if only one of these conditions fluctuates beyond the organism's own tolerance limits ("Leibig's Law of the Minimum). Thus, a working knowledge of the tolerance limits of an individual fossil or a small taxonomic group can be used to interpret ancient environmental conditions. This method of analysis is known as paleoautecology. The power of autecological analysis is that it can be integrated with sedimentological data to enhance the interpretation of depositional environments.

When studying the autecology of ancient fossil groups, the concept of uniformitarianism must be invoked. Ager (1963) points out that uniformitarianism works well for physical processes, such as erosion and deposition, because the laws of physics probably have not changed with the passage of time. However, uniformitarianism may not apply well to fossils, because biological processes may have changed with the passage of time and evolution. Furthermore, the validity of any comparison between recent and ancient groups depends on how close their phylogenetic relationship is; ideally, the fossil form should have a living counterpart at a low taxonomic level. Because most Paleozoic species and genera are extinct, uniformitarianism is therefore most applicable to higher taxonomic groups (i.e., phyla and classes), and conclusions are necessarily tentative. For this reason, only the autecology of Cincinnatian phyla and classes is considered. Table 6 compares the environmental variables of 12 Cincinnatian fossil groups. Some fossil groups such as conodonts, scolecodonts, and sponges were not included, either because they occur in small numbers or because they have very little interpretive value on the basis of current knowledge. Table 6 can be used to deduce water depth, water clarity, salinity, and sediment characteristics (such as type of substrate, water content, probable organic content, and amount of bioturbation). The information given in Table 6 is generalized for each fossil group as a whole. However, in some cases only those data which pertain to specific Cincinnatian fossils are given. For example, although members of the class Gastropoda are represented by deposit feeders, suspension feeders, predators, and scavengers, most *Cincinnatian* gastropods were probably deposit feeders (Felton, 1982, pers. comm.).

Another way to utilize fossils for environmental interpretation is to study the morphologic variations that exist within a given taxonomic group. Through evolution, organisms can adapt themselves morphologically or behaviorally to changing environmental conditions, or in response to the presence of other organisms. Behavioral modifications are difficult to detect in the fossil record, but morphologic adaptations are not. In the shallow marine environment, numerous environmental and ecologic factors undoubtedly correlate with morphologic variability. Substrate type and hydraulic regime are the most important of these factors from a sedimentological viewpoint. Because substrate type is largely a function of hydraulic regime, only the adaptations to substrate need to be considered. For the purposes of this paper, substrates can be divided into two types: coarse, shelly substrates and muddy substrates.

Table 6: Autecologic comparison of major fossil groups in the Cincinnatian Series. "Salinity Tolerance" refers to the relative amount of salinity fluctuation that an organism can tolerate ("low" means a range of fluctuation $<$ 15 ppt.; "moderate" is 15 to 20 ppt.; "high" is 25 to 30 ppt.; "very high" is $>$30 ppt.). "Fecal Pellet Production" refers to the relative capacity of organisms to deposit pelletal muds. Table compiled from various sources (Pojeta, 1971; Heckel, 1972; Richards, 1972; Pryor, 1975; Wilson, 1975; MacDaniel, 1976; Benedict and Walker, 1978; Peel, 1978; Elias, 1979; Brandt, 1980; Frey, 1980; Hinterlong, 1981).

FOSSIL GROUP	TROPHIC TYPE	SALINITY TOLERANCE	SUBSTRATE RELATIONSHIPS (a) life position (b) mobility (c) substrate type	WATER DEPTH	FECAL PELLET PRODUCTION	WATER CLARITY
Red Algae (Rhodophyta)	photosynthesis	moderate (normal marine)	(a) epiphytic (b) encrusting (c) hard to firm	most abundant in shallow subtidal (mostly < 10 m)	N/A	clear
Blue-Green Algae (Chlorophyta)	photosynthesis	very high (fresh to hypersaline)	(a) epiphytic (b) encrusting (c) hard to soft mud	most abundant in shallow subtidal to supratidal	N/A	clear to turbid
Brachiopods	suspension feeders	low (normal marine)	(a) epifaunal (b) mostly sessile (c) hard to soupy	deep basin to shallow subtidal	moderate to low?	clear to slightly turbid
Bryozoans	suspension feeders	moderate (normal marine to brackish)	(a) epifaunal (b) attached (c) hard to firm	deep basin to shallow subtidal	high	clear
Rugose Corals (solitary)	suspension feeders	low (normal marine)	(a) epifaunal (b) sessile (c) mostly soft mud	deep basin to shallow subtidal	moderate to low?	clear to slightly turbid
Tabulate Corals (colonial)	suspension feeders	low (normal marine)	(a) epifaunal (b) sessile (c) mostly firm	inner shelf to shallow subtidal (mostly < 20 m)	moderate to low?	clear to slightly turbid
Pelmatozoans (crinoids)	suspension feeders	low (normal marine)	(a) epifaunal (b) mostly attached (c) hard to soft	deep basin to shallow subtidal	moderate to low	mostly clear
Cephalopods	predators	low (normal marine)	nektonic	deep basin to shallow subtidal	N/A	N/A
Gastropods	mostly deposit feeders and scavengers; some possible predators	very high (fresh to hypersaline)	(a) infaunal and epifaunal (b) mostly mobile (c) hard to soft mud	deep basin to supratidal	high	clear to very turbid
Pelecypods	mostly suspension feeders; some deposit feeders	very high (fresh to hypersaline)	(a) mostly epifaunal (b) sessile (c) soft mud	deep basin to intertidal	moderate to high	mostly clear
Ostracods	suspension feeders, scavengers, and deposit feeders	very high (fresh to hypersaline)	(a) epifaunal (b) mobile (c) firm to soupy	deep basin to supratidal	low	clear to very turbid
Trilobites	deposit feeders	moderate to low (normal marine)	(a) mostly infaunal (b) mobile (c) soft to soupy mud	deep basin to shallow subtidal	high	clear to very turbid

Coarse, sand-to-gravel size, shelly substrates are generally produced in shallow, turbulent environments, where water circulation and winnowing effects are maximal. Although this type of environment has its advantages, it also presents some problems for benthic organisms, including (1) mobile, shifting sediments, (2) lack of abundant suspended nutrients, (3) lack of hiding places from predators (except in reefs), and (4) difficulty in attachment to substrates because of turbulent conditions. Morphologic adaptations to these conditions mostly involve mechanisms for attachment and protection from breakage. These adaptations are shown in Table 7.

Fine, muddy substrates are usually produced in deeper, quiet-water environments where abundant, organic-rich muds slowly settle out of suspension. Unlike coarse substrates, this environment is an open, unexplored niche for opportunists because it contains abundant suspended nutrients, is rarely overcrowded, and offers a refuge from predators. Nevertheless, benthic organisms living in this environment must cope with a different set of problems, including (1) buoyancy (in thixotropic muds), (2) burial of larvae and juveniles in soft muds, (3) clogging of feeding mechanisms (for suspension feeders), (4) lack of hard attachment surfaces, and (5) decreased mobility (in thixotropic muds). Morphologic adaptations mainly involve buoyancy, and are summarized in Table 8.

The types of Cincinnatian fossils and their morphologic characteristics will be described for each rock facies in the Cincinnatian Series (see "Lithogenetic Sequences"). This information will be used to enhance the interpretation of the paleoecologic conditions of each sequence.

MORPHOLOGIC ADAPTATION	CINCINNATIAN REPRESENTATIVES
(1) Mechanisms for strong attachment	
(a) cementing	(a) bryozoans, some crinoids
(b) boring	(b) algae, pelecypods, sponges(?)
(c) byssal threads	(c) some pelecypods (Ambonychia)
(d) encrusting (of individual shells)	(d) some bryozoans, algae
(e) pedicles	(e) most brachiopods
(f) entwining	(f) some crinoids
(2) Bulk density (large, thick shells)	some brachiopods (Platystrophia, Hebertella, Retrorsirostra, etc.)
(3) Heavy ornamentation	some brachiopods (Platystrophia, Lepidocyclas, Leptaena, Rhynchotrema, etc.)
(4) Rounded shells	some brachiopods (Platystrophia, Lepidocyclas)
(5) Very large shells (regardless of bulk density)	some Rafinesquina
(6) Massive colonial skeletons	bryozoans (Monticulipora) corals (Tetradium)

Table 7: Adaptations of benthic invertebrates to coarse (gravelly or sandy) substrates. Compiled from various sources (Ager, 1963 and 1965; Stanley, 1970; Raup and Stanley, 1971).

MORPHOLOGIC ADAPTATION	CINCINNATIAN REPRESENTATIVES
(1) Reduction of bulk density (light shells)	some brachiopods (Onniella, Sowerbyella, Holtedahlina, etc.)
(2) Snowshoe effect (wide, flat shells)	some brachiopods (Rafinesquina, Onniella, Strophomena, etc.)
(3) Iceberg effect (partial burial)	solitary corals (Grewingkia)
(4) Thin valves	some brachiopods (Onniella, Sowerbyella)
(5) Finely ornamented or smooth shells	some brachiopods (Rafinesquina, Sowerby-ella, Thaerodonta, Strophomena)
(6) Branching roots, pedi-cles, or byssal threads	Pedicles--most brachiopods Byssal threads--some pelecypods (Ambony-chia)
(7) Spines	some trilobites
(8) Siphons	no siphonate fossils
(9) Attachment to objects projecting above the mud	encrusting bryozoans, ramose bryozoans, crinoids, edrioasteroids, algae, some brachiopods (Zygospira)
(10) Concavo-convex shells	some brachiopods (some Rafinesquina, Sowerbyella)

Table 8: Adaptations of benthic invertebrates to soft, muddy substrates. Compiled from various sources (Ager, 1963 and 1965; Purdy, 1964; Stanley, 1970; Raup and Stanley, 1971; Snyder and Bretsky, 1971; Richards, 1972; Rhoads, 1973; Walker, 1973; Alexander, 1975; Thayer, 1975; Seilacher, 1978).

CYCLIC SEDIMENTATION AND THE VERTICAL SEQUENCE

Vertical Sequences and Walther's Law

A "vertical sequence" is defined in this report as a succession of vertically stacked rock strata which are genetically related. Vertical sequences are herein divided into two categories, based on the type of lithogenetic relationship: the "process" type (produced by short-term depositional events within one environment), and the "Walther" type (produced by migrating consanguineous environments).

The "process" type vertical sequence is deposited *within* a given sedimentary environment, and is the result of relatively short-term changes in environmental or depositional conditions. For example, consider pelagic sedimentation in a deep marine basin. As long as climatic conditions are favorable for high organic productivity in the overlying shallow water zone, thick foraminiferal muds can accumulate on the deep ocean floor. However, if an adverse change in climate occurs, organic productivity would drop, and sedimentation on the ocean floor would slow down considerably. The resulting vertical sequence would grade upward from a thick layer of foraminiferal mud to a thin layer of unfossiliferous mud. Such a sequence would reflect a change in environmental conditions (i.e., climate, organic productivity, sedimentation rate), with both lithologies being deposited in the *same* broad environmental setting.

A second example of a "process" type sequence is a turbidite. Turbidites are rapidly deposited by gravity-induced turbidity currents, and they usually accumulate in deep ocean basins. A "complete" turbidite is composed of five stacked divisions and is known as a "Bouma sequence" (see Bouma, 1962, and Walker, 1967). The vertical stacking of Bouma units occurs during a *single* depositional event, with each division representing a successively lower flow regime. Furthermore, the vertical transition from a turbidite sequence to an interbedded layer of pelagic mud also reflects changing environmental conditions *within* the same depositional environment (i.e., a change from turbidity flow to hemipelagic deposition).

The recognition of "process" type vertical sequences in ancient rocks is important for two reasons: (1) They can demonstrate changing environmental or ecologic conditions within a given depositional environment, and (2) they can be used to deduce depositional environments (e.g., Bouma sequences are diagnostic of deep basin submarine fans). In the Cincinnatian Series, two examples of "process" type vertical sequences occur--"storm cycles" and "megacycles." The recognition of these sequences is sedimentologically important and will be discussed in the next section, "Cincinnatian Age Cycles."

The second type of vertical sequence is the "Walther" sequence, which is based on the facies concept of Gressley (1838) and on Walther's "Law of the Correlation of Facies" (1894). The word "facies" is currently used to describe the sum total of the lithologic and paleontologic characteristics of a given body of rock from which its environment of deposition may be deduced (see Gressley, 1938; Teichert, 1958b; Reading, 1978, Chapter 5; Hallam, 1981, Chapter 1). Thus, a facies can be thought of as a body of rock having lithologic and biologic characteristics unlike those of contiguous bodies of rock, because it was originally deposited in an area of uniform depositional conditions (i.e., a depositional environment or "lithotope"). This concept was first proposed by Walther as follows:

> The various deposits of the same facies areas and similarly the sum of the rocks of different facies areas are formed beside each other in space, though in cross-section we see them lying on top of each other. As with biotopes, it is a basic statement of far-reaching significance that only those facies and facies areas can be superimposed primarily which can be observed beside each other at the present time. (translation by Middleton, 1973)

In general, Walther's statement has been interpreted to mean that the vertical succession of facies in a *conformable* sequence of rocks represents the lateral juxtaposition of the environments that produced those facies. Furthermore, the vertical stacking of lithofacies is produced by the *lateral migration of consanguineous environments*. Any vertical sequence produced in this manner is herein referred to as a "Walther" sequence. The application of Walther's Law to geologic problems in North America was pioneered by Williams (1913), Chadwick (1933), and Caster (1934).

Walther's Law represents a powerful tool in the study of ancient strata for several reasons: (1) Many facies cannot be adequately studied by themselves. In order to identify its environment of deposition, a facies must usually be studied along with other facies in a lithogenetic sequence. (2) The vertical succession of present-day rock facies can be used to deduce the lateral relationships of ancient depositional environments. In some cases, the apparent lateral relationship between paleoenvironments (as predicted by Walther's Law) may not exist at the present time. Hence, the use of vertical sequences in identifying lateral relationships between ancient environments becomes most significant in those cases where no modern analogue exists. (3) Vertical sequences can demonstrate *how* paleoenvironments migrated with the passage of time. In other words, they can show the depositional and environmental *evolution* of a given locality. By correlating vertical sequences over large areas, geologists can identify the movement of major sediment packages, and thereby reconstruct paleogeography.

The application of Walther's Law has long been overlooked in the study of the Cincinnatian Series. Rock facies have often been studied as isolated units in time and space, even though three major Walther sequences exist (i.e., "Shoaling-Upward Shelf Cycles," to be discussed in a later section). As a result, other geologists have interpreted Cincinnatian rock strata in terms of "transgressions" and "regressions" of the sea, relying heavily on the outdated concept of "layercake stratigraphy."

Cyclic Sedimentation

Cycles are recurring sequences of lithologically distinctive strata that are representative of recurrent depositional or environmental conditions. Cyclic deposition may be caused by *external* factors such as eustatic sea level changes ("allocyclic deposition"), or by *internal*, self-perpetuating factors such as migrating river channels ("autocyclic deposition"). Furthermore, cycles may assume one of two basic patterns: "symmetric" (A B C B A B C) or "asymmetric" (A B C A B C). Symmetric cycles are typical of marine basins, and may represent repeated transgressions and regressions of the sea with few unconformities. Conversely, asymmetric cycles are composed of stacked A B C packages which are always separated by unconformities. These cycles are deposited by numerous environmental processes, and may occur in many depositional settings. Asymmetric cycles can also be produced by transgressive and regressive events provided that they are erosive in nature.

Cyclic deposition has been described and interpreted since the early 1800's. The earliest workers (such as Cuvier and d'Orbigny in Europe, and Newberry, Ulrich, and Grabau in America) recognized thick, long-term cycles in the sedimentary record which they attributed to worldwide catastrophes, such as periodic sea level fluctuations or diastrophic pulsations. Moreover, these early geologists believed that cycles could be correlated on a global basis. Their successors (Weller, Wanless, and Shepherd) recognized thinner, short-term cycles, but continued to attribute their origins to sea level fluctuations or "yo-yo" tectonics. An excellent summary of the early development of cyclic theory has been produced by Weller (1964).

Since the mid-1970's, geologists have recognized that cyclic deposition can also be caused by internal, sedimentologic factors. Therefore, the origin of cycles need not be attributed to external controls such as eustatic sea level changes, climatic fluctuations, or tectonics. For example, Pryor and Sable (1974) demonstrated that Pennsylvanian cyclothems in the Illinois basin were produced by alternating progradation and abandonment of deltas. Furthermore, they showed that cyclothems were arranged in overlapping lens-shaped "packages," and were therefore not correlative throughout the basin as a whole. Current ideas concerning the causes of cyclicity (both internal and external) are summarized below:

1. Intermittent subsidence of a basin with constant sedimentation.

2. Alternating subsidence and tectonic uplift of a basin.

3. Climatic control over the distribution of climate-sensitive lithologies.

4. Uneven compaction of basin sediments.

5. Shifting current patterns within a basin.

6. Sedimentological control (e.g., broken barrier bars and levees, migrating rivers, shifting deltas, etc.).

7. Intermittent tectonic activity of a source area (i.e., sediment supply).

8. Climatic changes which affect weathering rates and discharge of a source area.

9. Shifting source areas (i.e., shifting deltas, etc.).

10. Eustatic sea level changes due to glaciation or large-scale movements of tectonic plates.

11. Transgressions and regressions caused by changing sedimentation rates.

12. Storm processes and gravity flows.

Cycles are highly variable in terms of thickness, lithology, environment of deposition, and periodicity. Cycles may be short term (i.e., daily, seasonally, or yearly) or long term (i.e., thousands to millions of years). Examples of short-term cycles include algal laminations, growth rings in fossils, lacustrine varves, and storm deposits. Examples of long-term cycles include Pennsylvanian cyclothems, Lofer cycles, and shoaling-upward shelf cycles. The longer the periodicity of a cycle, the more likely it is to be preserved in the geologic record, because day-to-day environmental processes tend to obscure or remove most short-term cycles. In addition, cycles may occur in numerous geologic settings, ranging from terrestrial to deep marine (see Table 9).

TYPE OF CYCLE	EXAMPLES	DESCRIPTION	POSSIBLE INTERPRETATION	REFERENCES
TERRESTRIAL CYCLES	Fluvial fining-upward cycles (numerous examples)	Thin sequences of gravels fining upward into sands and shales.	Migrating river channels.	Reading (1978, Chpt. 3)
	Alluvial fan cycles	Thin coarsening-upward cycles; evaporites and clays grade upward into sandstones and gravels.	Prograding alluvial fans.	Reading (1978, Chpt. 3)
MARGINAL MARINE CYCLES	Cyclothems (Pennsylvanian, Illinois Basin)	Thin sequences (50-200'); shales and open-marine limestones grade into shales, sandstones, and coal.	Alternating progradation and abandonment of deltaic complexes.	Pryor and Sable (1974)
	Lofer cycles (Triassic, Alps)	Very thin sequences ($<$ 15'); argillaceous limestones, shales, and dolomite grade into semi-restricted limestones.	Facies migration due to eustatic sea level changes or tectonic uplift.	Fischer (1964)
EVAPORITE CYCLES	Zechstein cycles (Permian, Germany)	Thick sequences (300-2500'); Carbonates grade upward into evaporites (anhydrite, halite, potash salts).	"Salina model" (shallow water sea level change + evaporation and subsidence); "Schmaltz model" (deep water density stratification).	Schmaltz (1969) Kendall and Skipwith (1969a) Taylor and Colter (1975)
	Pinnacle Reef cycles (Silurian, Michigan Basin)		Shallow water sea level fluctuation and facies migration	Mesolella et al (1974)
CARBONATE SHELF CYCLES	Permian Reef Complex (Permian, West Texas)	Thick sequences (450-900'); evaporites and carbonates grade into sandstones and shales.	Facies migration due to long-term sea level change.	Silver and Todd (1969) Wilson (1975)
	Yoredale cycles (Mississippian, England)	Thin sequences (20-130'); dark crinoidal limestone grades into shale, sandstone, and coal.	Open-marine carbonate sedimentation followed by prograding deltaic sedimentation.	Moore (1959)
	Shoaling-Upward Shelf Cycles: Oolite-grainstone (Jurassic)	Thin-to-thick sequences; argillaceous limestone grades into open-marine packstones, oolite grainstones, and evaporites or dolomites.	Shallow water facies migration due to sea level fluctuations.	Wilson (1975)
	Shoaling-Upward Shelf Cycles: Lime-mud sabka (Devonian)	Thin sequences ($<$ 15'); open-marine wackestones grade into restricted wackestones and dolomites.		Wilson (1975)
	Storm cycles (Ordovician, Pennsylvanian)	Very thin fining-upward sequences similar to turbidites.	Periodic resuspension, transportation, and redeposition of bottom sediments by hurricanes.	Ball (1971) Kreisa (1981)
DEEP MARINE CYCLES	Gravity flow deposits--turbidites, grain flows, debris flows (numerous examples)	Thin-to-thick gravity flow sequences are interbedded with pelagic sediments.	Periodic gravity flows.	Middleton and Hampton (1976)

Table 9: Summary of the major varieties of ancient cyclic deposits.

C I N C I N N A T I A N A G E C Y C L E S

The presence of sedimentary cycles in the Cincinnatian Series has rarely been discussed in the literature. Magorian (1954) believed that the simple alternation of limestone and shale in the Fairview Formation reflected cyclic sedimentation. Similarly, Potter and Blakely (1968) demonstrated that the dominant lithologic transition in the Cincinnatian Series is the alternation of shale and "muddy calcarenite" (i.e., packstone). Anstey and Fowler (1969, p. 678) interpreted these small-scale "cycles" to be the result of ". . . random changes in sites of organic communities on the sea floor that were controlled mainly by the distribution of minor prominences and subsequent burial by terrigenous muds" and hence, are not cycles at all. However, Anstey and Fowler (1969) noted that large-scale sedimentary cycles caused by major sea level changes probably do exist in the Cincinnatian Series. Recently, Hay (1981) described large-scale "transgressive-regressive" cycles in the Cincinnatian Series which she also attributed to eustatic sea level changes.

In this paper, three types of cycles are described and interpreted: storm cycles, megacycles, and shoaling-upward shelf cycles (see Figure 30 for comparison). "Storm cycles" are thin, laterally discontinuous, fining-upward sequences of limestone, siltstone, and shale. Storm cycles were deposited directly by storms or indirectly by storm-generated gravity flows. "Megacycles" are moderately thin sequences composed of a carbonate hemicycle overlain by a shale hemicycle, which may represent periodic fluctuation of terrigenous sediment supply. Both of these cycles are the

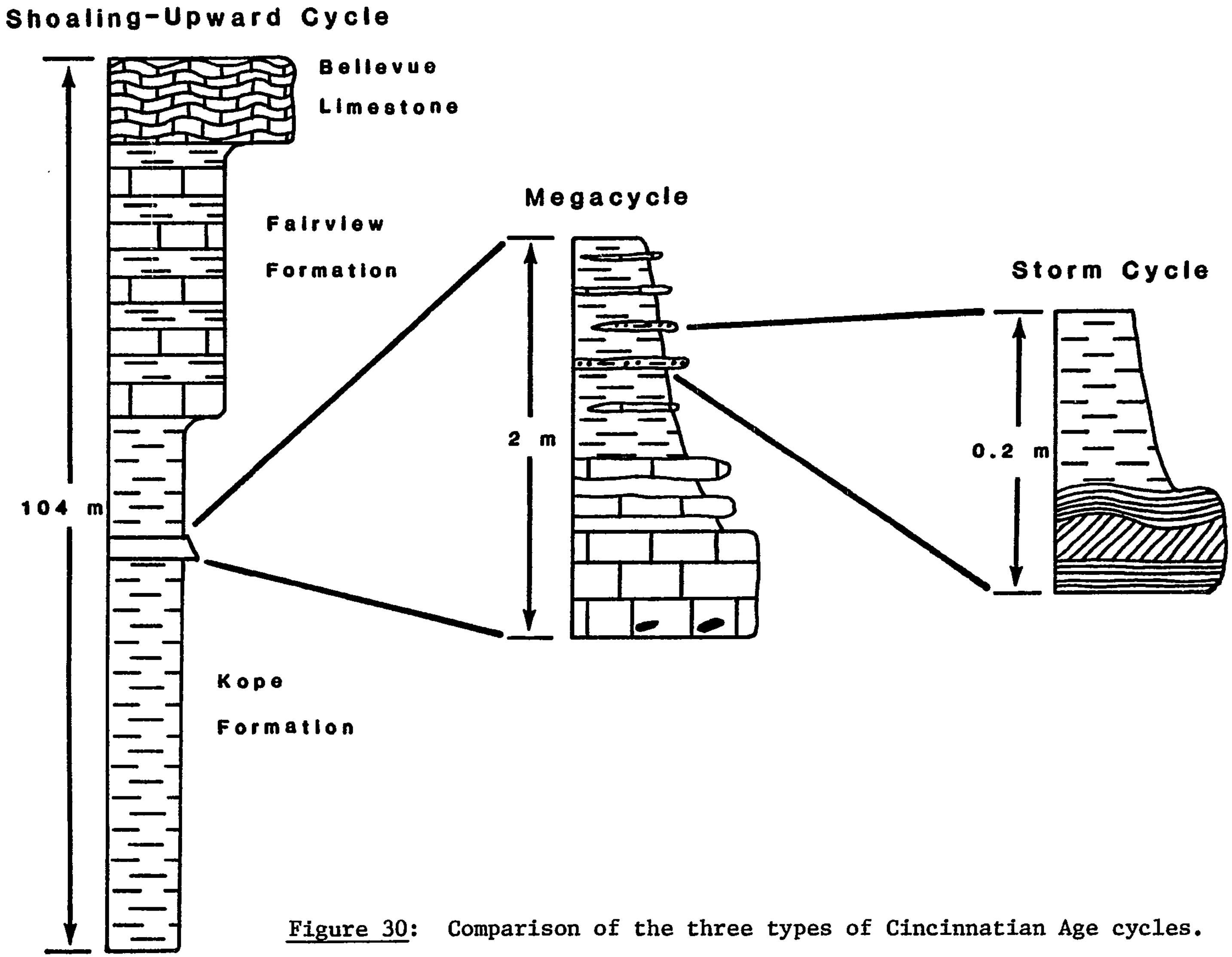


Figure 30: Comparison of the three types of Cincinnatian Age cycles.

"process type" discussed in the preceding section. "Shoaling-upward shelf cycles" are thick, "Walther type" sequences which represent offshore-to-shoreface depositional profiles.

Storm Cycles

Modern Storms

Storms are atmospheric disturbances accompanied by strong winds and precipitation which occur in a variety of forms, ranging from mild gusts and thunderstorms to hurricanes and tornadoes. Geologically, the most significant of these is the hurricane, because of its great size, tremendous wind speeds, and subsequent effect on ocean bottom sediments.

Hurricanes are storms of tropical origin having a cyclonic wind circulation in excess of 74 miles per hour (Battan, 1961). Most hurricanes have wind circulations ranging from 100 to 150 mph, and some may exceed 200 mph. The speed of a moving hurricane can range from as little as 12 to 15 mph in its initial stages to over 60 mph in its mature stages. Hurricanes are very large, ranging from a few tens of miles wide to over 400 miles wide, although most are about 200 to 250 miles in diameter.

Modern hurricanes in the Atlantic Ocean originate in the Tropics (usually within 10-20^{o} of the Equator) where they drift westward in the easterlies ("tradewinds"). As hurricanes approach the North American continent, they begin to deflect poleward (north) in response to the Coriolis effect and the presence of a continental land mass. The presence of a continent disrupts the zonal wind system because of the differing thermal regimes of land and water (i.e., low and high pressure systems--see Ziegler et al., 1981; and Simpson and Riehl, 1981, Chapters 1 and 5). This northward drift eventually brings some hurricanes to the northern limit of the Tropics where the westerly winds cause them to recurve (i.e., move eastward). Thus, the ideal hurricane is generated in the tropical Atlantic, moves westward towards the North American continent, and is deflected northward in a clockwise "gyre" (see Figure 31).

The study of storm processes is quite old. Mariners and scholars have recorded storm activities for centuries. However, the geological significance of storms has only been studied for about 20 years. Because of the inherent difficulty of making observations while a storm is still in progress, much of what is known about the effects of storms on marine sediments is based on "before and after" studies (e.g., Ball et al., 1967; Hayes, 1967; Perkins and Enos, 1968). Kreisa (1981) has noted that other problems exist in studying modern storm processes on continental shelves, including: limitations of sample size; the possibility of higher levels of bioturbation today than during previous geologic periods; relict Pleistocene sediments left on most continental shelves; and normal day-to-day processes which often destroy storm layers (e.g., tidal currents). In spite of these difficulties, much information has been obtained about the influence of storms on modern shelf sediments in terms of erosion, transportation, and deposition.

Storms erode shelf sediments by lowering wave base to depths greater than normal (a maximum of 200 meters--see Ewing, 1973; Butman et al., 1979). Furthermore, the frequency of storm-induced erosional events decreases with increasing water depth. Hence, *most* storms can erode sediments on the inner shelf, but only a *few* storms (those with exceptionally

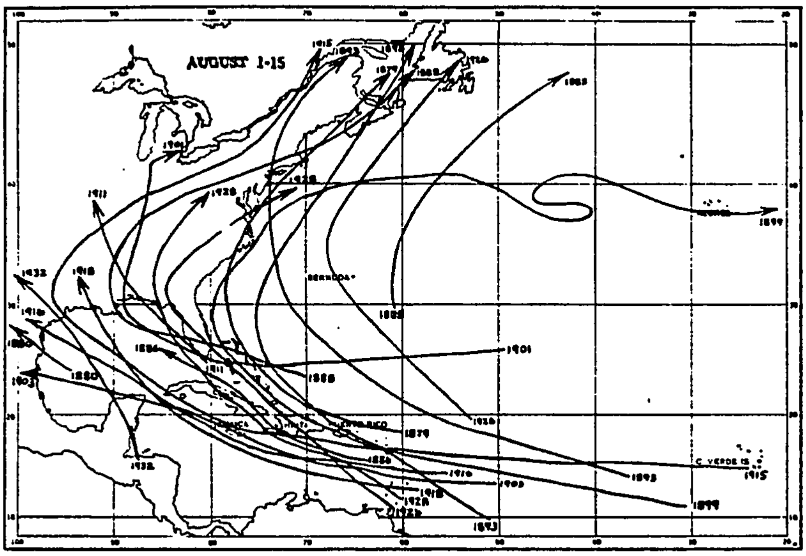


Figure 31: Tracks of tropical cyclones of hurricane intensity, August 1 to 15, 1874 to 1933, inclusive (from Tannehill, 1938, fig. 34).

strong winds) are capable of eroding outer shelf sediments. The oscillatory currents set up by storms are highly erosive, capable of dislodging and transporting large boulders. For example, Hayes (1967) notes that Hurricane Carla eroded large blocks of coral and rock from the offshore shelf and transported them shoreward onto the beach. In the nearshore zone, storm erosion is produced by abnormally large breaking waves which are capable of planing-off large dunes. In addition, storm surge and ebb flow often produce large hurricane channels which can erode barrier bars. Once part of a barrier bar is eroded, fair weather wave energy is no longer dissipated offshore. Consequently, higher than normal wave erosion can occur closer to shore.

Once sediments have been entrained by storms, they can be transported in several ways: (1) Storm surge can erode outer shelf sediments (muds, silts, sands, and large clasts) and transport them shoreward where they are deposited. (2) Washover fans can deposit sand from barrier bars into lagoons where they become trapped. (3) Storm ebb can remove sands and silts which normally accumulate in nearshore zones, and transport them to deeper parts of the shelf where they are deposited. (4) Storms may also trigger gravity-driven sediment flow into deeper water (i.e., outer shelf, slope, and basin plain) via "low-velocity, turbid-layer transport" (Moore, 1969), "diffuse, fluid gravity flows" (Reineck and Singh, 1972), or "turbidity currents" (Hayes, 1967). Hence, storms may influence nearly every part of the marine realm, either directly or indirectly. Resulting storm deposits are highly variable in terms of thickness, geometry, lateral extent, and vertical sequences produced.

In summary, although many problems still exist in studying modern storms, some valuable information has been obtained about storm processes. Below is a list of generalizations about modern storm processes that are geologically important:

1. Storms may erode, transport, and deposit sediments on continental shelves. The recognition of storm activity in the geologic record may provide clues to the interpretation of ancient continental shelves.

2. Storms can indirectly affect the deposition of sediments in deep water via storm-generated gravity flows. Thus, storms affect all parts of the marine realm.

3. Storms can produce stratification of sediments through hydraulic sorting.

4. Storms can displace or create new sedimentary environments (e.g., hurricane channels, washover fans).

5. No two storms affecting a particular locality, even if of equal intensity, will leave the same geological imprint (e.g., see Perkins and Enos, 1968, Hurricanes Betsy and Donna).

6. Storms may mix sediment types, producing textural inversions.

7. Storms can mix benthic faunas from different habitats. Furthermore, some organisms will try to re-establish themselves in similar environments after a storm has passed.

8. Storms can result in the catastrophic demise of benthic communities and can temporarily halt the process of community seccession. Catastrophic burial of benthic organisms by storm deposits may account for many cases of exceptional fossil preservation (Fossil-Lagerstatten; Seilacher, 1970).

9. Storms are frequent events and therefore should be common in the geologic record, even though "day-to-day" processes tend to obliterate or obscure them. For example, Hayes (1967) notes that an average of 7.5 hurricanes per year occur in the Gulf Coast area.

Late Ordovician Storms

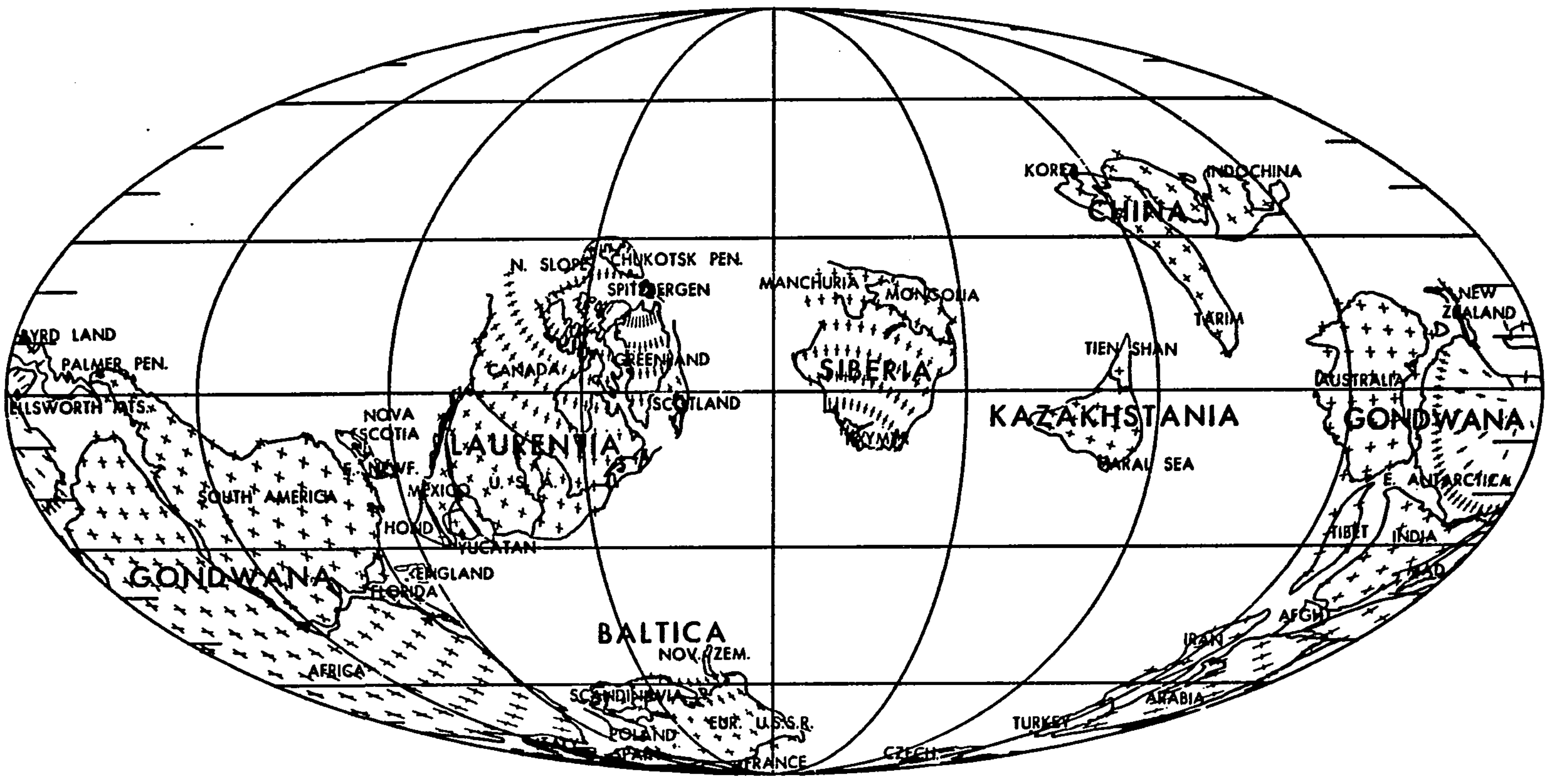
The Cincinnati Arch region was an ideal location for storm activity during Late Ordovician time. Storms may well have been so frequent that they were the dominant depositional mechanism. Five lines of evidence exist to support this conclusion: (1) The Cincinnati area lay approximately 15-25^{o} south of the Equator within the tropics zone--an ideal location for hurricane activity (Tannehill, 1938; Battan, 1961; Simpson and Riehl, 1981). (2) The Cincinnati area was part of a continental landmass ("Laurentia"--see Figure 32) which may have been situated on the western edge of a very wide ocean basin (based on Middle Ordovician restorations)--a typical position for hurricane belts (see Tannehill, 1938; Scotese et al., 1979; Bambach et al., 1980; Marsaglia and Klein, 1981). (3) The Ordovician was one of only five geologic periods in which numerous examples of ancient storm sequences have been described in the literature (Marsaglia and Klein, 1981). Furthermore, of these five geologic periods, the Ordovician is believed to have the highest percentage of probable hurricane sequences (Marsaglia and Klein, 1981). (4) Storm sequences have been documented in Middle and Upper Ordovician strata (Martinsburg Formation) in nearby southwestern Virginia (Kreisa, 1981). (5) Numerous examples of graded sequences which are very similar to those previously described in the Martinsburg Formation are known to exist in the Cincinnatian Series.

Ordovician hurricanes may have originated in the open ocean which lay to the east of Laurentia. Driven westward by the tradewinds, storms approached Laurentia and were deflected toward the south pole. Kreisa (1981) notes that this situation is essentially a mirror image of the modern U.S. Gulf Coast (see Figure 33). In addition, Ziegler et al. (1981) have depicted inferred surface ocean currents during Ordovician time which coincide with the reconstruction shown in Figure 33 (see Figure 34 for comparison). This reconstruction is supported by Cincinnatian paleocurrent data (see Table 10 and Appendix 7). Although paleocurrent orientations are variable, the dominant trend is NE/SW (68^{o}). Similar trends have been documented by Hoffman (1966) and Potter and Pettijohn (1977, p. 117). Also note that the paleowind vectors shown in Figure 34 roughly coincide with a modern-day NE/SW orientation.

Storm-Generated Vertical Sequences

Very few geological studies of modern storm sequences have appeared in the literature. Probably the most comprehensive analysis of modern storm deposits is that of Reineck and Singh (1972). The authors studied storm sequences in Holocene cores taken from the North Sea and from the Gulf of Gaeta, Italy. Although individual sequences are variable, the majority exhibit the following six characteristics: (1) Thickness ranges from a few mm to nearly 1 meter. (2) Most have a sharp base and a burrowed or diffuse top. (3) They often occur as couplets of shell or gravel lag and laminated sand and silt. (4) Sands and silts are weakly graded and laminated ("graded rhythmites"). (5) Escape structures are common. (6) Lamination is usually horizontal, although "gentle discordances" are common. In addition, the lateral geometry of storm deposits has been studied by Hayes (1967). Hayes showed that sediments deposited in the inner neritic zone (60 to 120 feet in depth) by Hurricane Carla (1963, Gulf Coast) occurred in isolated, sheet-like layers having irregular thicknesses.

Studies of ancient storm sequences are more common in the geologic literature. Most of these studies have taken place within the last ten



<u>Figure 32</u>: Middle Ordovician paleogeography (from Scotese et al., 1979, fig. 8).

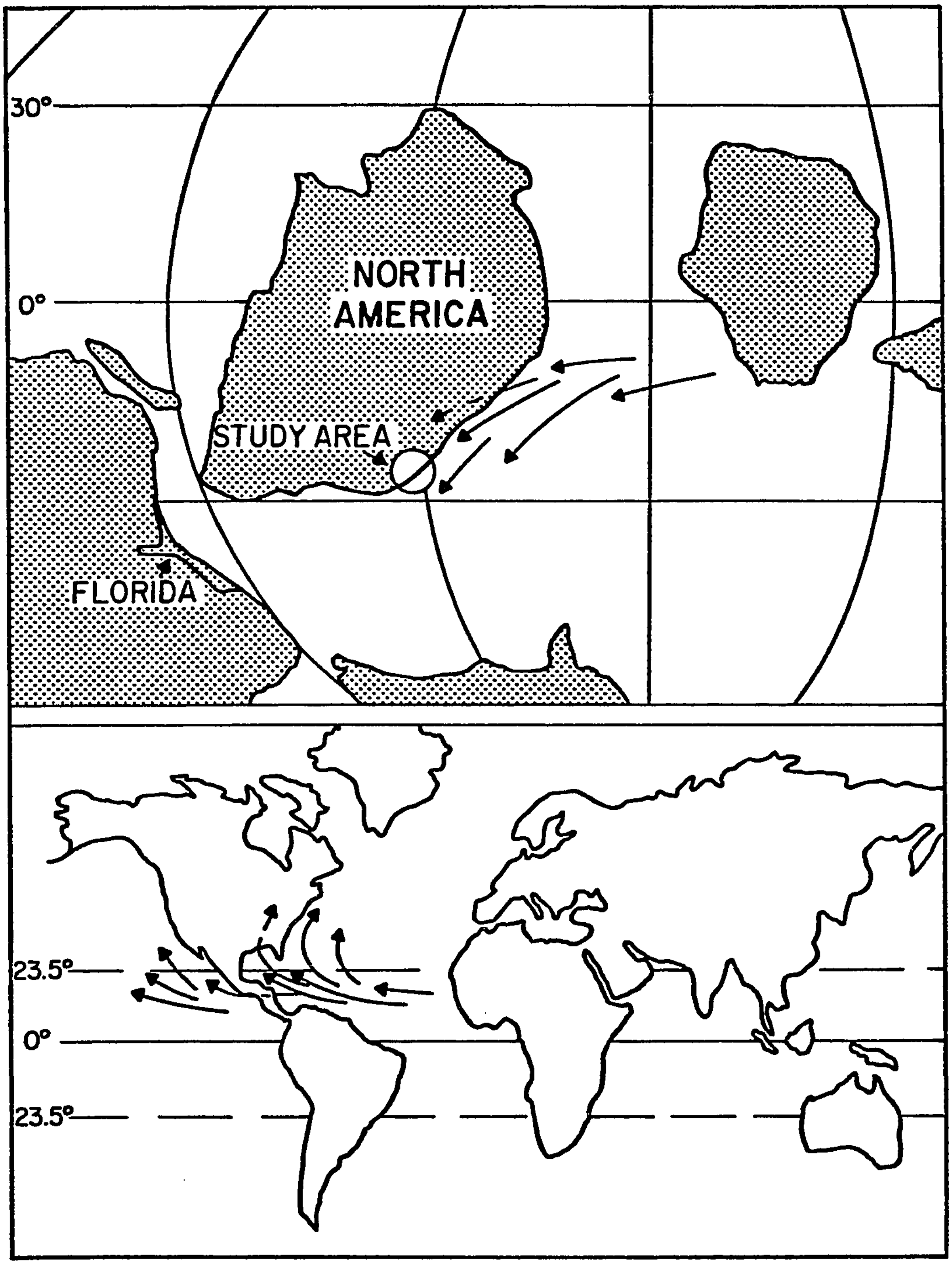


Figure 33: Comparison of storm tracks of hurricanes which influence North America, modern and inferred Middle and Late Ordovician (from Kreisa, 1981, fig. 13).

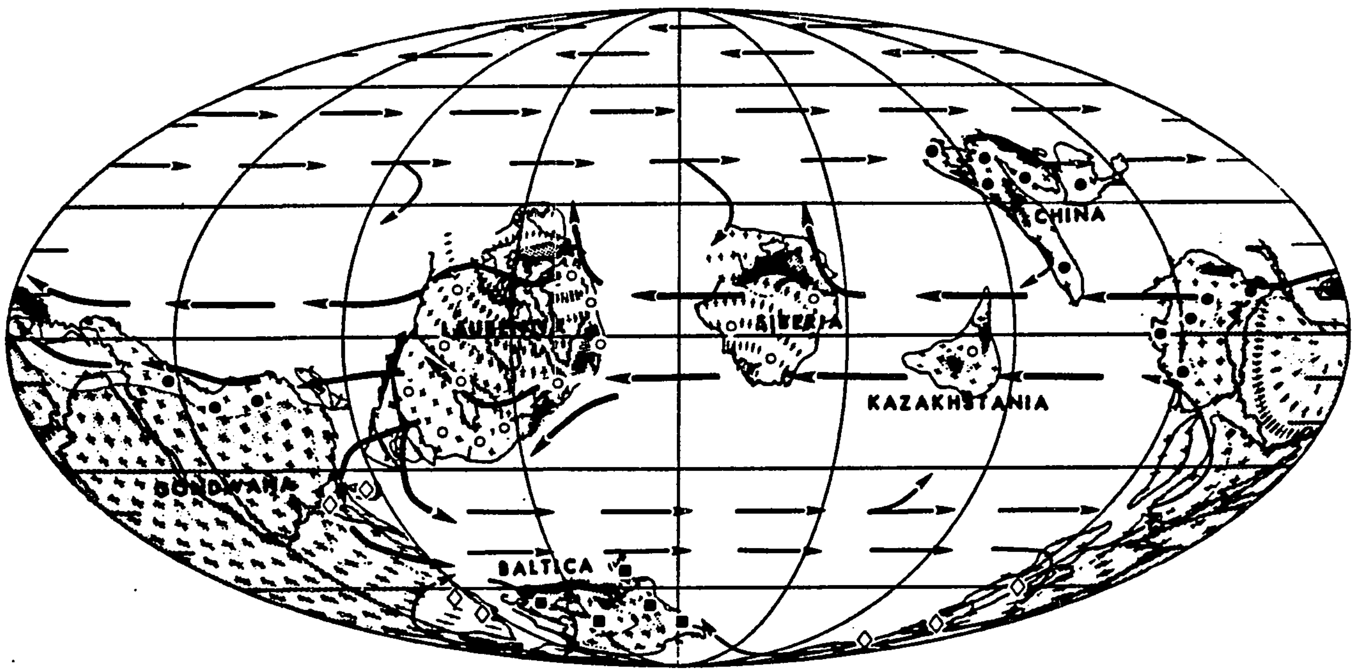


Figure 34: Middle Ordovician paleogeography and inferred surface ocean currents: thick arrows = warm, thin arrows = cold (from Ziegler et al., 1981, fig. 7.2).

COMPARISON		MEAN PALEOCURRENT ORIENTATION
MEGACYCLE SUBDIVISION	Shale Hemicycle	63° (n = 11)
	Carbonate Hemicycle	60° (n = 12)
STRATIGRAPHIC	Waynesville to Whitewater Sequence	78° (n = 2)
	Corryville to Oregonia Sequence	94° (n = 10)
	Kope to Bellevue Sequence	55° (n = 21)
ALL SAMPLES		68° (n = 33)

Table 10: Comparisons of mean paleocurrent orientations in the Cincinnatian Series. Arrows show two possible current directions (180° apart) because in most of the structures measured, the absolute direction of current flow could not be determined (e.g., symmetric ripples, most gutter casts).

years, and have included Paleozoic and Mesozoic sequences from North America, Europe, and Africa. Based on this literature, Kreisa (1981) has summarized the important sedimentary features which are characteristic of ancient storm sequences, including (in order of abundance): (1) interbedded coarse (storm) and fine (fair weather) beds; (2) sharp or scoured bases and gradational or burrowed tops; (3) wave-generated undulatory lamination; (4) thickening and thinning and lenticular beds; (5) vertical sequences of sedimentary structures from plane-lamination to wave-generated lamination; (6) pot and gutter casts at the base of sequences; (7) laminated beds with upward-thinning laminae, increase in matrix, and weak grading; (8) reworked, but autochthonous fauna; (9) lag deposit/suspension deposit couplets; (10) escape burrows; and (11) infiltration textures. Additional features of ancient storm deposits which were not discussed in Kreisa (1981) include textural inversions, mixtures of fossil preservational states within the same bed, presence of articulated fossils (e.g., crinoid stems, brachiopods, etc.), omission surfaces, and intraclasts or lithoclasts.

Of the ancient storm sequences which have been recorded in the literature, those described by Kreisa (1981) from the Middle and Upper Ordovician Martinsburg Formation are probably most similar to storm cycles in the Cincinnatian Series. Kreisa observed thin, fining-upward sequences (1 to 80 cm thick) which are composed of three stacked units (Figure 35): (1) a basal, coarse-grained "whole fossil packstone," having an abrupt or erosional base and containing intraclasts, oriented whole or slightly broken fossils, and abundant infiltration textures; (2) a graded "laminated unit" (laminated calcarenite, calcisiltite, or siltstone), and (3) a layer

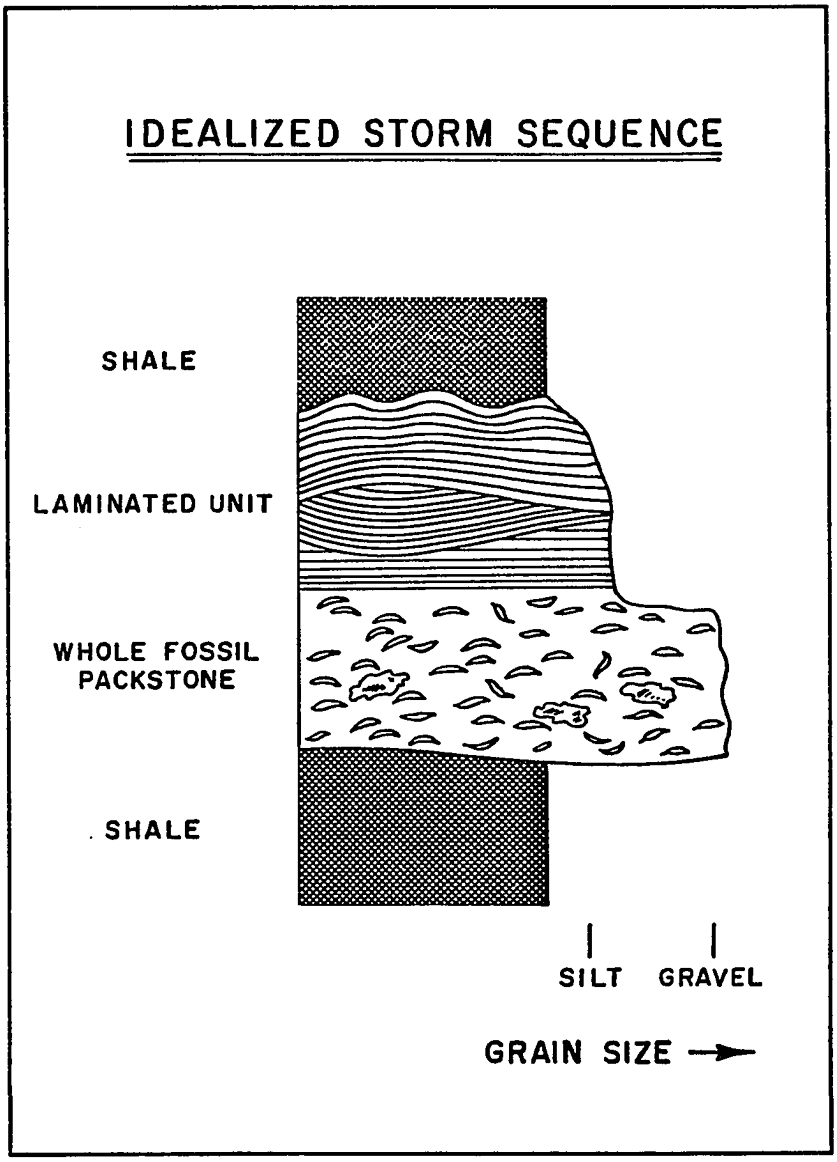


Figure 35: Idealized vertical succession of sedimentary structures and lithologies in fining-upward sequences, Martinsburg Formation, southwestern Virginia (from Kreisa, 1981, fig. 3).

of unfossiliferous shale. Both the "laminated unit" and "shale unit" exhibit gradational contacts. Kreisa attributes these sequences to deposition from high-energy storm events. The basal "whole fossil packstone" with its erosional base represents upper flow regime during the early stages of a storm. The middle "laminated unit" typically grades upward from planar lamination to various types of cross lamination, representing the transition from upper to lower flow regime as the storm is waning. Finally, the upper shale layer represents deposition of the finest storm-suspended material (silts and clays) at the end of the storm event. Storm-deposited shales typically grade upward into bioturbated, fossiliferous shales which represent post-storm, fair-weather sedimentation.

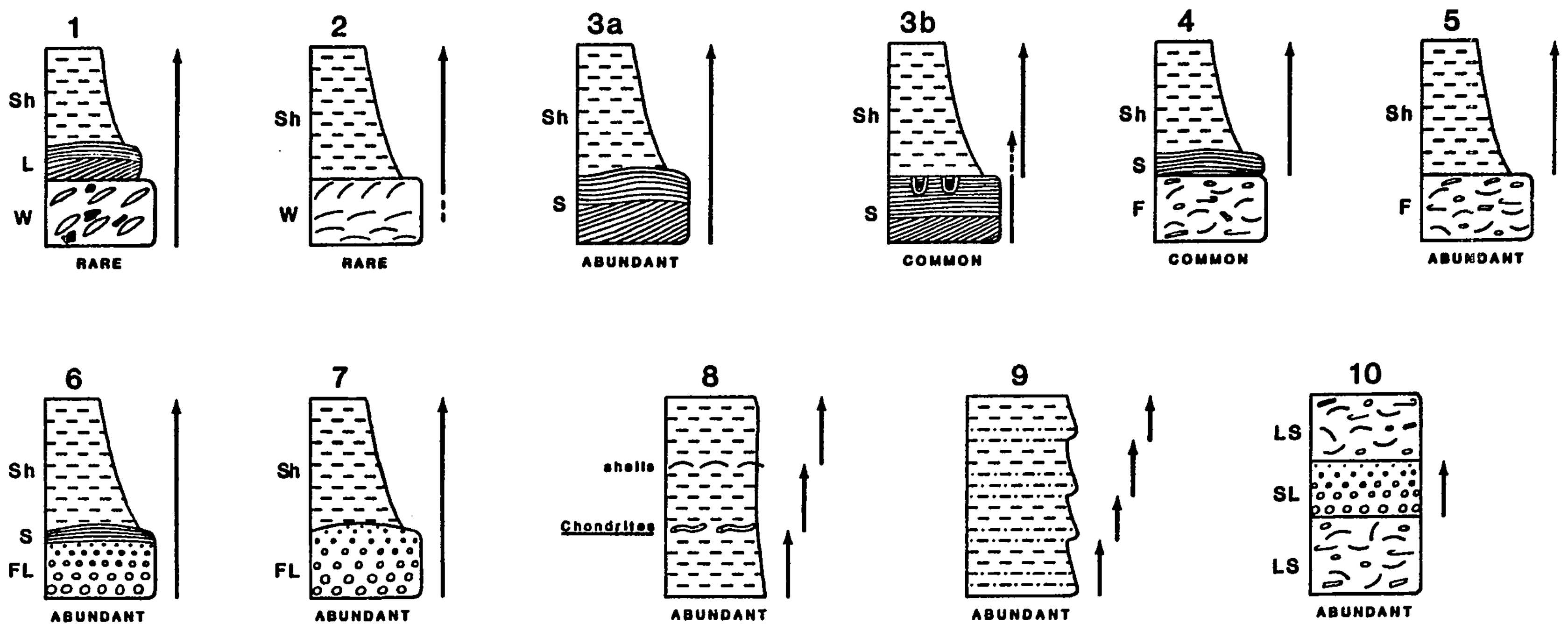
Graded limestone beds have also been noted in the Cincinnatian Series. Bucher (1917, 1919), Potter and Blakely (1968), and Anstey and Fowler (1969) have all described graded beds of sparry, skeletal limestone (grainstones?) which were attributed to periodic storm deposition. More importantly, Kreisa et al. (1981) have described fining-upward sequences in Richmondian strata in the Brookville, Indiana, area which are similar to those found in the Martinsburg Formation. However, the complete fining-upward sequence described by Kreisa is very rare in the Cincinnatian Series. Usually, only part of the ideal sequence occurs in outcrop. In addition, numerous Cincinnatian limestone beds (i.e., packstones, wackestones, and some grainstones) show no evidence whatsoever of storm deposition. In this study, ten recurrent variations of the "complete" storm cycle have been identified (see Figure 36).

Storm sequences would appear to be more variable in the Cincinnatian Series than in the Martinsburg Formation for two reasons: First,

Figure 36: Storm cycle variants. Arrows denote layers of sediment which were deposited by single storm events. Sh = shale, L = laminated unit, W = whole fossil packstone or grainstone, S = siltstone, F = fragmental limestone (coarse grainstone, poorly washed grainstone, or packstone), FL = fine limestone (fine grainstone or calcisiltite), SL = storm layer (carbonate or shale), Ls = any kind of limestone.

Variation 1 is the "complete" storm cycle after Kreisa (1981). Variation 2 is the same sequence without the laminated unit, and Variation 3a lacks the whole fossil packstone bed. Variation 3b represents two storm events, the first of which deposited a sequence similar to 3a. Afterwards, organisms burrowed downward from the top of the shale layer into the underlying layer of silt. The second storm eroded part of the previously deposited sequence, resulting in the omission surface (truncated *Diplocraterion*), and deposited a second layer of shale. Variation 4 represents storm deposition following a period of in situ carbonate sedimentation. Variation 5 is the same sequence without the siltstone unit. Variations 6 and 7 are similar to turbidites and may represent storm deposits or storm-generated gravity flows. Variations 8 and 9 represent frequent shale-depositing storm events, and demonstrate that individual shale beds probably represent multiple storm events (see "Shale Petrology--Interpretation"). Variation 10 represents periodic storm erosion and deposition within the time span of a single carbonate bed.

STORM CYCLE VARIANTS



Martinsburg strata are tectonically deformed, resulting in the non-preservation of many storm sequences. Conversely, storm sequences are exceptionally well preserved in the undeformed strata of the Cincinnatian Series. Secondly, the fundamental difference in paleogeographic location of the two study areas may have favored a greater variety of storm sequences in the Cincinnatian Series. Martinsburg sediments were deposited on a shallow-water shelf relatively close to a major source of terrigenous clastics (the Taconic Mountains), whereas Cincinnatian sediments were deposited on a shallow shelf more than 200 miles farther away from the same source area (see Figure 11). Because the Martinsburg shelf was closer to the Taconics, moderate amounts of terrigenous clays and silts were constantly being deposited, even during periods of fair weather. If storms had not occurred during Late Ordovician time, unstratified, fossiliferous shales would have been the only lithology deposited on the Martinsburg shelf (Kreisa, pers. comm., 1981). Thus, the major influence of storm activity was to *produce* stratification by resuspending previously admixed carbonate and terrigenous sediments, and hydraulically separating them into three distinct strata. Hence, nearly every storm that occurred in this setting produced a repetitive, three-part sequence which was capped by shale.

Conversely, terrigenous sediments were never deposited during fair weather on the Cincinnatian shelf because of the greater distance from the Taconics. Thus, if storms had not occurred during Late Ordovician time, only carbonates would have been deposited, and stratification would probably have been limited to thick, major facies changes. Therefore, the major influence of storm activity in the Cincinnati area was *not* to produce stratification by resuspending and separating previously admixed carbonates and clays, but instead to produce stratification by transporting allochthonous terrigenous sediments into the area from outside, thereby producing shale interbeds (see Figure 37), and by reworking previously deposited carbonate sediments. As storms approached the Cincinnati Arch region, previously deposited carbonate sediments were winnowed, hydraulically sorted, and redistributed to varying degrees. Furthermore, transportation occurred in several directions (i.e., upslope, downslope, and parallel to slope). The result of this variable hydraulic sorting and redistribution was to produce the "recurrent carbonate rock types" discussed earlier (see Figure 38). Many of these hydraulically separated carbonate layers were preserved by the deposition of a protective stratum of shale at the end of the storm event. However, because of the greater distance between depositional site and terrigenous source area, many of the storm surges that crossed the Cincinnati area were not shale bearing. As a result, some vertical storm sequences are capped by shales and some are not (e.g., Figure 36, variation 10). Hence, storms that crossed the Cincinnati Arch region during Late Ordovician time had a greater variety of effects than those which crossed southwestern Virginia, resulting in a greater variety of storm sequences.

Paleoecologic Implications

The preceding section described the effects of storm activity on sedimentation in the Cincinnati Arch region. In this section, the influence of frequent storm activity on the paleoecology of benthic organisms is considered. Late Ordovician storms strongly affected the paleoecologic

Figure 38: Flow diagram of storm effects on carbonate sedimentation. "Original Sediment," which accumulates through normal fair-weather processes, is occasionally disturbed by storm events. Storms hydraulically separate the different particle sizes and transport them to varying degrees, either upslope, downslope, or parallel to slope. Redeposition of these sediments results in the "recurrent carbonate rock types" discussed earlier. Packstones and wackestones represent muddy, poorly sorted sediments which have not been winnowed and transported by storms.

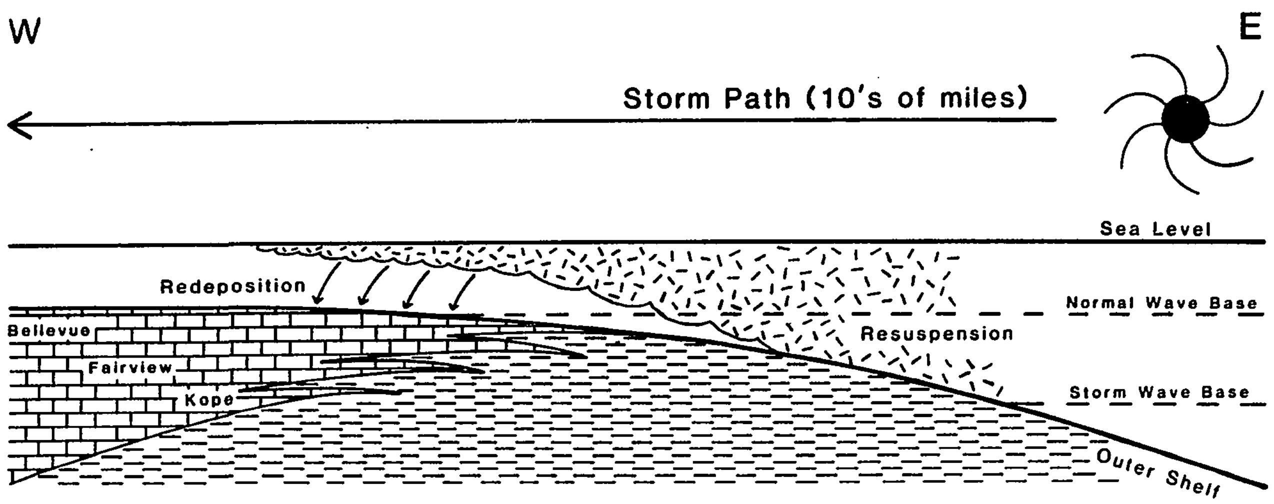
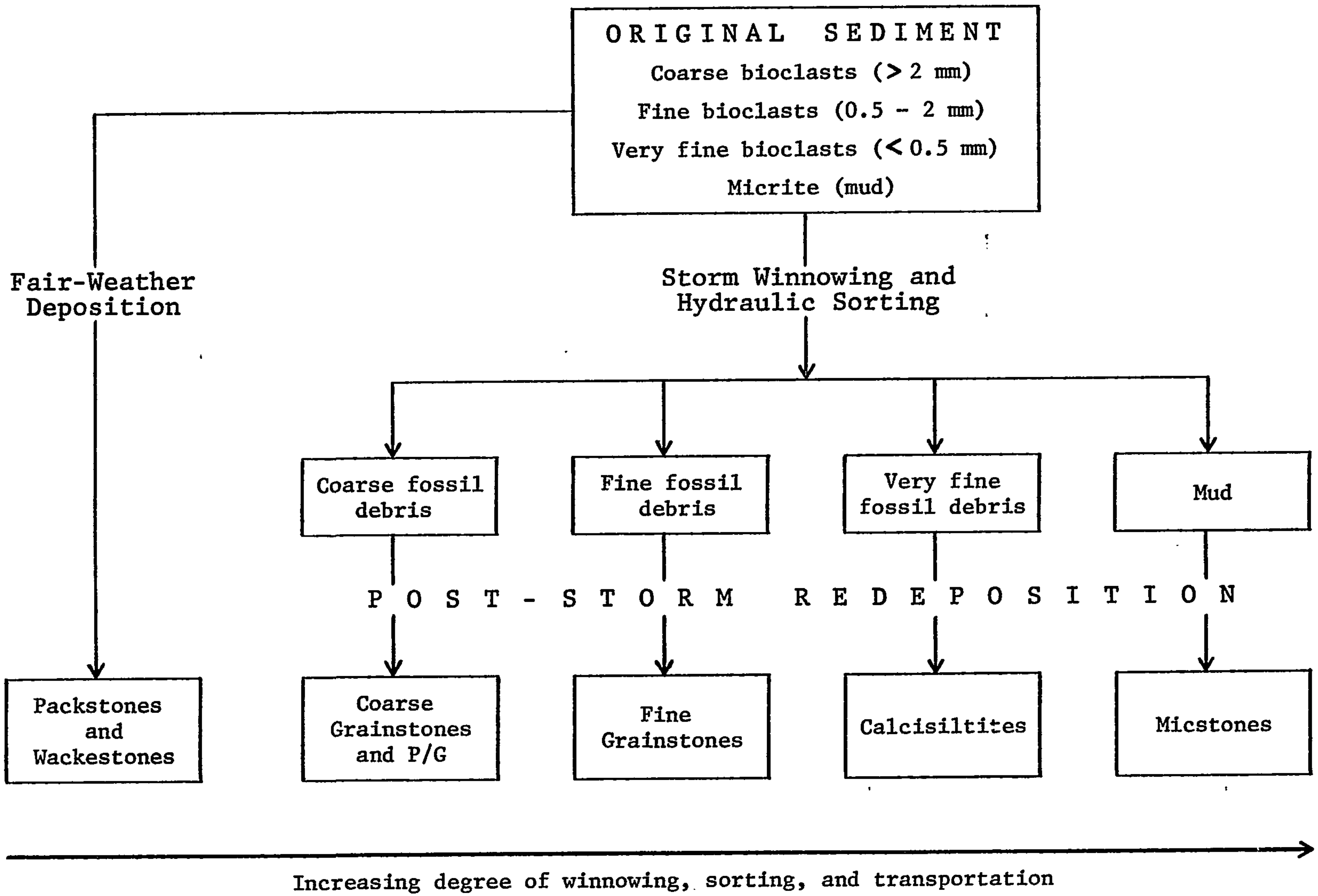


Figure 37: Dip section profile of part of the Cincinnatian sea floor, showing erosional and depositional processes. As storms moved into the area, they eventually reached a point where storm wave base intersected the sea floor bottom. Outer shelf muds localized in this region were then resuspended and transported short distances (tens of miles) toward shallower water, where they were quickly redeposited in the offshore to shoreface zone.


ORIGINAL SEDIMENT
Coarse bioclasts (> 2 mm)
Fine bioclasts (0.5 - 2 mm)
Very fine bioclasts (< 0.5 mm)
Micrite (mud)
Fair-Weather Deposition
Storm Winnowing and Hydraulic Sorting
Coarse fossil debris
Fine fossil debris
Very fine fossil debris
Mud
POST-STORM REDEPOSITION
Packstones and Wackestones
Coarse Grainstones and P/G
Fine Grainstones
Calcisiltites
Micstones
Increasing degree of winnowing, sorting, and transportation

record of the Cincinnatian Series in three important areas: (1) short-term community succession and its preservation in the rock record; (2) the preservation of *in situ* benthic communities; and (3) the success of opportunistic species.

"Short-term community succession" (Walker and Alberstadt, 1975) occurs in unstable environments in which occasional environmental catastrophes destroy a mature benthic community, and rebuilding involves a rapid, biologically-induced re-establishment of the original community. These events occur rather quickly, within the time span of the deposition of a single bed. Harris and Martin (1979) proposed a model for community succession in the Cincinnatian Series wherein soft, muddy substrates (i.e., the tops of shale beds) were initially colonized by thin, flat brachiopods (Figure 39). These "pioneer" shells created a firm, stable pavement upon which erect bryozoans and crinoids could grow. As time progressed and the community matured, the bryozoans and crinoids formed a dense organic baffle capable of trapping fine carbonate mud, thereby producing a thick layer of carbonate sediment.

The process of short-term community succession probably did occur during Cincinnatian time, but unquestionable examples of this process are quite rare. The numerous examples of community succession that are described by Harris and Martin (1979) are highly doubtful for the following reasons: (1) According to the model, the maximum amount of depositional carbonate mud should occur in bed centers where the bryozoan-crinoid thicket was presumably most dense, rather than in bed margins where the thicket was probably less dense. Recalculation of the amount of original mud, based on Harris and Martin's interpretation of diagenetic alteration,

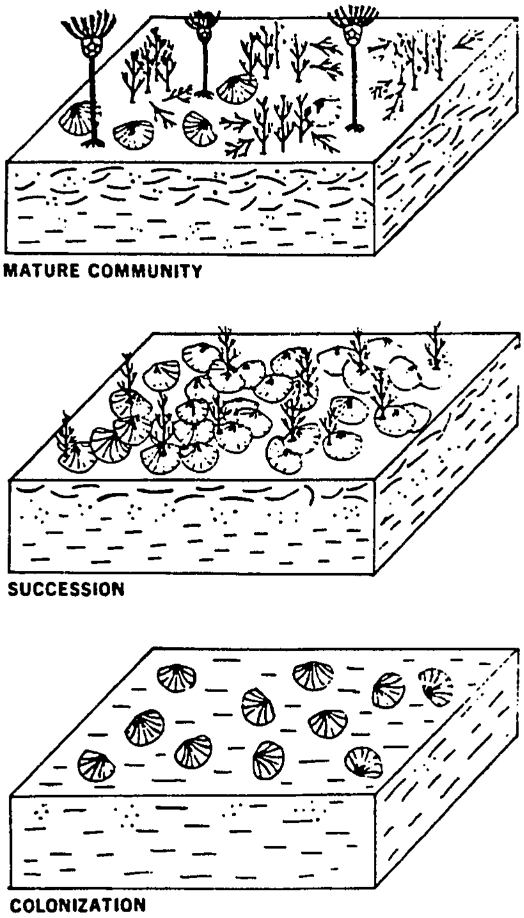


Figure 39: Colonization of soft mud substratum by *Onniella* (from Harris and Martin, 1979, fig. 5).

shows that the reverse is true (see discussion in Tobin, 1980, pp. 103-104). (2) According to arguments proposed by Oldroyd (1978), Cincinnatian limestones do not contain enough bryozoans and crinoids to indicate that these organisms were capable of effectively trapping fine sediments. (3) Mahan and Harrison (1980) point out that storms probably reworked some carbonate sediments into discontinuous bioclastic shoals. Hence, it was not necessary for all organisms to colonize muddy, inhospitable substrates as long as these firm bioclastic shoals were available. Thus, faunal communities did not always have to go through the entire sequence from the "pioneer" to "mature" stages, but could renew development higher in the successional sequence--thereby obscuring any vertical evidence of succession that might exist. (4) According to Schindel (1980), the microstratigraphic interval required to show community succession in the fossil record is probably much too thin to discern.

The last argument can be illustrated by estimating depositional rate and storm frequency for Late Ordovician time. By assuming that the amount of time required for the deposition of shales was minimal, and by assuming that all limestones were deposited at nearly the same rate, limestone depositional rates can be roughly estimated by dividing the total thickness of limestone in the Cincinnatian Series (99.6 meters) by the length of Cincinnatian time (10 million years). This method yields a depositional rate of 1 cm/1,000 years. Alternatively, if it is assumed that limestones and shales were deposited at the same rate, then the estimated depositional rate for all sediments becomes 2 cm/1,000 years. These estimates are close to those calculated for similar ancient carbonate strata by Wilson (1975, p. 15) of 4 cm/1,000 years. Consider a typical 4 cm thick Cincinnatian limestone bed which Harris and Martin (1979) might regard as an example of community succession. If Wilson's estimated rate of 4 cm/1,000 years is assumed to be the most plausible, then such a limestone bed would represent about 1,000 years of Cincinnatian time. Schindel (1980) points out that short-term biologic processes such as community succession should take 10 to 100 years to develop. This means that a complete, uninterrupted example of community succession should be represented by only 0.4 mm to 4.0 mm of the total thickness of this bed. Hence, 10 to 100 complete successions could have occurred within the time span of this bed, rather than only one.

Modern shallow-shelf carbonate sediments are deposited at an average rate of 100 cm/1,000 years (Wilson, 1975, p. 15). Obviously, a rate of 4 cm/1,000 years is much too slow, even if the effects of compaction are considered. Wilson attributes this discrepancy to the intermittent, discontinuous nature of carbonate sedimentation, which ". . . may cease abruptly and start again when conditions are favorable. Carbonate sedimentation resembles a powerful Cadillac with a defective carburetor" (1975, p. 16). In the case of the Cincinnatian Series, the principal "defect" was frequent storm activity. This concept was also discussed by Schindel (1980, p. 415) with respect to the preservation of short-term biological processes in the rock record:

> In reality, potentially recoverable details of faunal history are obliterated by everyday processes that rework sediments after deposition. Once mixed by these processes, either vertically or laterally, the original distribution patterns of fossilizable organisms are irretrievably lost. Further, the mixing processes discussed here act to destroy the physical evidence of hiatuses. *Without such evidence, an intermittently formed sedimentary sequence might appear to be the product of continuous deposition.* (emphasis added)

Hence, the estimated rate of 4 cm/1,000 years does not represent the instantaneous rate of deposition, but rather the net rate of rock accumulation (see Shaw, 1964, p. 139). Although the previously mentioned 4 cm thick limestone bed probably does represent 1,000 years of Cincinnatian *time*, it does not represent 1,000 years of *continuous sedimentation*. Instead, it represents 1,000 years of alternating periods of storm and fair-weather deposition, storm erosion, and non-deposition. Therefore, most Cincinnatian limestone beds are probably *amalgamated* (i.e., fair-weather deposits and previous storm deposits were periodically destroyed by subsequent erosional storms, leaving behind a "condensed" bed). As Schindel (1980) points out, the evidence of such hiatuses may be lost through day-to-day processes, including compaction and diagenesis. Therefore, the "proof" of amalgamation in many Cincinnatian limestone beds must be inferred from the time relationships previously discussed, and from the recognition of *preserved* diastems in limestone polished slabs (see Appendix 8 and Figure 36).

The idea that frequent storm activity masked biological processes in the Cincinnatian rock record can be further illustrated by estimating *storm frequency*. A total of 6,497 *observable* storm sequences are known to exist in the Cincinnatian Series. Dividing this number by the length of Cincinnatian time (10 million years) yields a frequency of 1 storm/1,539 years. Obviously, this estimate is much too low in comparison to modern hurricane frequencies (7.5 storms/year; see Hayes, 1967). Even if the concept of the 100-year storm is invoked (i.e., the idea that storm paths may only cross some given locality once every 100 years--based on recent storm tracks shown in Tannehill, 1938), such a frequency would still be too low by a factor of 15 to 1. This suggests that the overwhelming majority of Cincinnatian-Age storms were *erosional*, rather than depositional in nature. Thus, to preserve an example of short-term community succession in the rock record would require a very unusual set of circumstances.

The second major paleoecologic effect of storm activity on the Cincinnatian Series involves the non-preservation of *in situ* benthic communities. Only a few examples of probable benthic communities are known to exist (e.g., the "Fossil-Lagerstatten" slabs described by Meyer et al., 1981). Ironically, in such cases it is the storm activity itself which was responsible for such rare preservation. Storms occasionally preserved carbonate layers by depositing a protective layer of shale on top.

In most cases, Ordovician storms mixed benthic faunas from neighboring communities through erosion, resuspension, and transportation. The common occurrence of a mixture of fossil preservational states on the top surfaces of many limestone beds supports this conclusion. Although all of the fossils *within* a limestone bed may be unabraded and unbroken, the tops of many beds display a mixture of small, highly abraded fragments and large, unabraded fragments, suggesting the mixing of bioclasts from different environmental settings. Thus, most limestone bedding-plane surfaces do not represent true "census" communities because some members of the original community have been transported away from their life site, while others have been introduced from outside. Accordingly, some workers have elected to use the terms "faunal assemblage" or "faunal association" in their studies of Cincinnatian paleoecology instead of the term "faunal community."

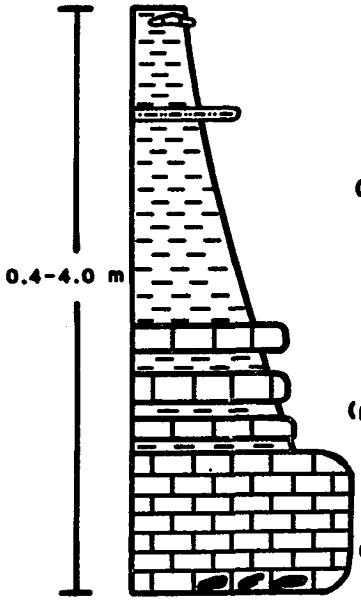
The third major consequence of frequent storm activity in the Cincinnati area was the success of certain opportunistic species. Opportunists are best adapted to conditions of environmental instability (i.e., frequent environmental disturbances such as storms, floods, etc.). The presence of frequent storm activity during Cincinnatian time favored the evolution of opportunistic benthic organisms, particularly the brachiopods *Rafinesquina*, *Onniella*, *Strophomena*, and *Zygospira*. These genera exhibit most of the characteristics of opportunists recognized by Levinton (1970): (1) They are found throughout the Cincinnatian Series and are not restricted to any one particular rock type or faunal association. (2) They are very abundant in most assemblages. (3) They are usually widespread within a given stratum, although patchy distribution and aggregation in clusters sometimes occurs. (4) They occur in numerous horizons with barren intervals between (i.e., shale interbeds). (5) They all occur in a variety of facies. (6) They all exhibit morphologic variations in different facies (i.e., each morphotype of a given genus occurs in its own characteristic facies).

Megacycles

Description

"Megacycles" are moderately thin (0.2-4.9 m thick), fining-upward, repetitive sequences that occur throughout the Cincinnatian Series. Based on observations of bedding characteristics in the Kope and Fairview formations, I initially described an "idealized" megacycle as a repetitive sequence having three members: (1) a basal grainstone member (unit A), composed of a thick grainstone bed, or several closely spaced, thin grainstone beds, poorly washed grainstone beds, or calcisiltite beds; (2) a middle packstone bundle (unit B), composed of interbedded packstones, wackestones, and thin shale beds; and (3) an upper shale-rich member (unit C), composed of thick shales interbedded with a few thin siltstones or micstones (see Meyer et al., 1981, pp. 52-53). A graphic representation of this "idealized" megacycle is shown in Figure 40.

Through subsequent field work in the summer and fall of 1981 and the spring of 1982, I examined nearly 200 megacycles from six different formations in the Cincinnatian Series (see Appendix 9). Analysis of these new data leads to four important conclusions about megacycles: (1) The "idealized" A B C package shown in Figure 40 is less abundant than originally predicted. Although the vertical transition from units A and B to unit C *always* occurs, the transition from unit A to unit B is infrequent (only 24% of megacycles show this transition). Hence, a megacycle is herein redefined as a two-part repetitive sequence composed of a moderately thin, basal *carbonate hemicycle* (formerly units A and B) which is overlain by a thicker *shale hemicycle* (formerly unit C). The carbonate hemicycle is characterized by relatively thick, planar-bedded, closely spaced limestones (mostly grainstones, poorly washed grainstones, packstones, wackestones, and calcisiltites) interbedded with shales. The shale content in carbonate hemicycles is low (usually less than 20 percent). Conversely, the uppermost shale hemicycle is characterized by relatively thin, wavy-to-nodular carbonate beds (mostly siltstones, micstones, and calcisiltites, but others occur as well) and thick shales. Shale content in this hemicycle is very high (greater than 70 percent).



UNIT C (shale-rich)	Relatively thick, shale-rich, and containing several very thin siltstone and/or silty micstone beds and nodules. Thin beds are usually planar-laminated, cross-laminated or rippled. Shales are barren of fossils, and bioturbation is nearly absent. Siltstone and micstone beds contain highly broken, very fine-grained, well-sorted fossil debris and quartz silt. Faunal diversity is very low.
UNIT B (packstones)	Interbedded packstones, wackestones and shale. Thin-bedded, planar to wavy. Limestones are matrix-rich, poorly sorted, coarse-grained with a moderate-to-low degree of breakage. Faunal diversity is fairly high, including Br, Bz, Cr, Tr, Bast., Pele., etc.
UNIT A (grainstone)	Thick-bedded grainstone. Planar-bedded, often rippled, with rare cross-bedding. Matrix-poor, well-sorted, medium- to fine-grained, with a high degree of breakage. Faunal diversity is moderate, including mostly crinoids and bryozoans. Occasional mud clasts near base.

Figure 40: Idealized megacycle from the Kope and Fairview Formations (from Meyer et al., 1981, fig. 22).

Moreover, thin-section data reveal that shales in the carbonate hemicycle are less silty and finer grained than shales in the shale hemicycle (see Table 11 and Figure 41). Examples of megacycles in outcrop are shown in Figure 42 and Appendix 3. (2) Megacycles thin upward stratigraphically within "shoaling upward shelf cycles." For example, megacycles are thick in the Kope Formation, thin in the Fairview Formation, and very thin or absent in the Bellevue Limestone. The same upward thinning pattern is repeated in the Corryville to Oregonia sequence and in the Waynesville to Whitewater sequence (see Table 12 and Figure 43). Furthermore, this upward thinning trend is reflected most strongly in the shale hemicycle (Table 12). (3) Lateral variations in megacycle thickness exist, but show no coherent pattern. For example, megacycles thin in an easterly direction in the Kope and Corryville formations (1.88 m to 1.57 m, and 1.60 m to 0.62 m, respectively), but thin in the opposite direction in the Sunset Formation (1.15 m to 0.85 m). Furthermore, megacycles in the Fairview Formation show no observable lateral thinning trends. (4) Megacycles exhibit homotaxial correlation over moderately short distances (see Figure 44).

Statistical Analyses of Cyclicity

Geological statisticians have long argued that because of man's inherent psychological need to make order out of randomness, geologists often attempt to organize sedimentary strata into repeating "cycles" whether their existence is real or not (Duff and Walton, 1962; Zeller, 1964; Carr, 1981). Furthermore, Zeller (1964, p. 631) points out that "Science, to an extent matched by no other human endeavor, places a premium upon the ability of the individual to make order out of what appears disordered."

SHALE CHARACTERISTIC		CARBONATE HEMICYCLE	SHALE HEMICYCLE
Composition		QF_{26} CM_{67} CD_{7}	QF_{40} CM_{48} CD_{12}
Rock Name		Claystone	Dolomitic mudstone
Quartz/Clay Ratio		0.43	0.95
Grain Size	Mean	22μ	26μ
	Median	21μ	24μ
Grain Shape	Sphericity	Low (.655)	Very low (.613)
	Elongation	Subelongate (.655)	Elongate (.613)

Table 11: Comparison of the average compositional and textural characteristics of shales in megacycles. "Grain size" refers to the silt + sand size fraction only.

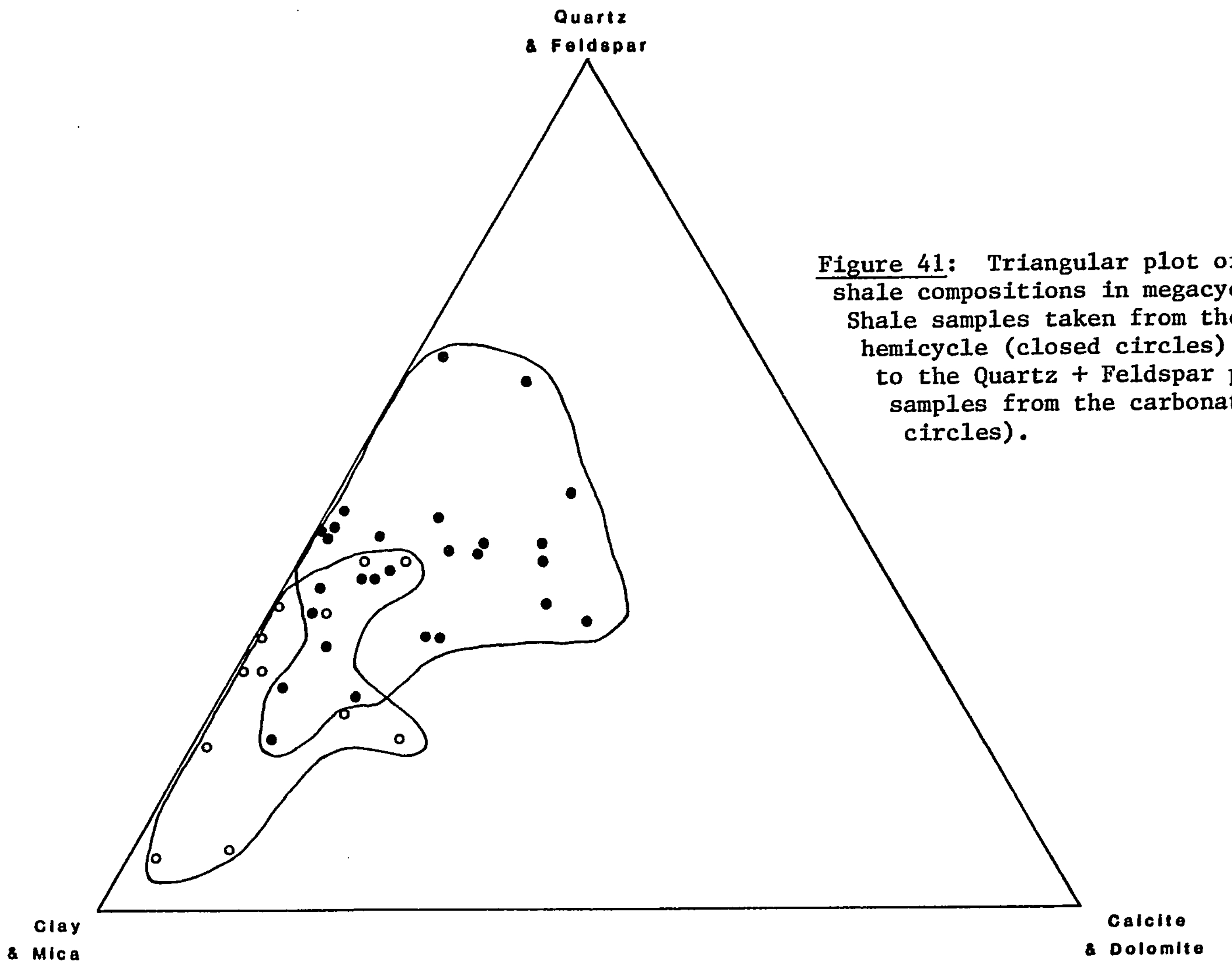


Figure 41: Triangular plot of shale compositions in megacycles. Shale samples taken from the shale hemicycle (closed circles) plot closer to the Quartz + Feldspar pole than shale samples from the carbonate hemicycle (open circles).

Figure 42A: Profile of megacycles in the upper Kope Formation, Bald Knob Hill locality. The Kope-Fairview contact occurs at the base of the prominent limestone ledge at the top of the hill.

Figure 42B: Profile of megacycles in the Fairview Formation, Reidlin Road locality. Note the similarity in weathering profile to that shown in Figure 42A. Note also the comparative thinness of Fairview megacycles.

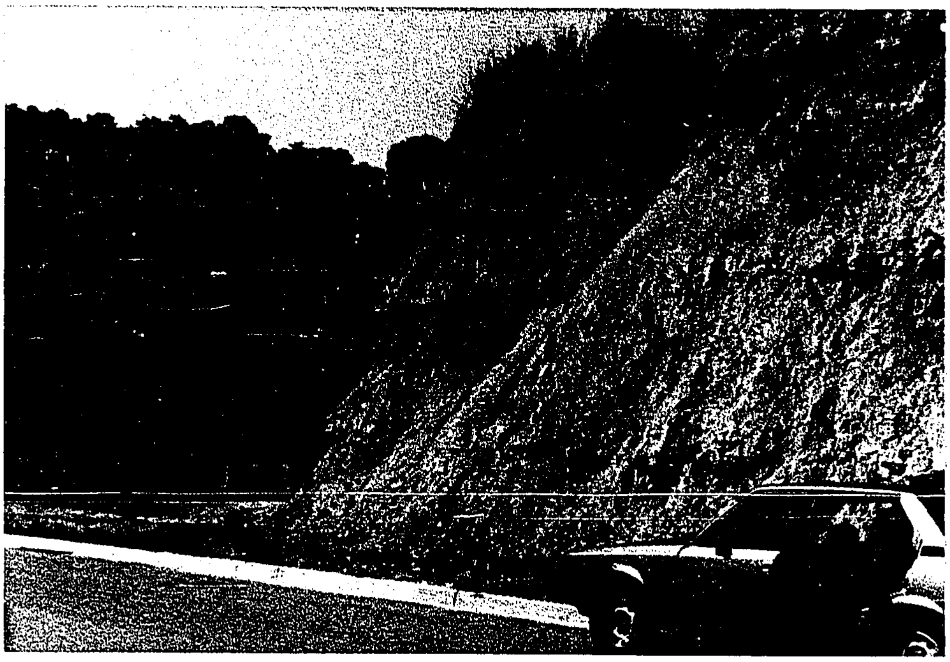
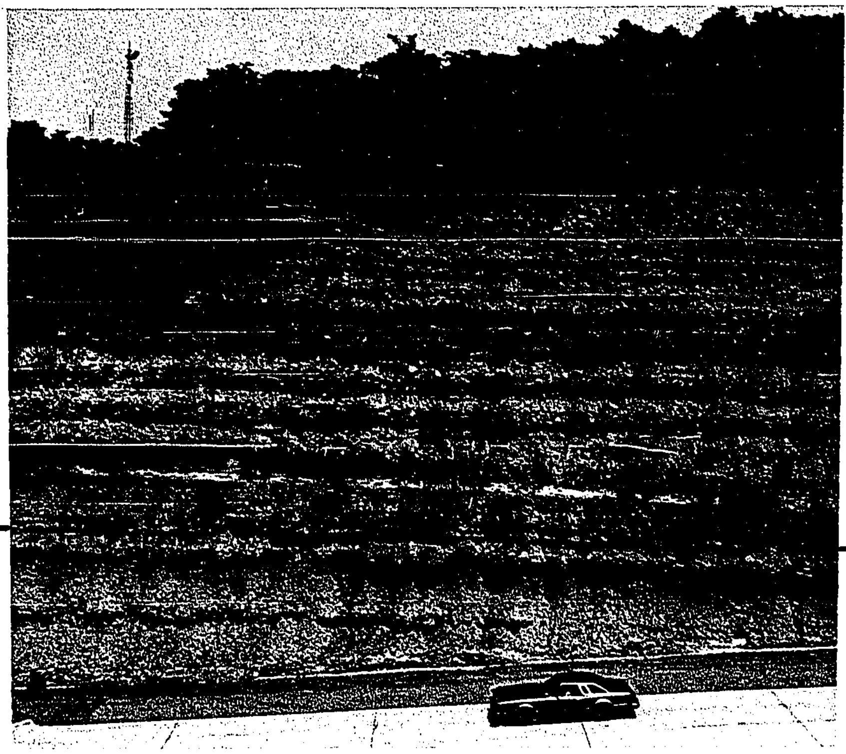
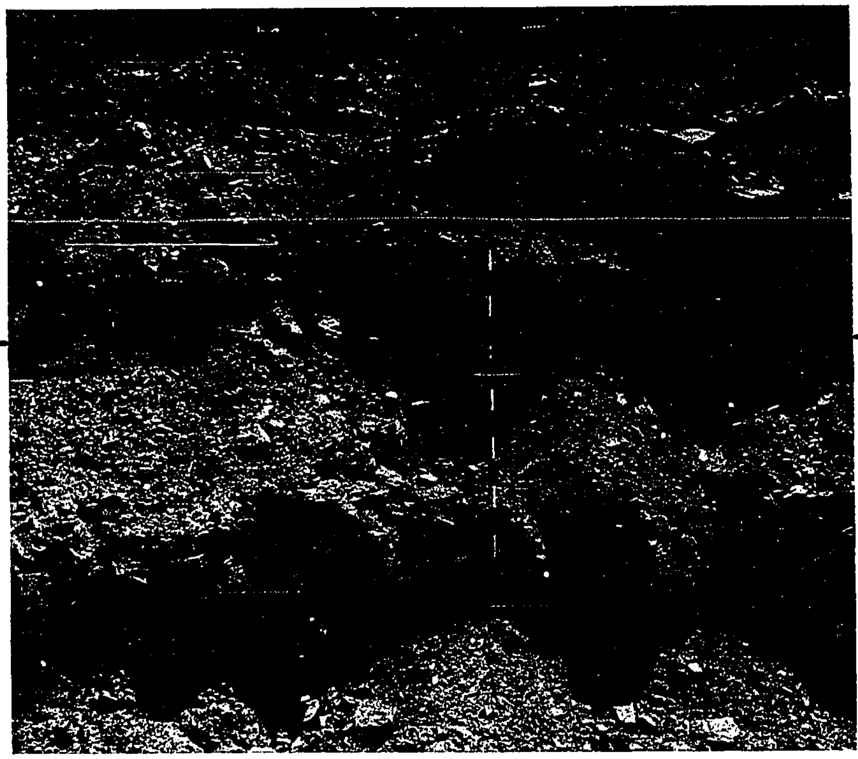


Figure 42C: Facing view of megacycles in the Kope and Fairview formations, Reidlin Road locality (bars indicate the Kope-Fairview contact). Note the upward thinning of megacycles.

Figure 42D: Close-up of the uppermost Kope megacycle, Reidlin Road locality (bars indicate the Kope-Fairview contact).





FORMATION	AVERAGE THICKNESS			PERCENTAGE OF A-B TRANSITIONS	SHALE CONTENT	
	TOTAL	CARBONATE HEMICYCLE	SHALE HEMICYCLE		CARBONATE HEMICYCLE	SHALE HEMICYCLE
Liberty (n = 33)	0.85 m	0.41 m	0.44 m	9%	11% (5 cm)	82% (36 cm)
Waynesville (n = 31)	1.18 m	0.30 m	0.88 m	29%	17% (5 cm)	82% (72 cm)
Sunset (n = 19)	1.02 m	0.38 m	0.64 m	16%	16% (6 cm)	73% (47 cm)
Corryville (n = 21)	1.09 m	0.38 m	0.71 m	35%	18% (7 cm)	74% (53 cm)
Fairview (n = 44)	0.68 m	0.26 m	0.42 m	18%	9% (2 cm)	72% (30 cm)
Kope (n = 48)	1.80 m	0.32 m	1.48 m	35%	18% (6 cm)	88% (130 cm)

Table 12: Stratigraphic comparison of megacycles. Megacycles are too thin to be detected in the Bellevue, Mt. Auburn, Oregonia, Whitewater, and Saluda formations, and are not included.

AVERAGE MEGACYCLES

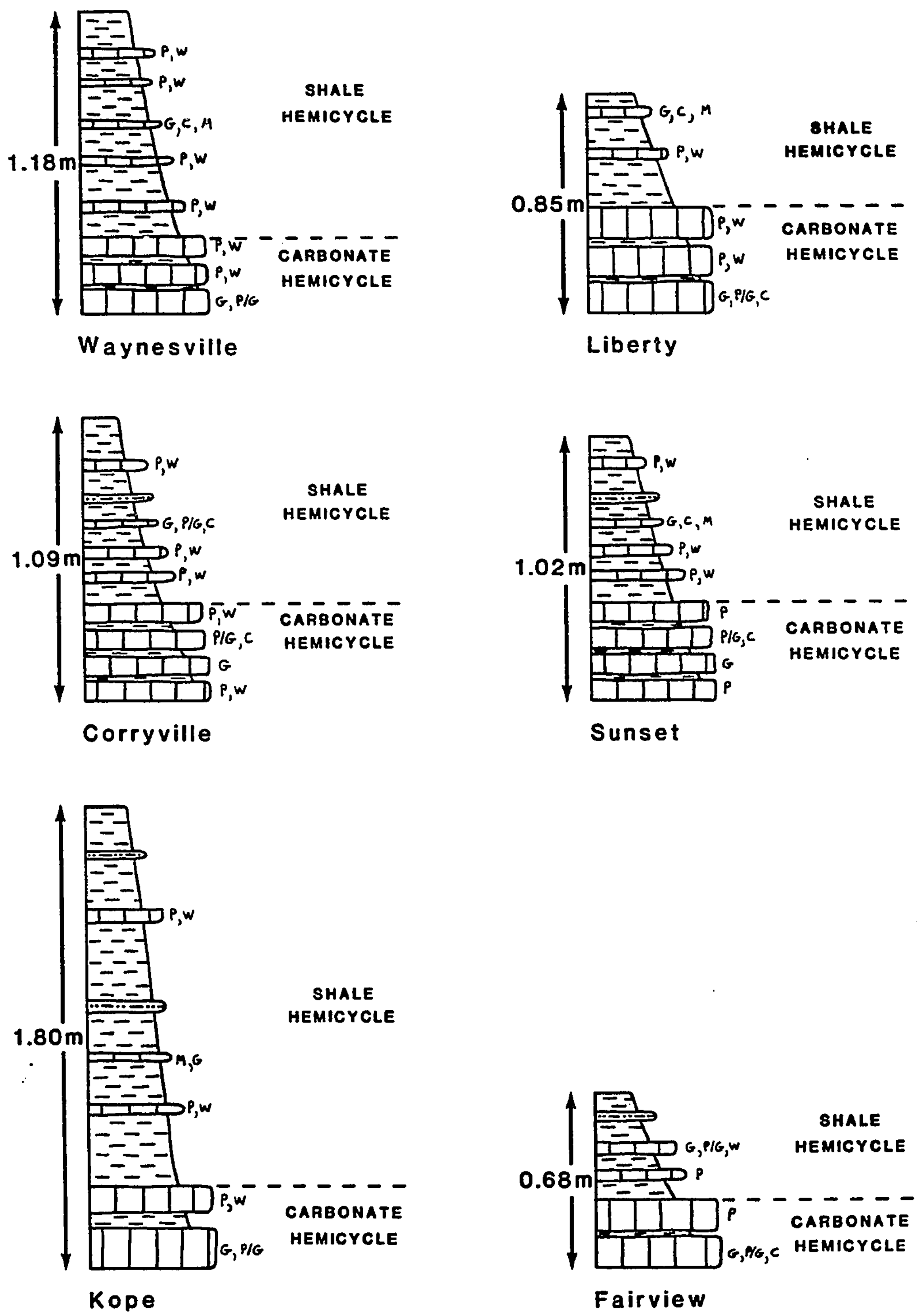
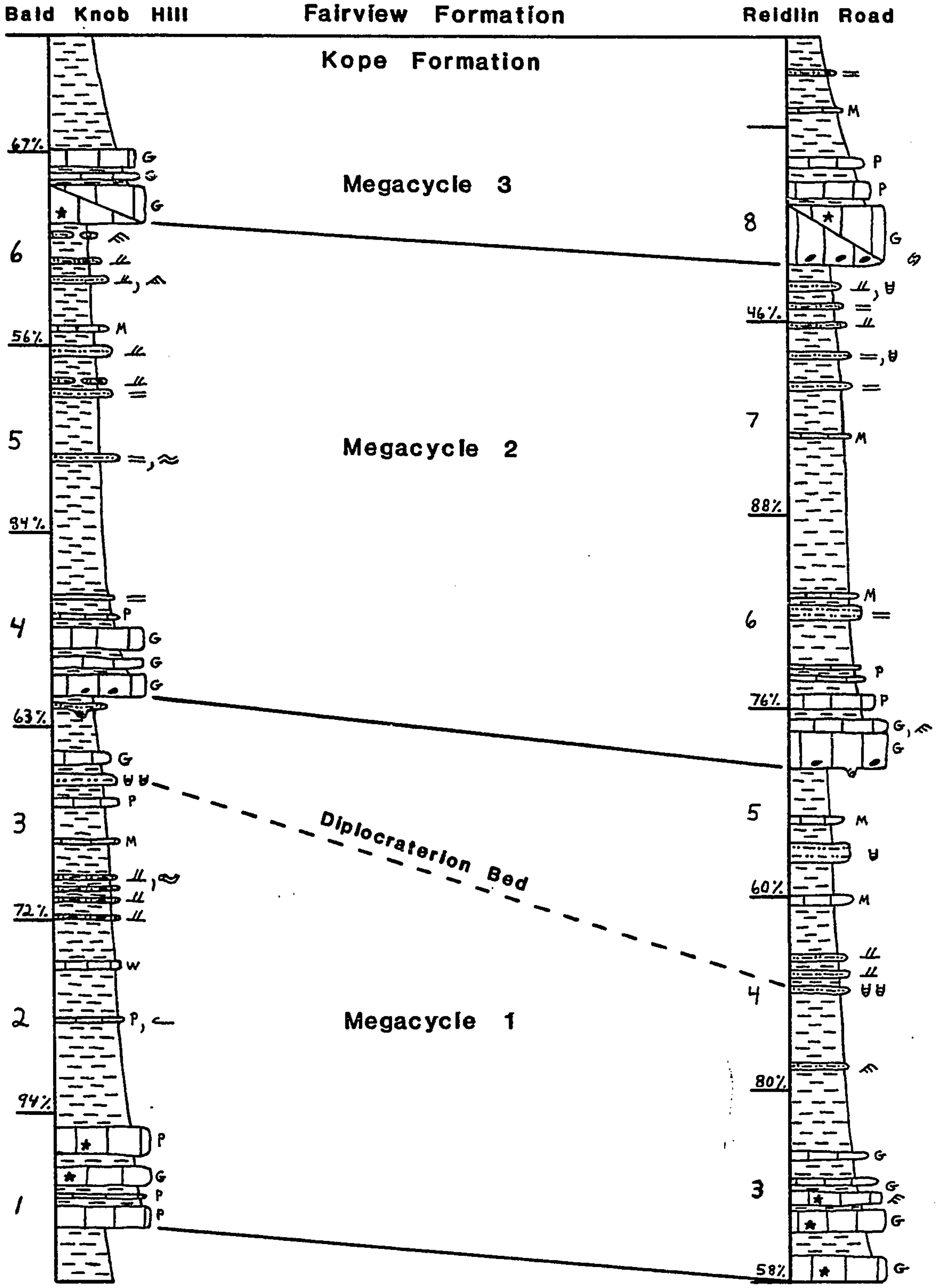


Figure 43: Graphic comparison of the "average megacycle" from six different formations in the Cincinnatian Series.

Figure 44: Homotaxial correlation of three megacycles in the upper Kope Formation.

Correlation of Kope Megacycles



Therefore, to attain a greater degree of objectivity about sedimentary sequences, a trend toward "proving" cyclicity through various statistical techniques has become commonplace in geology. Such techniques include "Markov chain analysis" (Krumbein, 1967; Gingerich, 1969; Miall, 1973; Fairchild, 1979), "time-series analysis" (Schwarzacher, 1967), "spectral-density analysis" (Mann, 1967), and "log-linear models" (Carr, 1981). Markov analysis has also been applied to the Cincinnatian Series (Potter and Blakely, 1968; Osborne, 1971).

In the case of the Cincinnatian Series, the use of statistics to "prove" the existence of sedimentary cycles is both unnecessary and inadvisable for the following reasons: (1) Such techniques all require large amounts of data, including numerous variables, or "states" (Potter and Blakely, 1968). In the case of megacycles, only three "states" are present (units A, B, and C of the "idealized" cycle). (2) A detailed working knowledge of statistics, in addition to the use of a computer, is usually necessary for such analyses. "The danger with this sort of research is that it may become too technical for the great majority to understand, and one sometimes tends to get the impression that these 'mathematical geologists' communicate only with each other and get seduced away from significant geological problems by the beauty of the techniques they work with" (Hallam, 1981, p. 12). (3) The artificial manipulation of raw data merely for the sake of rigorous mathematical testing is not only unnecessary but inappropriate when sedimentary cycles are obvious by visual inspection alone. (4) The concept of statistical testing for cyclicity assumes that an "idealized" cycle exists and that such a cycle should be frequently encountered within a given vertical sequence (Reading, 1978, pp. 5-8).

However, in most cases the "ideal" cycle is usually the least frequently encountered. As mentioned earlier, only 24 percent of Cincinnatian megacycles have the complete A B C vertical transition characteristic of the "idealized" cycle. (5) Statistical analyses commonly ignore the fact that the lateral variations of an "ideal" cycle can often have the most interpretive value. For example, variations of the complete Bouma sequence are quite useful in determing the specific part of the turbidite fan system in which deposition occurred (see Nelson and Kulm, 1973; and Walker, 1975).

To illustrate the ineffectiveness of statistical testing for cyclicity, I applied the use of a simple technique, the "transition matrix" (from Selley, 1969) on parts of two megacycle-bearing formations (Kope and Fairview). Four sets of variables were tested: (1) carbonate hemicycles vs. shale hemicycles, (2) units A, B, and C of the ideal megacycle, (3) individual carbonate beds (shales ignored), and (4) all beds (carbonates and shales). The results of this analysis (Appendix 10) reveal what is already obvious about megacycles from careful field observation and from the data averaged in Table 12: (1) The vertical transition from the carbonate hemicycle to the shale hemicycle is *always* present. (2) The A B C transition is present but not as strong as the B C B and A C A transitions. (3) The "ideal" limestone transition (i.e., grainstone--poorly washed grainstone--packstone or wackestone--siltstone and micstone) is rare. (4) The most common lithologic transition in the Cincinnatian Series is limestone--shale--limestone. Thus, in the case of the Cincinnatian Series, rigorous testing for cyclicity using Markov chains and other statistical techniques has been rejected. Such techniques would seem to be useful only when dealing with large amounts of data, when bedding patterns visually appear random, or when good outcrop exposures or cores are unavailable.

Interpretation

The recurrent vertical transition from the shale-poor *carbonate hemicycle* to the shale-rich *shale hemicycle* was caused by change in depositional or environmental conditions with the passage of time (i.e., a "process type" cycle). The carbonate hemicycle represents a period of time during which carbonate sedimentation greatly exceeded shale sedimentation. Conversely, the shale hemicycle represents a period of time during which terrigenous sedimentation dominated, punctuated only by a few brief periods of carbonate deposition.

This change in sedimentation can be attributed to either fluctuating water depth, or fluctuating supply of terrigenous sediments. In the first case, the carbonate hemicycle would represent deposition during a time of relatively shallow-water conditions, whereas the shale hemicycle would represent a change to relatively deeper water conditions. This explanation assumes that most of the shale was deposited farther offshore in deeper water. Although this assumption is probably correct, the change in water depth can only be explained by eustatic sea-level fluctuations caused by periodic shifts in climate, or large-scale plate tectonic movements. The abundance of low-energy packstones and wackestones in the carbonate hemicycle (54 percent in *both* hemicycles), in addition to the low percentage of complete A B C transitions (24 percent), precludes the possibility of fluctuating sea level. Furthermore, the average periodicity for megacycles is much too short to represent major tectonic movements (57,000 years: based on an estimated depositional rate of 2 cm/1,000 years and an average megacycle thickness of 1.14 meters).

Thus, I believe that the second explanation for cyclicity (fluctuating terrigenous sediment supply/constant water depth) is the most plausible. The transition from the carbonate hemicycle to the shale hemicycle probably represents an increase in the *supply* of terrigenous sediments into the Cincinnati Arch region. Two causative mechanisms are possible: (1) climatic fluctuation, and (2) shifting source areas. In the first case, the carbonate hemicycle would accumulate during a colder climatic period, when weathering rates, erosion, and runoff at the source area would be relatively low. Consequently, lower amounts of terrigenous sediment could enter the ocean, to be later transported by storms into the Cincinnati area. Furthermore, the average megacycle periodicity of 57,000 years compares somewhat favorably with global climatic fluctuation.

Alternatively, if periodic shifts in climatic regime occurred, global atmospheric circulation systems may have also changed. Perhaps the carbonate hemicycle represents a period of time during which the paleoatmospheric circulation patterns shown in Figure 34 had shifted. If this is true, then the lack of shales in the carbonate hemicycle might be the result of low levels of storm activity. However, this last explanation seems unlikely because examples of storm sequences and amalgamated limestone beds are present in all carbonate hemicycles, and because paleocurrent orientations in both hemicycles are essentially the same (see Table 10). Thus, storms were probably just as frequent during the time span of carbonate hemicycles as they were during the time span of shale hemicycles, although they rarely transported and deposited terrigenous sediments. This may partially account for the lower percentage of siltstone beds in carbonate hemicycles (1.5 percent compared to 30 percent in shale hemicycles). Without an overlying protective layer of shale, storm-deposited siltstones were more vulnerable to subsequent periods of storm erosion and redistribution, and therefore were rarely perserved in carbonate hemicycles.

The second possible explanation for the fluctuation of terrigenous sediments is the periodic shifting of terrigenous source areas. As previously noted, shales in the carbonate hemicycle are less abundant and thinner bedded than shales in the shale hemicycle. In addition, thin-section analysis reveals that shales in the carbonate hemicycle contain less silt, and are finer grained than those in the shale hemicycle (see Table 11 and Figure 41), suggesting that they were derived from a more distal source area. Thus, the vertical transition from the carbonate hemicycle to the shale hemicycle may represent a lateral shift from a distal terrigenous source area to a more proximal source area. Such a shift in source area could result from delta switching (see Reading, 1978, pp. 121-125) or lateral changes in sediment supply or discharge due to tectonic or volcanic activity.

The lateral variations in megacycle thickness discussed earlier are conflicting and difficult to interpret. However, the fact that megacycles occur everywhere in the field area and exhibit a limited amount of homotaxial correlation suggests that cyclic deposition was caused by *regional*, rather than local factors. Furthermore, the upward-thinning trend of megacycles within "shoaling-upward shelf cycles" coincides with a formational (or stratigraphic) upward-thinning trend. This suggests that the thickest megacycles accumulated farther offshore in deeper water where the majority of terrigenous muds were deposited (see the next section, and Figure 45). Thus, megacycles may represent time lines.

Shoaling-Upward Shelf Cycles

Description

The Cincinnatian Series can be subdivided into three similar lithogenetic sequences: the Kope to Bellevue sequence, the Corryville to Oregonia sequence, and the Waynesville to Saluda sequence (see Figure 4). These sequences are similar in some aspects to the "shoaling-upward shelf cycles" (oolite-grainstone type) described by Wilson (1975, pp. 281-297).

Wilson (1975) has described three types of asymmetric, regressive shoaling-upward cycles in modern and ancient carbonates: (1) oolite-grainstone (outer shelf), (2) lime-mud sabkha (inner shelf), and (3) loferites (high-relief platforms with intense diagenesis). Each type has a diagnostic succession of lithology and fauna, and each follows a standard sequence of "phases," from an early "terrigenous clastic phase" to a "terminal phase" (see Table 13).

Oolite-grainstone cycles occur on wide, shallow cratonic shelves seaward of any barrier bars or reefs, and on wide, flat-lying banks that occur on the shelf. Ooids are well developed, and bioclasts (mostly crinoids) are coated and/or abraded. The upper and lower contacts of each sequence are sharp (usually erosional contacts or hardgrounds). An idealized cycle is composed of four members (from bottom to top): (1) silty or argillaceous

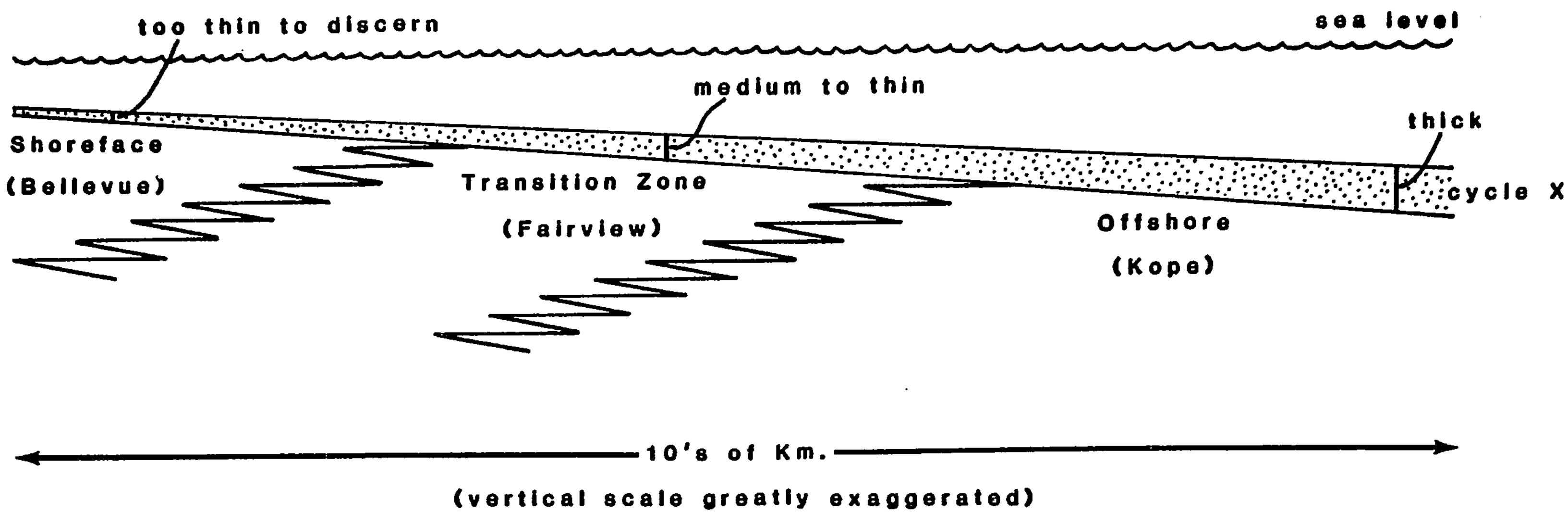


Figure 45: Inferred lateral correlation of megacycles.

STANDARD FACIES BELTS	SUBENVIRONMENTS	PHASE OF CYCLES
9	Marine hard ground or surface of subaerial exposure	Terminal phase
	Sabkha-pond evaporite	
8	Tide flat	Clear water carbonate-shoaling phase
	Lagoon and tidal channels and shelf mud mounts and low banks	
6-7	Immediate back reef shoals and tidal bars	
2 or 7	Widespread marine water of depth sufficient for circulation, at or approaching wave base	Normal marine, open circulation phase
	Below wave base, terrigenous influx < subsidence	Beginning terrigenous clastic phase
	Lagoonal — littoral, terrigenous influx > subsidence	

Table 13: Outline of recurring environmental sequences in upward-shoaling carbonate cycles (from Wilson, 1975, p. 282).

micstones; (2) laminated, pelletal-bioclastic micstones and wackestones; (3) well-sorted, cross-bedded oolitic grainstones; and (4) dolomites, evaporites, or a hardground. Ancient examples of oolite-grainstone cycles are mostly Jurassic and Mississippian in age, although other periods are represented as well. Figure 46 compares an idealized oolite-grainstone cycle to four ancient examples.

Shoaling-upward shelf cycles in the Cincinnatian Series are thick (ranging from 49 m to 104 m), asymmetric, and bounded by sharp upper and lower contacts. An idealized cycle is composed of four lithofacies (from bottom to top): *Facies A* (a thick, planar-bedded, shale-rich member), *Facies B* (a medium-to-thick, planar-bedded, mixed carbonate-shale member), *Facies C* (a thin, wavy-to-nodular bedded, limestone-rich member), and *Facies D* (a medium-to-thin, massive- or nodular-bedded member composed of dolomitic shale, dolomite, and dolomitic limestone). Facies A, B, and C occur in all three shoaling-upward cycles, but Facies D only occurs in the uppermost cycle (i.e., Waynesville to Saluda). Intertonguing of these facies is common in all three cycles. A more complete summary of the characteristics of the generalized cycle is given in Figure 47.

Interpretation

Both the shoaling-upward shelf cycles described by Wilson (1975), and those described herein for the Cincinnatian Series represent the lateral migration of paleoenvironments, and hence are "Walther type" sequences. Although both cycles are similar in appearance, they were produced in two very different depositional settings. Wilson's oolite-grainstone cycle is based on the *barred shelf model*. According to this

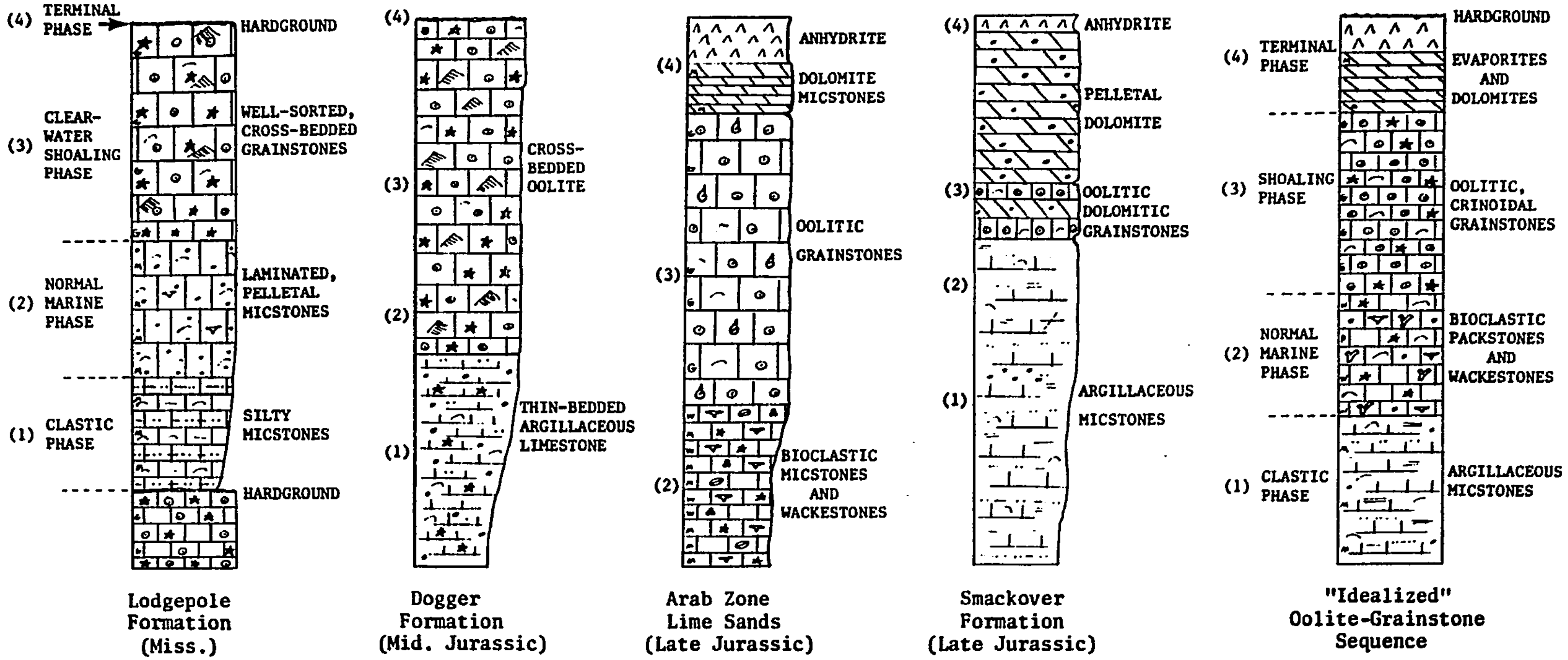
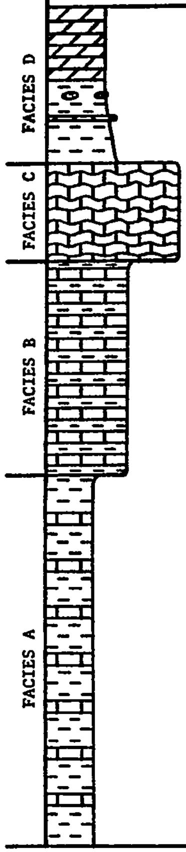


Figure 46: Ancient examples of oolite-grainstone sequences.



GEOLOGIC COLUMN	FACIES THICKNESS	BEDDING: THICKNESS	BEDDING: STYLE	SHALE PERCENT	DOMINANT CARBONATE ROCKS	SHALES	FOSSILS: TYPES	FOSSILS: PRESERVATION	MEGACYCLES	TYPICAL FORMATIONS
FACIES D	Range = 4 m - 23 m	Thick; massive	Planar; massive, some nodular; mod. continuous	Variable 10% (Saluda) to 87% (Drakes)	Mostly dolomites, dolomitic micstones, and wackestones; some grainstones	Mostly claystones	Restricted; mostly corals, gastropods, and ostracods; some open-marine	Well preserved	Absent	Saluda, Elkhorn, Drakes
FACIES C	Range = 7 m - 12 m	Thin; 4 cm (ave.)	Wavy or nodular; discontinuous	Low* (16%)	Mostly grainstones (65%)	Mostly claystones	Open-marine; robust, thick skeletons	Variable; some boring, abrasion, encrustation	Very thin or absent	Bellevue, Mt. Auburn, Oregonia, Whitewater
FACIES B	Range = 14 m - 32 m	Medium; 8 cm (ave.)	Planar; mod. continuous	Mod. (49%)	Mostly packstones and wackestones (57%); some grainstones (32%) and siltstones (9%)	Mudstones and claystones	Open-marine; mixture of shell types	Well preserved	Thin cycles	Fairview, Sunset, Liberty
FACIES A	Range = 23 m - 59 m	Thick; 11 cm (ave.)	Planar; mod. continuous	High (71%)	Mostly packstones and wackestones (64%); some grainstones (17%) and siltstones (16%)	Mostly mudstones	Open-marine; many thin-shelled, delicate forms	Well preserved	Thick cycles	Kope, Corryville, Waynesville

*Except Mt. Auburn (37%) and Oregonia (44%).

Figure 47: Generalized model for shoaling-upward shelf cycles in the Cincinnatian Series.

model, cycles were produced by regressive sedimentation on a nearly *flat* marine platform having an abrupt organic buildup (i.e., continuous reef trends) or a buildup of inorganic shoal sands (i.e., grainstones and oolites) at the outer edge of the shelf. This buildup acted as a barrier to the open sea, dissipating incoming wave energy far offshore. Thus, low-energy, muddy carbonates were able to accumulate shoreward of this buildup (see Figure 48).

Conversely, Cincinnatian shoaling-upward cycles are based on the *carbonate ramp model* (Ahr, 1973). According to this model, cycles were produced by regressive sedimentation on a slightly *inclined* platform that extended basinward without a pronounced break in slope (i.e., shelf-edge buildups did not exist). Without a shelf-edge "barrier," incoming wave energy was dissipated closer to the shore. Thus, carbonate sands (i.e., grainstones) did not accumulate at the shelf edge, but instead were localized closer to the shore.

Two basic models have been proposed to describe facies patterns developed on open, unbarred ramps: the *epeiric sea model* (Shaw, 1964; Irwin, 1965) and the *nearshore sand model* (Heath et al., 1967; Ahr, 1973; Townson, 1975). The first model presumes that on wide, nearly flat epeiric sea floors most of the incoming wave energy is dissipated by frictional drag within a narrow belt in the *middle* of the shelf profile. An ancient example of this model is the Helderberg Group (Devonian) of New York State (see Figure 49). The second model assumes that the maximum amount of wave energy is dissipated farther inshore, producing an offshore-to-shoreface profile in which the textural maturity of bottom sediments increases shoreward. In addition, terrigenous sediments become more

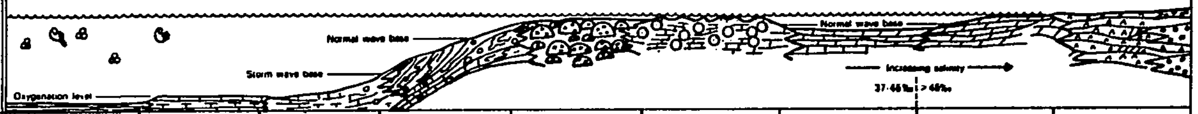
DIAGRAMMATIC CROSS SECTION									
FACIES NUMBER	1	2	3	4	5	6	7	8	9
FACIES AND GENERAL ENVIRONMENT	Basin (euxinic or evaporitic) (a) Fine clastics (b) Carbonates (c) Evaporites	Open marine neritic (a) Carbonates (b) Shale	Toe of slope carbonates	Foreslope (a) Bedded fine grained sediments with slumps (b) Foreset debris and lime sands (c) Lime mud masses	Organic build up ("reef") (a) Boundstone (b) Encrusting masses (c) Bafflestone	Sands on edge of platform (a) Shoal lime sands (b) Islands with dune sands	Open platform (a) Lime sand bodies (b) Wackestone mudstone areas bioherms (c) Areas of terrigenous clastics	Restricted platform (a) Bioclastic wackestones, lagoons and bays (b) Litho bioclastic sand in tidal channels (c) Lime mud on tidal flats (d) Fine grained terrigenous clastic interbeds	Platform evaporites (a) Nodular anhydrite and dolomite on salt flats (b) Laminated evaporites in desiccated ponds
LITHOLOGY	Dark shale or silt thin limestones (starved basin) Evaporites fill basin if desiccation occurs	Very fossiliferous limestone with marl interbeds	Fine grained limestone, locally cherty	Variable depending upon water turbulence upslope, sedimentary breccia and lime sands	Massive limestone, dolomite.	Calcarenitic oolitic lime sand or dolomite.	Variable carbonates and terrigenous clastics.	Often dolomite and dolomitic limestone.	Irregularly laminated dolomite and anhydrite locally may grade into red beds
COLOUR	Dark brown black and red	Grey green red brown	Dark to light	Dark to light	Light	Light	Dark to light	Light	Red, yellow, brown
GRAIN TYPE AND DEPOSITIONAL TEXTURE	Lime mudstones, fine calcisiltites	Bioclastic and whole fossil wackestones, some calcisiltites.	Dominantly lime mudstone with some calcisiltites	Lime silt and bioclastic wackestone packstone, lithoclasts.	Boundstones and pockets of grainstone packstones	Grainstones well sorted, rounded	Variable textures in grainstone and mudstone Bioturbation	Clotted pelleted mudstone and grainstone, laminated mudstone, coarser wackestones in channels	
BEDDING AND SEDIMENTARY STRUCTURES	Very even lamination on mm scale Rhythmic bedding, occasional ripple cross lamination	Bioturbated, thin to medium bedded with nodular layers	Minor lamination Often massive beds, lenses of graded sediment. Lithoclasts and exotic blocks.	Slumps, foreset bedding, slope build ups, exotic blocks	Massive organic structure or open framework with roofed cavities Injection dykes Sometimes stromatactis	Medium to large scale cross bedding	Intense bioturbation	Birdseye, stromatolites, fine laminations, dolomite crusts Cross bedded sand in channels	Anhydrite after gypsum nodular rosettes, "chicken wire" and blades, irregular lamination, caliche
TERRIGENOUS CLASTIC COMPONENT	Quartz silt and shale, fine grained siltstone, often cherty	Quartz silt and shale in well segregated beds	Some shales, silt and fine grained sandstone	Some shales and silts	None	Local quartz sand	Terrigenous and calcareous beds, well segregated	Interbedded terrigenous and calcareous beds possible.	Aeolianites and terrigenous interbeds may be important
BIOTA	Planktonic and nektonic only Occasional mass mortality deposits	Diverse. Shelly fauna and trace fossils represent both infauna and epifauna	Bioclastic debris derived mostly from upslope	Colonies of whole fossil organisms and bioclastic debris	Major frame building colonies and communities associated with them	Few indigenous organisms. Specialised community. Mostly abraded shell debris from other platform environments	Fauna dominated by more tolerant groups (e.g. bivalves, gastropods, sponges, forams, some algae); less tolerant groups (e.g. cephalopods, brachiopods and echinoderms) often restricted	Limited fauna. Mostly grazing gastropods, algae and some forams (e.g. miliolids) and ostracodes	Stromatolitic algae almost the only indigenous biota

Figure 48: Idealized sequence of standard facies belts proposed by Wilson (1975, fig. II-4).

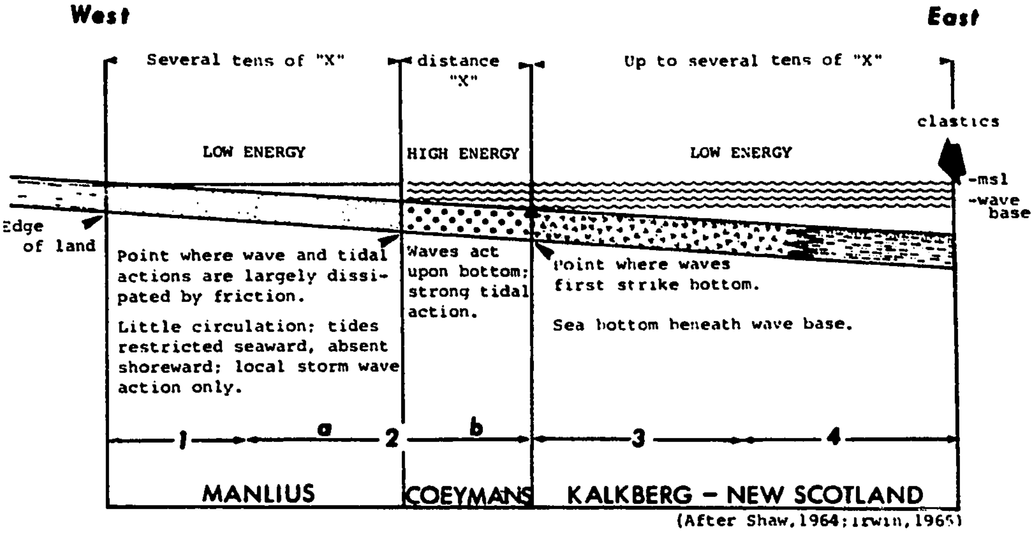


Figure 49: Cross section of epeiric sea in middle Helderberg time, New York State (from Laporte, 1969, fig. 14).

abundant toward the outer shelf. Examples of this model include the Bird Spring Group (Pennsylvanian) of Nevada (see Figure 50), the Portland Group (Jurassic) of England (see Figure 51), and the modern Yucatan shelf (see Ahr, 1973). In the case of the Portland Group, nearshore sands were redistributed by longshore currents into discontinuous shoals, behind which low-energy lagoonal sediments accumulated (see Figure 51).

The shoaling-upward shelf cycles in the Cincinnatian Series are most similar to the vertical sequences that are characteristic of the *nearshore sand model*. Late Ordovician sedimentation probably occurred on a gently sloping carbonate ramp upon which high-energy carbonate sands (i.e., Facies C) graded basinward into successively muddier carbonates and increasing amounts of terrigenous clastics (i.e., Facies B and A). Furthermore, examination of a core from the Ohio State Geological Survey (sample number 2499, Fairfield Township, Highland County; 50 miles northeast of Cincinnati) reveals that as the Cincinnatian Series is traced basinward, it loses its cyclic character altogether and is dominated by shale (74 percent), indicating that a shelf-edge barrier did not exist during Late Ordovician time.

In conclusion, the generalized Cincinnatian shoaling-upward shelf cycle may be interpreted as follows: *Facies A* probably represents deposition below wave base in the offshore position. *Facies B* represents deposition mostly below wave base in the offshore-to-transition zone. *Facies C* represents higher energy deposition, mostly above wave base, in the transition zone to shoreface position. Sediments in Facies C may have accumulated in laterally discontinuous shoals, similar to the pattern displayed in Figure 51. *Facies D* probably represents moderate-to-low-energy deposition in a back-shoal, lagoonal-to-intertidal setting (see Figure 52).

All four facies represent lithotopes which existed contemporaneously, side by side. The superposition of these facies is the result of regressive sedimentation produced by either a gradual lowering of sea level, or by sedimentation rates exceeding the rate of sediment compaction and basin subsidence. In the next major section, "Lithogenetic Sequences," each of the three shoaling-upward cycles will be described and interpreted in detail.

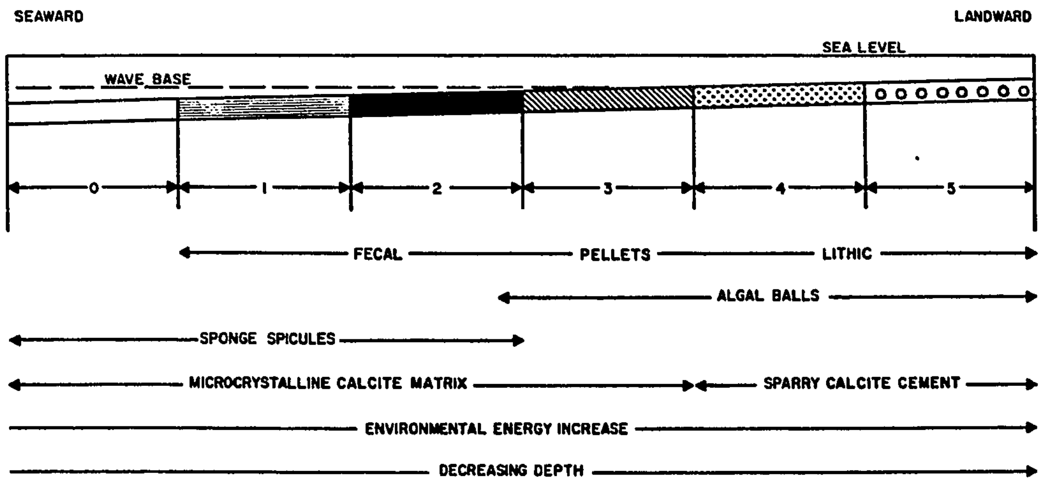


Figure 50: Generalized horizontal interpretation of facies relationships in the Bird Spring Group (Pennsylvanian) of Nevada (from Heath et al., 1967, fig. 7).

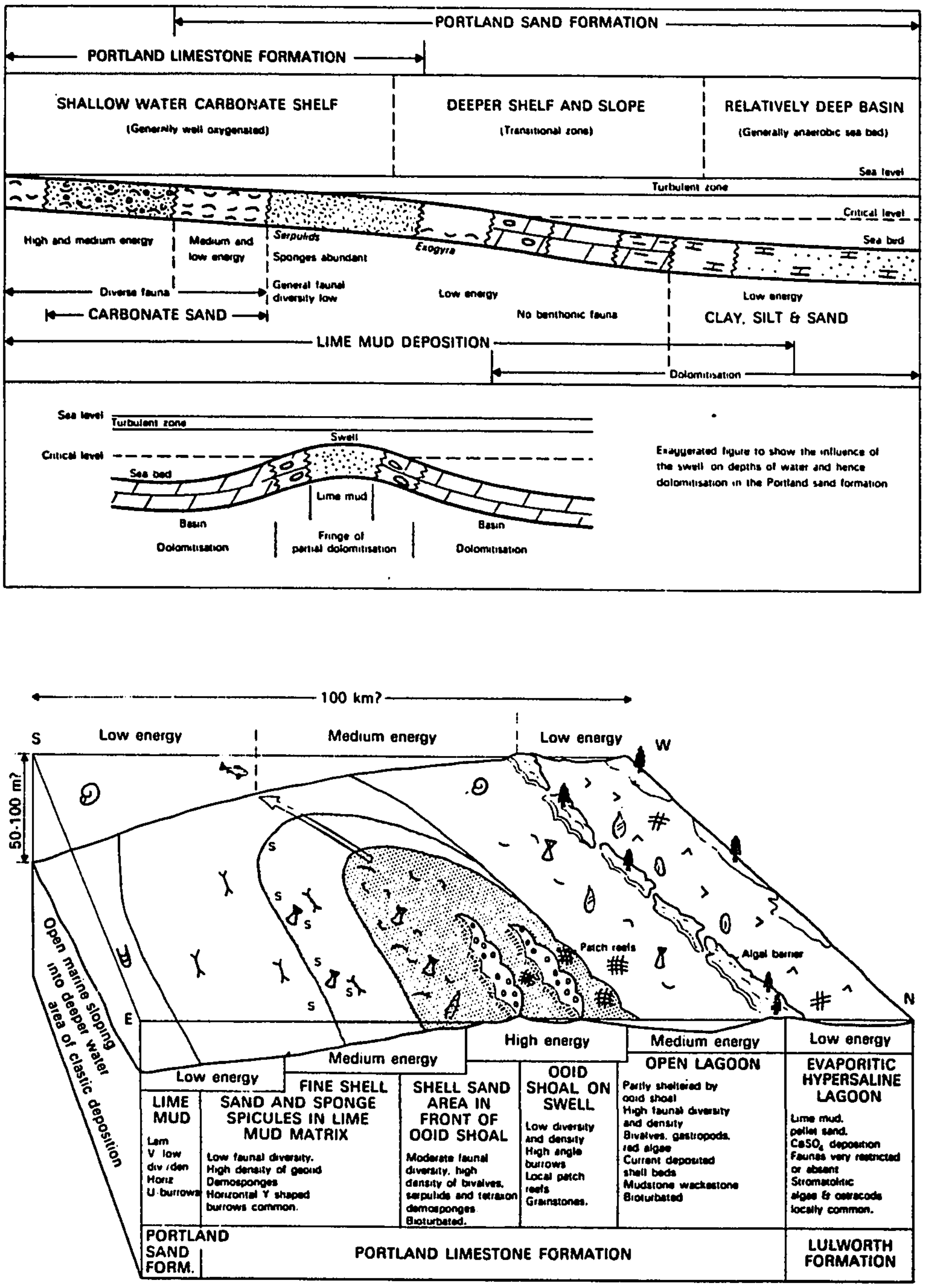


Figure 51: Generalized model for facies relationships in the Portland Group (Jurassic) of England (from Reading, 1978, figs. 10.31A - 10.31B).

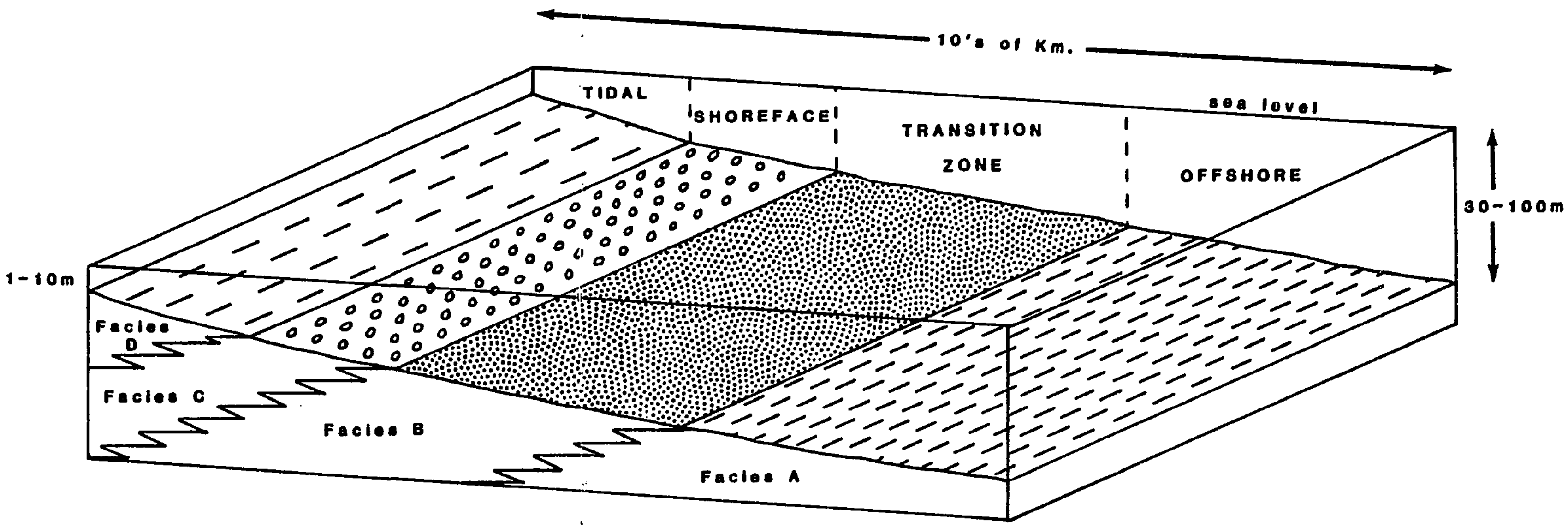


Figure 52: Generalized model for facies relationships in shoaling-upward shelf cycles of the Cincinnatian Series.

L I T H O G E N E T I C   S E Q U E N C E S

Kope to Bellevue Sequence

Stratigraphy

The lowermost sequence (i.e., shoaling-upward shelf cycle) in the Cincinnatian Series is composed of four stratigraphic units (from bottom to top): the Kope Formation, the Fairview Formation, the Miamitown Shale, and the Bellevue Limestone (see Figure 4). The *Kope Formation* was originally defined from exposures in Kope Hollow, north of Levanna, Ohio, as a medium-bedded, shale-rich formation consisting of minor amounts of highly fossiliferous gray limestones interbedded with thick, unfossiliferous gray shales (see Weiss and Sweet, 1964). The upper and lower boundaries were described as "conspicuous" on both clastic ratio and bedding index logs, as well as in outcrop. However, the exact nature of these boundaries was not described.

Ford (1967) extended the use of the term Kope Formation to equivalent strata in the Cincinnati area. Because the basal contact with the underlying Point Pleasant Member (Cynthiana Formation) was not exposed in the Cincinnati area, it was once again not defined. However, Ford (1967, p. 929) did describe the upper contact with the overlying Fairview Formation. Ford (1967) also described two intertonguing members of the Kope Formation: the *Grand Avenue Member* (a thin layer of shale-poor strata, lithologically similar to the Fairview Formation, which occurs in the upper part of the Kope Formation), and the *Wesselman Tongue* (a thicker layer of shale-rich strata which occurs in the middle of the Fairview Formation). In addition, Ford noted that the Wesselman Tongue is vertically separated from the main body of the Kope Formation by a layer of Fairview strata which he named the *North Bend Tongue*.

The term "Kope Formation" was subsequently used in the Maysville, Kentucky, area (Peck, 1966), in the Dayton, Ohio, to Maysville area (Lee, 1974), in northern Kentucky (Meyer et al., 1981), and in southeastern Indiana (Brown and Lineback, 1966). The only published objection to the use of the term Kope Formation was voiced by Anstey and Fowler (1969). The authors believed that the term "Kope Formation" should be replaced by the term "Eden Shale" (from Newberry, 1873) because the latter has priority, and because more than 75 percent of the formation is composed of shale. However, I agree with Weiss and Sweet's (1964) argument that the name "Eden" should be avoided in a rock-stratigraphic sense because of its prior (and current) usage in a time-stratigraphic sense (i.e., "Edenian Stage"). My own field observations demonstrate that the Kope Formation is an easily recognizable rock-stratigraphic unit, and therefore should continue to be utilized. Nevertheless, the lower contact of the Kope Formation should be lithologically defined in order to conform to the rules of the Code of Stratigraphic Nomenclature (Article 5), and for reasons of practicality. Ford (1967, p. 929) originally defined the *top* of the Kope Formation as the base of a limestone bed overlying the ". . . uppermost terrigenous stratum greater than two feet thick." In reality, "terrigenous stratum" is an ambiguous term used to describe a thick stratum of shale, usually containing very thin, discontinuous carbonate beds, nodules, or lenses. As long as this interpretation of the term "terrigenous stratum" is clearly understood, the Kope-Fairview contact can be readily identified in outcrops (see Appendix 3, Bald Knob Hill and Reidlin Road localities). To conform with this definition, I suggest that the basal contact of the Kope Formation with the underlying Point Pleasant Member be defined as the base of the lowermost terrigenous stratum greater than two feet thick. Good exposures of this contact can be found along Kentucky Route 8 near the Meldahl Dam (see Meyer et al., 1981, and Figure 53), and along U.S. Route 52, just east of River Downs Race Track (Felton, 1982, pers. comm.).

The Kope Formation is overlain by the *Fairview Formation*, which was originally defined by Bassler (1906), and redefined by Ford (1967, p. 928) as follows:

> It consists of an unbroken sequence of interbedded limestone and terrigenous rocks in which no stratum is persistently thicker than 1.5 feet and generally not more than 0.6 foot. The uninterrupted close spacing of the limestone strata in the bulk of the formation is a significant intrinsic lithic property.

Ford's emphasis on "close spacing" of limestone beds (i.e., low shale content and thin bedding of shales) is ideal for field identification of the Fairview Formation. However, while the Kope-Fairview contact has been adequately defined, the *top* of the Fairview Formation has not. Ford (1967, p. 929) defined the top of the Fairview Formation as ". . . the top of a limestone underlying terrigenous rocks which are more than two feet thick and which exhibit marked lithologic contrast" (i.e., the Miamitown Shale). This definition creates four major problems: (1) As before, the meaning of this two-foot-thick stratum of terrigenous rocks is unclear since the basal two feet of the Miamitown Shale commonly contain limestone nodules, lenses, or thin, discontinuous beds. (2) Ford's definition is not applicable wherever the Miamitown Shale is less than two feet thick (e.g., the Reidlin Road locality; see Figure 54C). (3) The definition does not apply

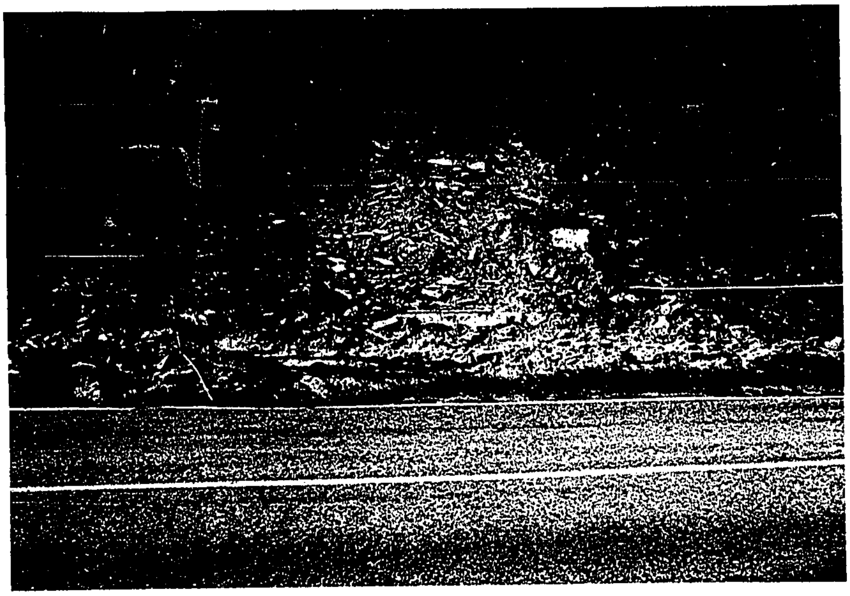


Figure 53: Field exposure of the Kope-Pt. Pleasant contact, KY Rt. 8. The Jacob's staff marks the uppermost occurrence of thick Pt. Pleasant limestone beds.

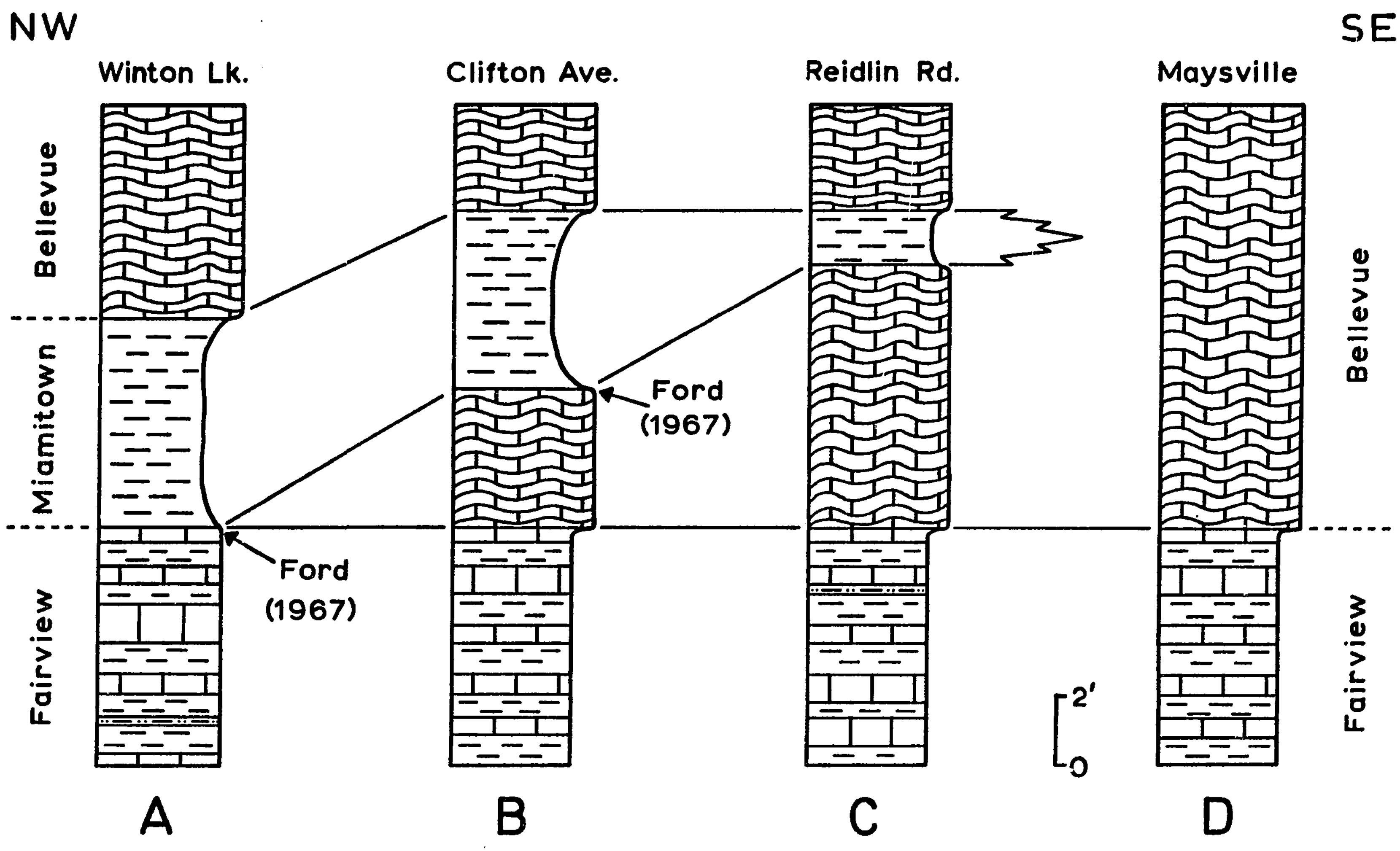


Figure 54: Four variations of the redefined upper Fairview Formation contact.

to exposures where the Miamitown Shale is absent (e.g., Maysville, Kentucky; see Figure 54D). (4) By definition, Ford included a thin unit of a different lithology in the Fairview Formation, the "shingled *Rafinesquina* zone" (from Caster, Dalvé and Pope, 1961), because it occurs below the Miamitown Shale. By placing this contact above the "shingled *Rafinesquina* zone," Ford has included rocks of a distinctly different type in the Fairview Formation (e.g., Clifton Avenue, Cincinnati; see Figure 54B).

Ford's reason for including the "shingled zone" in the Fairview Formation is not given. I can only assume that he followed the recommendation of Hyde (1959) who suggested that the "operational contact" between the Fairview Formation and the Bellevue Limestone be placed at the top of the Miamitown Shale, since the "shingled zone" is often covered by weathered shale and is not persistent in the Cincinnati area. However, I have observed that the bedding type and thickness, shale content, dominant rock type, and fauna of the "shingled zone" are equivalent to that of the Bellevue Limestone. For that reason, the upper contact of the Fairview Formation should be redefined independently of the overlying rock types or their thicknesses, and in such a way that the "shingled zone" is included as part of the Bellevue Limestone. Thus, the top of the Fairview Formation is herein redefined as the uppermost stratum of medium, planar-bedded limestone and shale, regardless of the overlying rock types. Hence, the redefined contact occurs at the point where medium, planar-bedded limestone and shale ends, and either thin, wavy-bedded rocks of the Bellevue Limestone or shale-rich, nodular-bedded rocks of the Miamitown Shale begin.

The Fairview Formation is overlain by a thin unit (0.4 to 6 m) composed of dolomitic shale interbedded with abundant limestone nodules (i.e., the *Miamitown Shale*). Ford (1967, p. 931) originally defined the Miamitown Shale as follows:

> . . . shale and mudstone with a few thin, widely spaced limestone interbeds. The limestone contains a high proportion of terrigenous detritus and a diagnostic gastropod-pelecypod faunal assemblage that includes forms of *Lophospira*, *Cyclonema*, and *Byssonychia*. Nodular-bedded limestone is common.

Although Ford's description of the Miamitown Shale is adequate for field identification, he failed to define the upper and lower boundaries of the unit. Hence, the upper and lower contacts of the Miamitown Shale are herein defined as the uppermost and lowermost vertical extents of its shale-rich, nodular-bedded lithology, regardless of the overlying or underlying rock types (see Appendix 3, Reidlin Road locality).

Another aspect of the Miamitown Shale that has not been previously discussed is its intertonguing nature and geographic extent. Ford (1967) described the Miamitown Shale as a unit that lies stratigraphically between the Fairview and Bellevue formations. However, the Miamitown Shale cannot be considered a continuous, sheet-like unit that always occurs between the Fairview Formation and the Bellevue Limestone, because it intertongues with both formations (see Figure 54). Furthermore, the Miamitown Shale covers a larger area than previously noted. Although Ford reported an absence of the Miamitown Shale south of the Ohio River, Tobin (1980, fig. 4) demonstrated that it blankets a fairly large part of northern Kentucky as well.

The *Bellevue Limestone* was originally defined by Nickles (1902), and later redefined by Ford (1967, p. 933) as ". . . a sequence of medium- to thin-bedded limestone and shale in which thin-bedded, massive, coquinite limestone (class 3c) predominates." Ford also noted that "it may represent a northwesterly tongue of the Grant Lake Formation that has been mapped south of Maysville, Kentucky (Peck, 1966)." The Grant Lake Limestone (not "Formation") occupies the same stratigraphic position as the Bellevue Limestone and is present at the eastern and southeastern extremities of my field area. The Grant Lake Limestone was defined by Peck (1966) for the Maysville, Kentucky, area and has subsequently been used by Lee (1974) in his field area (Maysville, Kentucky, to Dayton, Ohio). Peck's original description follows (1966, pp. B14-B16):

> The Grant Lake is chiefly irregularly bedded argillaceous limestone and minor interbedded shale. Limestone, which makes up 70-90 percent of the formation, is mainly medium to light gray and has light olive-gray mottling. The dominant type of limestone consists of a micrograined- to medium-grained poorly sorted argillaceous limestone matrix surrounding jumbled large fossil fragments and whole fossils. The beds are thin, very irregular, and rubbly weathering. Thin- to thick-bedded fine- to coarse-grained well sorted clastic limestone in even beds occurs locally. Gray calcareous shale occurs as irregular partings and thin beds separating limestone layers.

Field observations of Bellevue and Grant Lake exposures in my field area indicate that the rock types, fauna, bedding characteristics, and shale content of both formations are very similar. Hence, both units are considered equivalent in this report.

Ford (1967, pp. 933-934) accurately defined the base of the Bellevue Limestone as ". . . the lower surface of the massive coquinite limestone . . . ." However, he defined the upper contact as "gradational and commonly concealed" (i.e., the contact is arbitrarily placed in the transition between the coquinite limestone of the Bellevue and the overlying interbedded limestone and shale, which Ford designated "unnamed strata"). Exposures of the Bellevue-Corryville contact in my field area (e.g., the Georgetown locality; the Muddy Creek and Lawrenceburg localities discussed in Tobin, 1980) demonstrate that this contact, although "commonly concealed," is definitely not gradational. In all three exposures, this contact is marked by the sharp termination of the thin, wavy-bedded, shale-poor strata characteristic of the Bellevue Limestone, and the beginning of the thicker, planar-bedded shales and limestones of the Corryville Formation. Hence, the upper contact of the Bellevue Limestone is herein redefined as the sharp boundary between these two different lithologies (see Appendix 3, Georgetown locality).

In summary, the lithostratigraphic nomenclature proposed by Ford (1967) for the Kope to Bellevue shoaling-upward cycle is considered dependable for this and future stratigraphic work because: (1) Lithologic descriptions, although outdated, can be easily used to distinguish all four formations. (2) Stratigraphers have successfully applied the classification to other field areas. (3) The rock-stratigraphic units described by Ford represent ancient lithotopes, and hence, conform to the facies concept discussed earlier. Thus, Ford's lithostratigraphic classification is applicable throughout the field area, and does not need to be revised (with the exception of formational contacts). In the next subsection, "Sedimentology," each of these formations will be described using new terminology.

Sedimentology

In this section, the sedimentologic characteristics of the Kope to Bellevue shoaling-upward cycle are thoroughly described. The lowermost unit in this sequence is the thick-bedded, shale-rich *Kope Formation*. The Kope Formation is a thick unit ranging from 59 meters (194 feet) to

82 meters (270 feet), and is composed of interbedded shales (80 percent) and carbonates (20 percent). Bedding is planar, moderately continuous, and thick (averaging 12 cm). Shale beds are very thick in comparison to carbonate beds (24 cm vs. 6 cm), and in comparison to shale beds in the Fairview and Bellevue formations. Kope megacycles are abundant and relatively thick (see Figure 43 and Table 12). In addition, sedimentary structures are abundant and well preserved, including: symmetric and asymmetric ripples, starved ripples, planar and cross lamination, tool marks, flute marks, gutter casts, load structures, and ball and pillow structures.

All eight of the "recurrent carbonate rock types" discussed earlier can be found in the Kope Formation, but packstones and siltstones are most abundant. The percentages of each of these recurrent rock types follow: packstones (45 percent), wackestones (3 percent), micstones (4 percent), siltstones (30 percent), poorly washed grainstones (4 percent), coarse grainstones (6 percent), fine grainstones (7 percent), and calcisiltites (1 percent). The ratio of coarse grainstones to fine grainstones has significant interpretive value, and thus is included here (0.86).

Shales in the Kope Formation contain more silt than shales in the overlying units. Seventy-one percent of the thin-section samples examined are mudstones, and only 29 percent are claystones. The "average" Kope shale is a mudstone (QF_{39} CM_{53} CD_8) having a silt/clay ratio of 0.85 and a grain size of 25 microns.

The overlying *Fairview Formation* is a medium-thick unit ranging from 24 meters (78 feet) to 33 meters (108 feet), and is composed of interbedded limestones and shales. The shale content is much lower than that of the Kope Formation (49 percent). In addition, the lower half of the Fairview Formation contains more shale (55 percent) than the upper half (45 percent). Fairview bedding is planar, moderately continuous, and medium thick (averaging 8 cm). Shale beds and carbonate beds both average about 8 cm in thickness. Fairview megacycles are abundant, but are thinner than those in the Kope Formation (see Figure 43 and Table 12). As in the Kope Formation, sedimentary structures are abundant and occur in a variety of forms.

All of the recurrent carbonate rock types occur in the Fairview Formation, but packstones are most abundant. In addition, grainstones are more abundant and siltstones are less abundant than they are in the Kope Formation. The percentage of each of these rock types follows: packstones (53 percent), wackestones (6 percent), micstones (3 percent), siltstones (12 percent), poorly washed grainstones (5 percent), coarse grainstones (8 percent), fine grainstones (6 percent), and calcisiltites (7 percent). The ratio of coarse grainstones to fine grainstones (1.33) is higher than that of the Kope Formation.

Shales in the Fairview Formation are less silty than shales in the Kope Formation. Sixty percent of the thin-section samples studied are claystones, and only 40 percent are mudstones. The "average" Fairview shale is a mudstone (QF_{33} CM_{58} CD_{9}) having a silt/clay ratio of 0.70 and a grain size of 25 microns.

Overlying the Fairview Formation are two intertonguing units, the Miamitown Shale and the Bellevue Limestone. The *Miamitown Shale* is a very thin formation, ranging from 0.4 meters (1.3 feet) to over 5 meters (17 feet) in thickness, and is composed of thick, unfossiliferous shales

(76 percent) interbedded with a few widely spaced, discontinuous limestone layers and abundant limestone nodules (24 percent). These nodules are small, ovoid- to ripple-shaped carbonate lumps that are no more than 15 cm in length, occur along moderately well-defined horizons, and are sometimes cross laminated. Unfortunately, the terms "nodule" and "concretion" are often used interchangeably, because their external shapes are similar. However, "concretions" are structures that have formed in place *diagenetically*, whereas "nodules" are primary bedding features formed by *sedimentary processes*. Nodules in the Cincinnatian Series were first studied by Ward (1966), who concluded that their characteristic rippled shapes and internal cross lamination were indicative of high-velocity current transport. Thus, the term "nodule" is used in this paper to refer to current-formed sedimentary structures. The environmental significance of nodules and nodular bedding is discussed on page

Overall bedding thickness averages 9 cm, but shales are relatively thick (averaging 13 cm) in comparison to carbonate beds (5 cm). Megacycles are absent in this formation, and sedimentary structures are limited to gutter casts and cross lamination. Gutter casts are most abundant in siltstone layers, where they range from 3 to 9 cm in depth, 10 to 38 cm in width, and up to 2 meters in length. Multiple gutter casts occurring along the base of a single horizon are usually oriented parallel to each other (within a few azimuth degrees). In cross section, these structures often exhibit several sets of overlapping, cross-laminated, U-shaped channels (see Tobin, 1980, fig. 15).

Carbonate rocks in the Miamitown Shale are limited to five of the recurrent rock types and are dominated by packstones, wackestones, and micstones. The average percentage of each of these five rock types follows: packstones (46 percent), wackestones (18 percent), micstones (32 percent), coarse grainstones (2 percent), and fine grainstones (2 percent).

Shales in the Miamitown Shale are more dolomitic and far less silty than those of the Kope and Fairview formations (Tobin, 1980). All of the thin-section samples examined are either claystones, dolomitic claystones, or very dolomitic claystones. The "average" shale in this unit is a dolomitic claystone (QF_{13} DM_{62} CD_{25}) having a silt/clay ratio of only 0.21 and a grain size of 32 microns.

The uppermost formation in this sequence, the *Bellevue Limestone*, is also thin, ranging from 6 meters (20 feet) to 15 meters (49 feet) in thickness, and is composed of thin, coarse-grained limestones (82 percent) interbedded with wavy, discontinuous shales (18 percent). Overall, bedding is wavy, discontinuous, and thin (averaging only 4 cm), but shale beds are very thin (2 cm), very discontinuous, and usually very fossiliferous. Carbonate beds are also thin (4 cm) and discontinuous. Megacycles are absent in the Bellevue Limestone, and sedimentary structures are rare.

Grainstones are the most abundant rocks in the Bellevue Limestone. The percentage of each of the six carbonate rock types present in the Bellevue Limestone follows: packstones (10 percent), wackestones (1 percent), poorly washed grainstones (1 percent), coarse grainstones (58 percent), fine grainstones (28 percent), and calcisiltites (2 percent). The coarse grainstone to fine grainstone ratio (2.07) is relatively high.

Shales in the Bellevue Limestone are thin, fissile, and usually fossiliferous, impeding sample collection and thin-section processing. Accordingly, only one sample was thin sectioned (sample MB 7.9; see Tobin, 1980, Appendix 4). This sample is a silt-poor, very dolomitic claystone (QF_{22} CM_{45} CD_{33}) having a silt/clay ratio of 0.49 and a grain size of 37 microns.

In summary, the upward vertical succession of facies in the Kope to Bellevue shoaling-upward sequence is reflected most strongly by the following trends: (1) a decrease in facies thickness, (2) a decrease in bedding thickness and lateral continuity, (3) a vertical change from planar bedding to wavy or nodular bedding, (4) a decrease in shale content, (5) a decrease in shale bedding thickness, (6) a decrease in the silt content of shales, (7) a decrease in siltstone content, (8) an increase in the percentage of grainstones (particularly coarse grainstones), and (9) a decrease in megacycle thickness.

Paleontology

In this section, the faunal characteristics of the Kope to Bellevue shoaling-upward sequence are described, including diversity, typical genera, fossil morphology, preservational states, and trace fossils. This information is summarized in Table 14. *In situ* limestones (packstones) in the Kope Formation have an average generic diversity of 4.8 and a petrographic diversity of 7.0. These rocks contain an open-marine assemblage of fossils dominated by brachiopods, bryozoans, trilobites, crinoids, gastropods, and pelecypods. Less abundant fossils include cephalopods, ostracods, graptolites, conodonts, and scolecodonts.

The most common brachiopod genera in the Kope Formation are *Onniella*, *Sowerbyella*, and *Zygospira*. All three of these brachiopods have small, lightweight shells. The most common varieties, *Onniella* and *Sowerbyella*,

FORMATION	DIVERSITY		DOMINANT FOSSIL ASSEMBLAGE	BRACHIOPOD MORPHOLOGY	BRYOZOAN MORPHOLOGY	FOSSIL PRESERVATION	ICHNO-FACIES
	Generic	Petro-graphic					
BELLEVUE	4.7	7.0	brachiopods bryozoans crinoids trilobites (open marine)	Large, rounded, thick shells with coarse ornamentation (Platystrophia, Hebertella) Some large, wide, flat shells (Rafinesquina)	Thick, massive lumps or fans (Monticulipora) Thick branching forms (Hallopora)	Micritization, bryozoan and algal encrustation, boring, abrasion	Mixed Skolithos/ Cruziana
MIAMITOWN	2.0	2.0	gastropods pelecypods brachiopods (restricted marine)	Large, wide, flat shells (Rafinesquina) Some large, rounded shells with coarse ornamentation (Platystrophia, Hebertella)	Not applicable	Well preserved; some bryozoan encrustation	Skolithos
FAIRVIEW	4.9	6.5	brachiopods bryozoans trilobites crinoids pelecypods gastropods (open marine)	Large, wide, flat shells (Rafinesquina, Strophomena, Zygospira) Some large, rounded shells (Platystrophia, Hebertella, Plectorthis)	Small, delicate, branching forms (Hallopora, Dekayia, Escharopora) Some large, robust, branch-forms (Constellaria, Heterotrypa, Homotrypa)	Well preserved; some boring and bryozoan encrustation	Cruziana
KOPE	4.8	7.0	brachiopods bryozoans trilobites crinoids pelecypods gastropods (open marine)	Small, thin shelled, flat, and finely ornamented (Onniella, Sowerbyella, Zygospira)	Small, delicate, branching forms (Hallopora, Batostoma, Dekayia)	Well preserved; some bryozoan encrustation	Cruziana

Table 14: Autecological comparison of rock facies in the Kope to Bellevue shoaling-upward sequence.

have valves that are wide, thin, smooth or finely ornamented, and hence, very delicate. Similarly, bryozoans in the Kope Formation are small and delicate. The most common genera (*Hallopora*, *Batostoma*, and *Dekayia*) are small branching forms with smooth surfaces. Other typical Kope fossils include the trilobites *Flexicalymene* and *Cryptolithus*, the high-spired gastropod *Lophospira*, and the pelecypod *Ambonychia*. A slight change in fauna occurs in the upper 25 to 30 feet of the formation, which is represented by the appearance of the brachiopods *Rafinesquina* and *Platystrophia*, and the gastropod *Cyclonema* (Felton, 1982, pers. comm.). All body fossils in the Kope Formation are unabraded and well preserved. However, encrusting bryozoans are occasionally found on some brachiopod shells.

Trace fossils in the Kope Formation are abundant and include the following varieties: *Chondrites*, *Diplocraterion*, color mottling, *Trichophycus*, *Paleophycus*, vertical tubes (probably escape structures), *Rusophycus*, and *Lockeia*. Although *Diplocraterion* and vertical tubes belong to the *Skolithos* ichnofacies, the majority of these trace fossils belong to the *Cruziana* ichnofacies (Seilacher, 1967).

In situ limestone beds (packstones) in the overlying *Fairview Formation* also contain an open-marine assemblage of fossils dominated by brachiopods, bryozoans, trilobites, crinoids, pelecypods, and gastropods. Minor amounts of cephalopods, ostracods, conodonts, scolecodonts, and graptolites also appear. These beds have a slightly lower petrographic diversity than their Kope counterparts (6.5), but about the same generic diversity (4.9).

The most common brachiopod genera in the Fairview Formation are *Rafinesquina*, *Strophomena*, and *Zygospira*. Other genera include *Platystrophia*

(*P. hopensis* and *P. sublaticosta*), *Hebertella*, and *Plectorthis*. The first two genera have wide, flat shells, and the last three have large, inflated shells with coarse, detailed ornamentation. Bryozoans in the Fairview Formation are composed of small, delicately branching forms such as *Hallopora*, *Dekayia*, and *Escharopora* in addition to larger, more robust forms such as *Constellaria*, *Heterotrypa*, and *Homotrypa*. Other Fairview genera include the trilobite *Flexicalymene*, the gastropod *Cyclonema*, and the pelecypod *Ambonychia*. Although body fossils in the Fairview Formation are unabraded, encrusting bryozoans and borings (some of which may have been produced by bryozoans--see Pohowsky, 1974) are occasionally found.

Trace fossils in the Fairview Formation are abundant and include the following varieties: *Chondrites*, *Paleophycus*, *Trichophychus*, *Diplocraterion*, color mottling, vertical tubes, *Phycodes*, mollusc trails, and *Rusophycus*. As before, these trace fossils belong to the *Cruziana* ichnofacies (Seilacher, 1967).

The overlying *Miamitown Shale* is perhaps the most unique formation in this sequence, both lithologically and paleontologically. *In situ* packstones in the Miamitown Shale contain a restricted-marine assemblage of fossils dominated by the high-spired gastropod *Lophospira*, and the pelecypods *Ambonychia* and *Modiolopsis*. *Cyclonema*--a supposedly characteristic gastropod of this unit (Ford, 1967, p. 931)--was not observed. Minor amounts of brachiopods, bryozoans, trilobites, ostracods, conodonts, scolecodonts, and crinoids also occur in the Miamitown Shale. Typical brachiopod genera include *Rafinesquina*, *Platystrophia* (*P. laticosta*), *Zygospira*, and *Hebertella*. Body fossils are usually well preserved, with the exception of some rare bryozoan encrustation. Trace fossils are less abundant than in the underlying formations and include *Chondrites*, *Diplocraterion*, color mottling, and vertical tubes.

In situ packstones and poorly washed grainstones in the overlying *Bellevue Limestone* contain an open-marine assemblage of fossils dominated by brachiopods, bryozoans, crinoids, and trilobites. In addition, minor amounts of gastropods, pelecypods, ostracods, conodonts, and cephalopods are present. Petrographic diversity (7.0) and generic diversity (4.7) are nearly the same as that of the Kope and Fairview formations. Red algae (fragments and onkoids) occur in minor amounts along the eastern and southeastern extremities of the field area (Grant Lake outcrops at Maysville, Kentucky, and Georgetown, Ohio).

The most common brachiopod genera in the Bellevue Limestone are *Rafinesquina*, *Platystrophia* (*P. ponderosa* and *P. cypha*), *Zygospira*, and *Hebertella*. With the exception of *Zygospira*, these brachiopods are very large, having either wide, flat shells (*Rafinesquina*) or thick, heavy, inflated shells with deep plications. Bryozoans in the Bellevue Limestone exhibit two dominant morphologies: (1) thick, massive lumps or fans (*Monticulipora*), or (2) thick, branching forms having steep, sharp monticules (*Hallopora ramosa*). Minor amounts of thin, delicate bryozoans are also represented by the genera *Dekayia* and *Batostomella*. In addition, rare specimens of the pelecypod *Ambonychia* and the enrolled trilobite *Flexicalymene* are present.

Body fossils in the Bellevue Limestone are mostly well preserved. However, algal encrustation (onkoids), micritization, bryozoan encrustation, boring, and abrasion are most abundant in this formation. Trace fossils are uncommon, and are limited to color mottling and vertical tubes. In addition, rare examples of *Fucusopsis* and *Chondrites* may be found.

In summary, both the body fossils and trace fossils characteristic of the Kope to Bellevue shoaling-upward sequence are very abundant and highly diverse (with the exception of the Miamitown Shale). However, the upward vertical succession of rock facies is accompanied by several faunal changes including: (1) an increase in the amount of abrasion, boring, micritization, and encrustation of shells; (2) a decrease in the amount and diversity of trace fossils; (3) an upward change from a dominantly *Cruziana* ichnofacies to a mixed *Cruziana/Skolithos* ichnofacies; (4) an upward change from small, thin, delicate shells to larger, thicker, more robust shells; and (5) a decrease in the relative amount of deposit feeders and a subsequent increase in the amount of suspension feeders (particularly brachiopods, bryozoans, and crinoids).

Interpretation

In this section, three important interpretations are discussed: (1) The Kope to Bellevue sequence represents deposition on the shallowest part of a gently sloping marine ramp in the offshore to shoreface position. (2) Frequent storm activity resulted in the loss of fine-grained sediments from the shoreface zone into deeper water. (3) The Miamitown Shale lithofacies may *not* represent a laterally adjacent lithotope contemporaneous with the Kope, Fairview, and Bellevue lithotopes. Instead, it may represent a short-term, region-wide change in environmental conditions.

According to the first conclusion, the Kope to Bellevue sequence represents shallow-water deposition on a gently sloping ramp. Several lines of evidence exist to support this interpretation: (1) Limestones contain a shallow-water fossil assemblage. (2) Trace fossils represent a mixture of the *Skolithos* and *Cruziana* ichnofacies (indicative of an inner shelf setting). (3) Limestones with textural inversions are present in both the Kope and Fairview formations, suggesting that at least two very different types of environmental settings existed at the same time, one above wave base and the other below wave base. (4) The presence of convolute lamination and ball and pillow structures indicate a sloping sea floor.

Specifically, deposition occurred in three zones--the "offshore zone," the "transition zone," and the "shoreface zone" (see Figure 55). The *offshore zone* is defined as that part of the coastal sea floor that is almost always below wave base (Reineck and Singh, 1975, pp. 322-349). Sediments in the offshore zone are disturbed only by large storms or hurricanes. Hence, the majority of sediments in this environment are mud rich (i.e., shales on clastic shorelines, and mudstones, wackestones, and packstones on carbonate shorelines). The offshore zone extends from average low wave base which, on modern shelves, ranges from 8 to 30 meters in depth, to the outer edge of the continental shelf. Shoreward of this zone is the *transition zone*, which is defined as that part of the coastal sea floor that lies between average high wave base (i.e., fair-weather wave base--2 to 20 meters in depth) and average low wave base (i.e., wave base during mild storms--8 to 30 meters). Sediments in this zone accumulate mostly under low-energy conditions, but are frequently subjected to higher energy events. Hence, a variety of rock types should appear, ranging from fine-grained muds and silts to clean sands. Shoreward of the transition zone is a zone that is almost always above average wave base, the *shoreface*

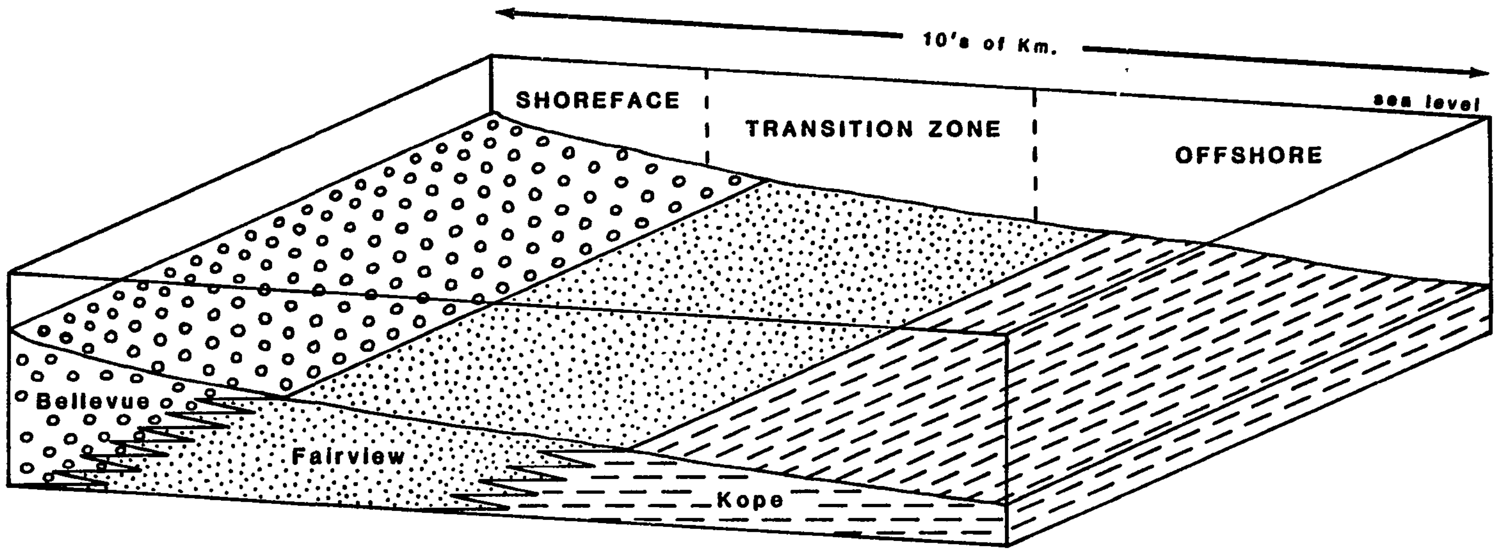


Figure 55: Interpretation of the Kope, Fairview, and Bellevue lithotopes. Vertical scale is highly exaggerated.

zone. Shoreface sediments are constantly being moved around by waves and currents, resulting in clean quartz or carbonate sands.

I believe that the Kope Formation represents deposition in the offshore position for several reasons: (1) The relative abundance of shale (80 percent), the relatively high silt content and thickness of shale beds, and the abundance of siltstones (30 percent of the carbonate rock fraction) all indicate low-energy deposition below wave base. (2) The excellent preservation of sedimentary structures and trace fossils indicates a lack of wave erosion. (3) The dominant carbonate rock types in this formation are packstones, wackestones, and micstones (52 percent). As discussed earlier, these rocks represent *in situ* deposition below wave base in a quiet-water zone. (4) Body fossils in the Kope Formation are small, thin, and fragile, indicating that these organisms lived in a protected, low-energy environment, probably below wave base. (5) The lack of abrasion, micritization, and boring of fossils indicates low-energy deposition beyond the reach of constant wave reworking.

The overlying Fairview Formation probably represents deposition in slightly shallower water than the Kope Formation, probably in the offshore to transition zone. The following vertical trends suggest that Fairview sediments accumulated in shallower water than Kope sediments: (1) the relative decrease in shale content (49 percent) and siltstone content (12 percent); (2) the lower silt content and bedding thickness of shales; (3) the greater trace fossil diversity; (4) the relative increase in grainstone content (26 percent vs. 18 percent); (5) the mixture of small, delicate fossils and larger, more robust forms in most limestones; and (6) the slightly higher degree of abrasion, boring, micritization, and encrustation of fossils.

Sediments in the overlying Bellevue Limestone were probably deposited in the shallowest setting of the three formations. The following evidence indicates that Bellevue sediments accumulated in a lower shoreface to transition zone setting: (1) The low shale content (18 percent), high claystone/mudstone ratio, and thin bedding of shales indicate that wave-induced winnowing effects were high. Thus, most of the storm-deposited terrigenous muds which accumulated in this setting were easily removed by winnowing processes. Only those muds which were trapped under or between shells were protected from erosion. (2) The characteristic wavy-to-lenticular, discontinuous bedding is generated primarily in the shallow subtidal to intertidal zones (Reineck and Singh, 1973, pp. 99-102). (3) The poor preservation of sedimentary structures and trace fossils indicates that substrates were highly mobile, and that wave erosion was dominant. (4) The dominant carbonate rocks in the Bellevue Limestone are grainstones (clean skeletal sands). (5) Most of the body fossils in this unit are large, robust forms capable of withstanding a high degree of water turbulence by virtue of their massive skeletons (e.g., the bryozoan *Monticulipora*), their ability to firmly attach themselves to more stable substrates (e.g., encrusting bryozoans), or their ability to roll around on the sea floor without being damaged (e.g., the brachiopod *Platystrophia ponderosa*). (6) Although a mixture of fossil preservational states exists in most beds (a mixture of fragmented, abraded bioclasts and undamaged, whole fossils), abrasion, micritization, boring, and encrustation of shells is most abundant in this formation. An interpretation of all three lithotopes is shown in Figure 55.

The second major conclusion to be discussed in this section is the concept that frequent storm activity resulted in the loss of fine-grained sediments (both terrigenous and carbonate) from the shoreface and upper transition zone into deeper water. As mentioned before, storms erode and rework bottom sediments primarily by lowering wave base to depths greater than normal. Furthermore, the frequency of storm-induced erosional events decreases with increasing water depth. Hence, bottom sediments in the shoreface zone (the Bellevue lithotope) were disturbed by every storm that occurred in the area, even the mildest of storms. Conversely, only those hurricanes having exceptionally strong winds were capable of eroding sediments in the offshore zone (the Kope lithotope). As a result, sediments in the Bellevue lithotope experienced a much higher degree of winnowing, breakage, and abrasion than sediments in the Kope or Fairview lithotopes. Therefore, Bellevue sediments should theoretically be represented by clean, *fine-grained*, carbonate sands (i.e., calcisiltites and fine grainstones). However, the reverse is true; the dominant carbonates in the Bellevue Limestone are *coarse-grained* rocks (i.e., poorly washed grainstones and coarse grainstones).

This anomalous situation suggests that fine-grained sediments in the Bellevue lithotope were frequently entrained by storms and transported out of the shoreface zone into deeper water via storm currents or storm-induced gravity flows (see Figure 56). I propose that large bioclasts in the Bellevue lithotope may have experienced the following "idealized" sequence of biostratinomic events: (1) disarticulation of valves or segments, (2) initial breakage and abrasion, (3) subsequent periods of breakage and abrasion, (4) hydraulic entrainment by a storm event, (5) transportation

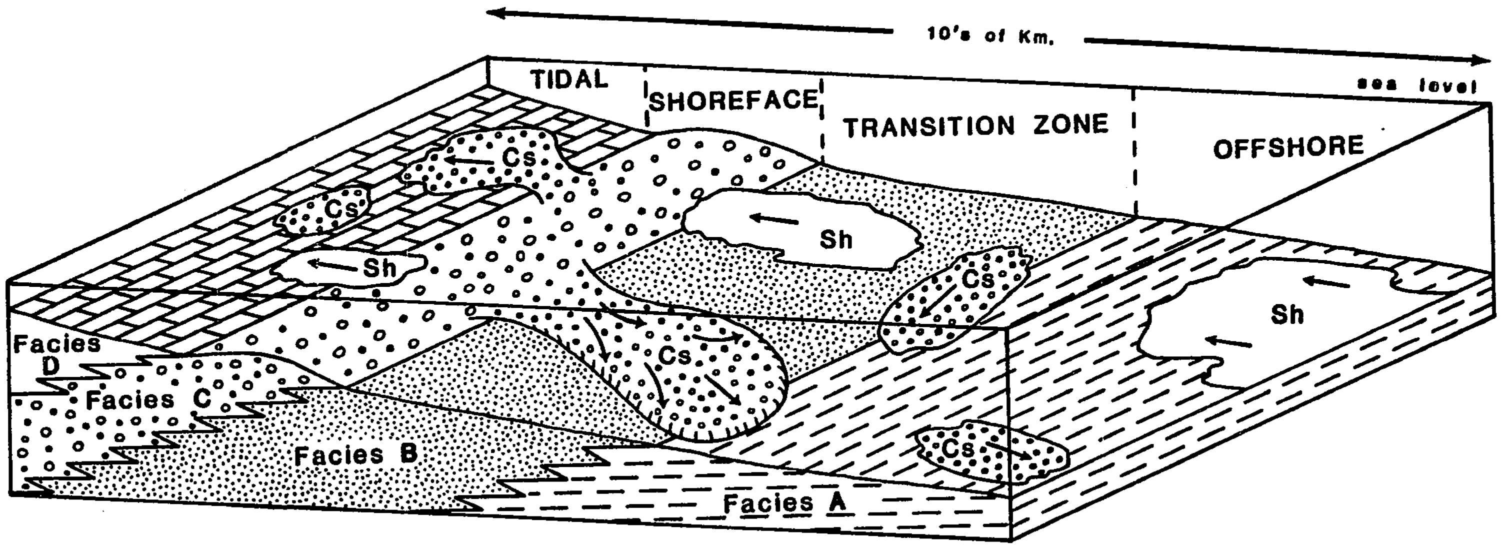


Figure 56: Generalized redistribution patterns of sediments by storm events, gravity flows, and currents. Incoming storms may transport and deposit layers of shale (Sh) upslope, and thin layers of carbonate sand (Cs) behind Facies C. In addition, carbonate sand may also be transported downslope into deeper water, where it is subject to further redistribution in several directions.

out of the Bellevue lithotope by downslope gravity flow, (6) subsequent period(s) of redistribution downslope in discontinuous sand sheets, (7) final deposition in the transition zone or offshore zone and burial by a rapidly deposited layer of shale. Steps 4 and 5 would have occurred only when bioclast fragments had been sufficiently reduced to some "critical size" (perhaps 2 mm?) below which they could be transported out of their environment of origin. Any grains coarser than this "critical size" would have remained in the Bellevue lithotope until further breakage and abrasion reduced their size below the "critical" point. Exceptionally robust skeletons, such as the massive bryozoan, *Monticulipora*, or the thick-shelled brachiopod, *Platystrophia ponderosa*, probably required such a long period of breakage to reach the "critical size" that many of them were bored, abraded, encrusted, and finally, buried long before they could be transported out of the shoreface zone. Hence, Bellevue limestone beds may represent coarse lag deposits from which the finer grained components have been removed by storm winnowing and transportation.

This process also explains several other unusual characteristics of the Kope to Bellevue sequence: (1) the thin, wavy, discontinuous bedding typical of the Bellevue Limestone; (2) the fact that the Bellevue Limestone is the thinnest facies in the entire sequence; (3) the low shale content of the Bellevue Limestone; (4) the presence of textural inversions in the Kope and Fairview formations; (5) the presence of fine grainstone and calcisiltite beds in the Kope and Fairview formations, plus the relatively low coarse grainstone/fine grainstone ratio in these two units (such breakage and abrasion could not be produced in a low-energy zone below wave base, and therefore must have originated in a shallower water setting).

The transportation and redistribution of sediments by storms, currents, and gravity flows is depicted in Figure 56. A similar interpretation has been proposed for sand deposits in the Hughley Shales of Shropshire (Silurian) by Benton and Gray (1981)--see Figure 57 for comparison.

According to the third major conclusion, the Miamitown Shale lithofacies may not represent a laterally adjacent lithotope contemporaneous with the Kope, Fairview, and Bellevue lithotopes. My initial interpretation of the Miamitown Shale was just the reverse--that it was an example of Facies D of the idealized shoaling-upward cycle, and therefore representative of a shallow subtidal (lagoonal?) to intertidal environment (see Figures 47 and 52). This assumption was based on several observations: (1) the association of the Miamitown Shale with Facies C (Bellevue Limestone); (2) its semi-restricted, molluscan-rich fauna; (3) the relative abundance of dolomite in shales; and (4) the presence of very elongate, oriented gutter casts (possibly tidal in origin).

However, I now believe that the Miamitown Shale could represent a short-term, region-wide change in environmental conditions, instead of a contemporaneous lithotope. This idea is based on the following observations: (1) The Miamitown Shale is very thin in comparison to other examples of Facies D in the Cincinnatian Series. (2) If the Miamitown Shale actually represents a low-energy lithotope with restricted circulation (e.g., a lagoon or tidal flat behind a protective barrier bar or shoal), then such a lithotope should have always been situated *shoreward* of the shoaling zone (the Bellevue lithotope). In a regressive vertical sequence such as the Kope to Bellevue cycle, this facies should always occur stratigraphically *above* or *in the middle of* Facies C. Instead, the Miamitown

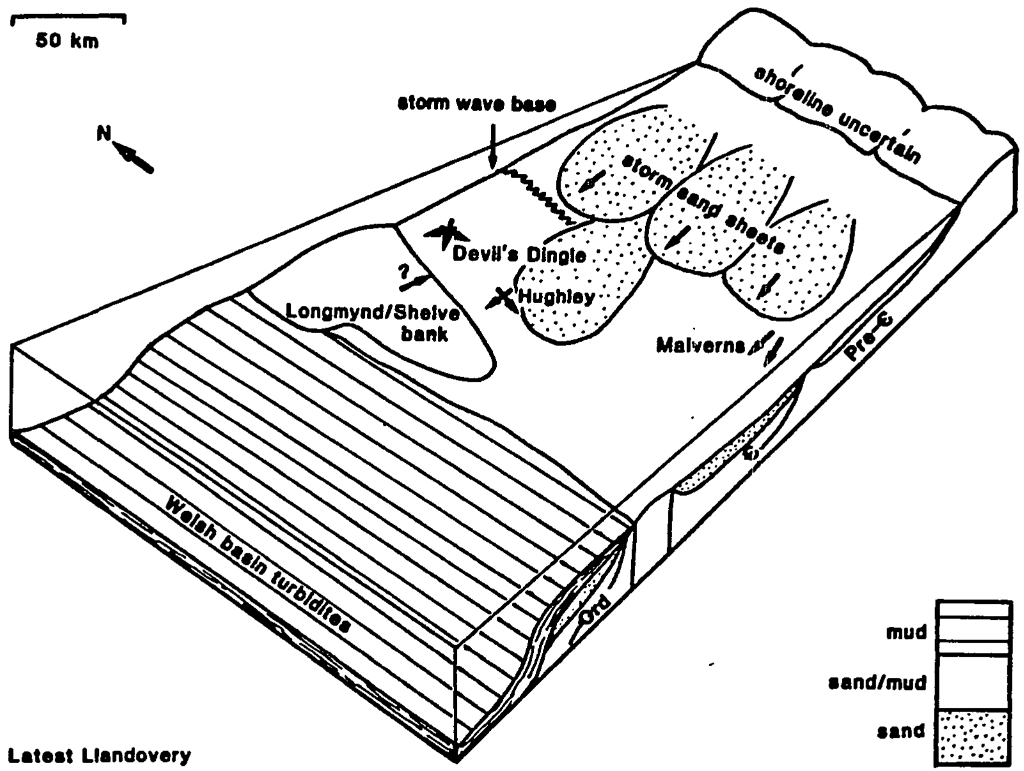


Figure 57: Generalized sediment distribution and paleocurrent patterns for the lower Silurian Hughley Shales (from Benton and Gray, 1981, fig. 13).

Shale never occurs above the Bellevue Limestone, and is known to occur in at least three other stratigraphic positions--in the middle of the Bellevue Limestone, between the Bellevue Limestone and the Fairview Formation, and in the middle of the Fairview Formation (see Tobin, 1980, Batavia locality). (3) Sedimentary features characteristic of shallow subtidal to intertidal environments are missing, such as bimodal current orientations, flasar bedding, mudcracks, massive dolomites, glauconite, birdseye structures, vuggy limestone, rip-up clasts, and omission surfaces. Most of these features can be found in the Saluda and Drakes formations, both of which are examples of Facies D.

Perhaps the Miamitown Shale represents a short-term change in environmental conditions that affected sediment type and faunal composition across much of the sea floor. The presence of abundant shales and siltstones, in addition to the presence of a semi-restricted fossil assemblage (brachiopods, gastropods, pelecypods), suggests that the Miamitown Shale may represent a period of time during which the influx of shale was very high. If so, the increased turbidity of the water column during this time period would have precluded a more open-marine fauna (e.g., crinoids, bryozoans, cephalopods, etc.). Figure 58 illustrates the proposed sequential development of the Miamitown Shale.

Regional Comparison

One of the original objectives of this study was to describe and interpret vertical sequences of strata in the Cincinnati area, and to compare those sequences on a regional scale (preferably from west to east). Ideally, a complete (or at least composite) section of each of the three

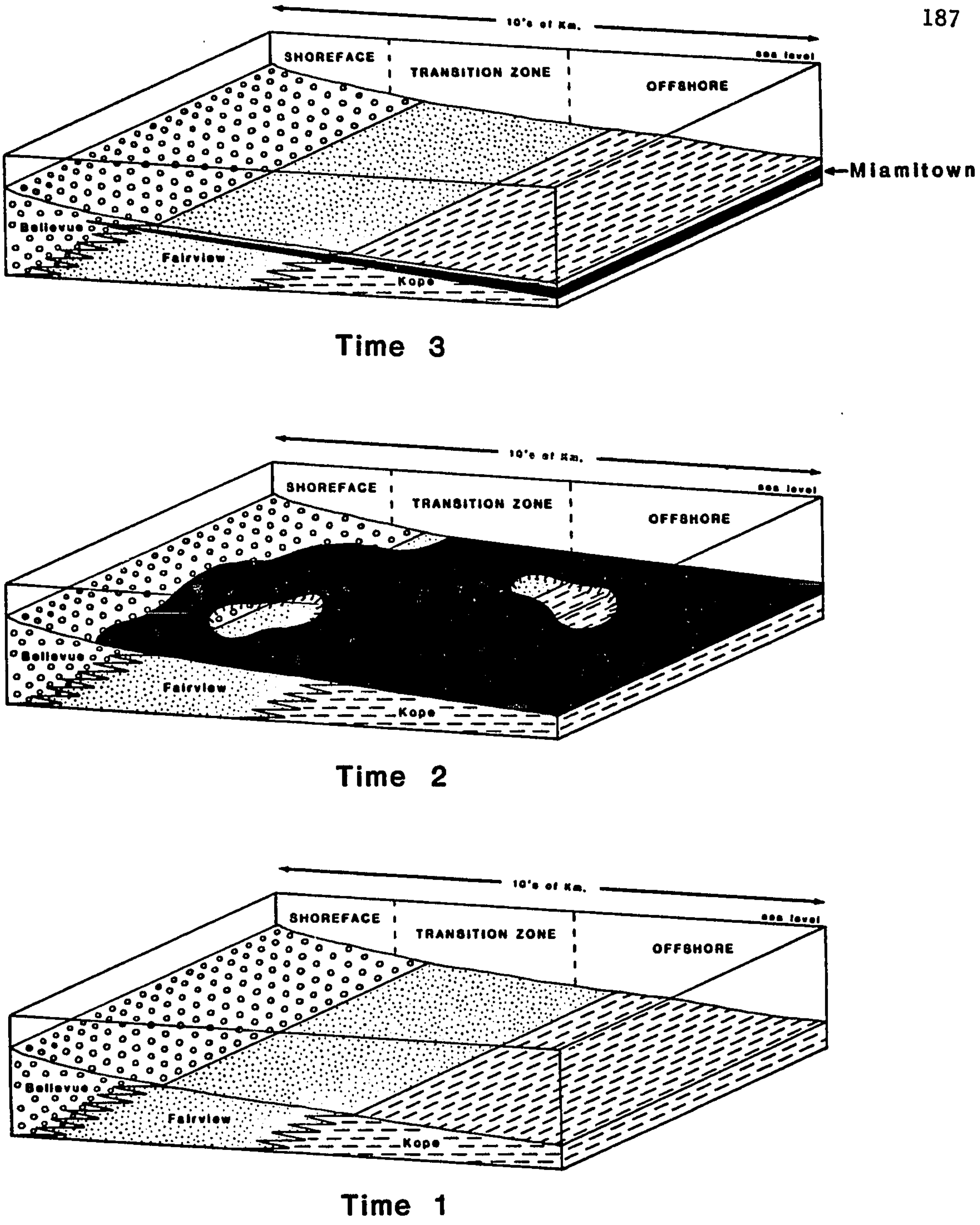


Figure 58: Sequential development of the Miamitown Shale intertonguing relationship. Time 1 is a cross section of the sea floor before deposition of the Miamitown Shale. At Time 2, the Miamitown Shale has accumulated across most of the ramp. Time 3 represents renewed deposition after Miamitown time. Hence, the Miamitown Shale could represent a time line.

shoaling-upward sequences should be exposed at several key localities from southeastern Indiana to the eastern edge of the outcrop belt. In the case of the Kope to Bellevue sequence, a detailed regional comparison was inhibited by the lack of good outcrop exposures in the field area. The only complete exposure of the entire sequence occurs in the Cincinnati area. Although the sequence is not exposed in Indiana, the Fairview, Miamitown, and Bellevue formations are exposed along the Indiana-Kentucky border (I-275 outcrop near Lawrenceburg; see Tobin, 1980, Appendices 1 and 2). The only exposure east of the Cincinnati area is the Georgetown locality. There, the Bellevue Limestone is completely exposed, but only one-sixth of the Kope Formation and one-third of the Fairview Formation are exposed. Hence, the regional trends discussed in this section are somewhat tenuous and should be more completely investigated by future workers.

A comparison was made of the sedimentary characteristics of the Kope Formation at two different localities (the I-275/Kentucky 445 outcrop in northern Kentucky, and the Georgetown, Ohio, outcrop). The only observable lithologic differences between these two areas are: (1) the shale content at the Georgetown locality is slightly lower (76 percent vs. 80 percent), (2) shale beds at that locality are slightly thinner (20 cm vs. 24 cm), and (3) ripples, starved ripples, and gutter casts are more abundant.

Two apparent west-to-east lithologic trends were also detected in the Fairview Formation: (1) Shale content decreases toward the east (50 percent at Lawrenceburg, 49 percent at Cincinnati, and only 35 percent at Georgetown). (2) the average bedding thickness of shales decreases to the east (8 cm at both the Lawrenceburg and Cincinnati localities, and only 4 cm at Georgetown).

Finally, three west-to-east trends were observed in the Bellevue Limestone: (1) Shale content decreases toward the east (20 percent at Lawrenceburg, 18 percent at Cincinnati, and 14 percent at Georgetown). (2) Exposure effects (micritization, boring, abrasion, and encrustation) increase toward the east. (3) The dominant brachiopod associations change from west to east. At the Lawrenceburg locality, *Rafinesquina* and *Zygospira* dominate. In the Cincinnati area, *Rafinesquina*, *Platystrophia* (*P. laticosta* mostly), and *Zygospira* dominate. At the Georgetown locality, *Platystrophia* dominates (mostly *P. ponderosa*, but also *P. laticosta* and *P. cypha*).

In summary, the only apparent west-to-east trends in the Kope to Bellevue sequence include a decrease in shale content and bedding thickness, an increase in exposure effects, and a change from flat, thin-shelled brachiopods to inflated, thick-shelled brachiopods. Perhaps these trends reflect a gradual lowering of sea level as these three facies prograded eastward across the shallow carbonate ramp.

Corryville to Oregonia Sequence

Stratigraphy

Unconformably overlying the Kope to Bellevue shoaling-upward cycle is a similar, but thinner sequence of strata, the Corryville to Oregonia sequence. This sequence comprises four distinct rock facies which roughly correspond to the following traditional biostratigraphic units: "Corryville," "Mt. Auburn," "Sunset," and "Oregonia" (see Figure 4). Previous lithostratigraphic analyses of this interval were conducted in two different field areas: southeastern Indiana (Brown and Lineback, 1966; Hatfield, 1968; Hay et al., 1981), and the Maysville, Kentucky, to Dayton, Ohio, area (Peck, 1966; Lee, 1974). The lithostratigraphy of this interval in the Cincinnati area has largely been ignored. Ford (1967, p. 934) believed that there were "no valid lithologic criteria" for subdividing rock-stratigraphic units above the Bellevue Limestone in the Cincinnati area, and therefore referred to these strata as "unnamed beds."

The first lithostratigraphic study of the Corryville to Oregonia sequence was Brown and Lineback (1966), who assigned the strata between the top of the Kope Formation and the top of the Liberty Formation to the "Dillsboro Formation" (see Figure 2). This "formation" is a thick (145 meters), undifferentiated unit containing eight lithologically distinct rock facies, which had already been described by biostratigraphers nearly 60 years before. Subsequent examples of the tendency to lump these rock facies into thick, undifferentiated units include Hatfield (1968; "Tanner's Creek Formation"--Sunset through Waynesville), Peck (1966; "Bull Fork Formation"--Sunset through Whitewater), Lee (1974; "Bull Fork Formation"), and Hay et al. (1981; "Excello Member of the Brookville Formation"--Corryville through Oregonia).

As discussed earlier, the traditional "biostratigraphic" units in this part of the Cincinnatian Series do indeed possess distinctive lithologic characteristics which can be correlated laterally. Perhaps these rock facies were not recognized and defined by the stratigraphic "lumpers" because of two interrelated factors: (1) As previously discussed, they ignored the traditional biostratigraphic units on the grounds that they were defined *faunally*. This incorrect assumption was based on summary articles, rather than on the original references. (2) They based their type sections in areas which are laterally distant from the Cincinnati area. In an effort to locate the traditional biostratigraphic units of the Cincinnati area in their *own* field areas, these stratigraphers looked for *faunal zones*, instead of the *rock facies* in which the characteristic fossils occur (again, because of the preconceived notion that these units were defined faunally). Hence, whenever the characteristic fossils could not be detected in their own field areas (fossil species sometimes pinch out laterally), the rock facies in which they occur were also not detected.

Because many of the traditional biostratigraphic units possess distinctive lithologic characteristics which can be correlated laterally and recognized in the *original* descriptions, they are herein reinstated as valid rock-stratigraphic units. In this section, the following formational names are proposed for four lithogenetically related rock facies (from bottom to top): *Corryville*, *Mt. Auburn*, *Sunset*, and *Oregonia*. Each unit will be described using modern terminology and redefined in accordance with the rules of the Code of Stratigraphic Nomenclature.

The lowermost unit in this sequence is the *Corryville Formation*. The "Corryville or *Chiloporella nicholsoni* Beds" were originally described by Nickles (1902, p. 83) as follows: "In this division the limestones are thinner and less frequent than in the quarry beds [Fairview] and the shales more yellowish. Blue shale also occurs." Although his description is archaic, Nickles has adequately described a shale-rich facies containing widely spaced ("less frequent") limestone interbeds which are thinner than those found in the Fairview Formation. Such a description is adequate for distinguishing this facies from the underlying thin-bedded, shale-poor "Bellevue Beds" and from the overlying nodular-bedded "Mt. Auburn Beds."

For this reason, I propose that the name "Corryville Formation" be used to designate the shale-rich facies which occurs stratigraphically between the Bellevue Limestone and the Mt. Auburn Formation. Although this newly defined formation does not exactly coincide with the vertical extent of Nickles' "*Chiloporella nicholsoni* Beds," the original description of the dominant lithology in which *C. nicholsoni* is found is the same as that of the Corryville Formation. Furthermore, the name "Corryville" has priority over the thick, undifferentiated "formations" discussed earlier.

In order to conform with the Code of Stratigraphic Nomenclature, the following characteristics of the Corryville Formation must be described: (1) its lithology (recast in modern terms), (2) its upper and lower boundaries (lithologically defined), (3) its lateral persistence, and (4) its type section or type area.

Accordingly, the Corryville Formation is herein proposed as a valid rock-stratigraphic unit. The Corryville Formation is a thick-bedded, shale-rich (64 percent) facies composed of thin (5 cm), widely spaced, planar-bedded limestones and thick (10 cm), flaggy shale interbeds. The dominant limestones are mud rich (packstones and wackestones) and contain a thin-shelled, open-marine fauna. Shale beds are dominantly composed of dolomitic mudstone. The Corryville Formation is the thickest unit in this sequence, reaching a maximum of 23 meters (76 feet) at the Stonelick Creek locality, about 20 miles east of Cincinnati (see Meyer et al., 1981, fig. 35). Figure 59 is a typical outcrop exposure of the Corryville Formation.

The upper and lower contacts of the Corryville Formation were originally defined as the vertical range of the bryozoan, *Chiloporella nicholsoni* (Nickles, 1902). In accordance with modern stratigraphic procedures, the lower contact of the Corryville Formation is herein redefined as the lowermost extent of its characteristic shale-rich, planar-bedded strata. This horizon is generally marked by a vertical transition from the uppermost wavy- or nodular-bedded, shelly limestone (of the Bellevue Limestone) to an overlying shale bed ranging from 5 to 10 cm in thickness (the lowermost shale bed of the Corryville Formation--see Appendix 3, Georgetown locality). Similarly, the upper contact of the Corryville Formation is redefined as the uppermost extent of its shale-rich, planar-bedded strata. This contact is indicated by the first (lowermost) appearance of the nodular-bedded limestone typical of the overlying Mt. Auburn Formation (see Appendix 3; Blue Rock Road, Middletown, and Rumpke localities--see also Figure 59). In the Brookville, Indiana, area the Mt. Auburn Formation is absent. Thus, in areas where the Mt. Auburn Formation has pinched out completely, the upper contact of the Corryville Formation is defined as the uppermost extent of its shale-rich, planar-bedded strata, and the beginning of the limestone-rich, planar-bedded strata of the Sunset Formation. At the Brookville Dam locality, this contact is clearly marked by the top of a 92 cm thick shale bed which is overlain by two very thick, closely spaced limestone beds (see Appendix 3).

Nickles did not define a specific type section for the Corryville Formation. However, Nickles (1902, pp. 83, 98) referred to the "Price Hill" locality in Cincinnati as a representative exposure. Other nearby exposures were described at Fairview Heights and McMillan Street. Because these outcrops are no longer exposed, a valid type section of the Corryville Formation does not exist. The only complete exposure of the formation at the present time is located at Stonelick Creek, east of Cincinnati (see Meyer et al., 1981, fig. 35). Perhaps this exposure should serve as a new type section for future study. Although this outcrop was not described in this study, its lithologic and paleontologic characteristics have been outlined by Meyer et al. (1981) and Hinterlong (1981). The Corryville Formation is laterally persistent throughout the field area, and may also be studied at the following locations: Brookville Dam, Middletown, Rumpke Landfill, and Blue Rock Road (see Appendix 3). Two other incomplete exposures of the Corryville Formation, which include its basal contact with the underlying Bellevue Limestone, occur at the Lawrenceburg and Muddy Creek localities (see Tobin, 1980, Appendices 1 and 2).

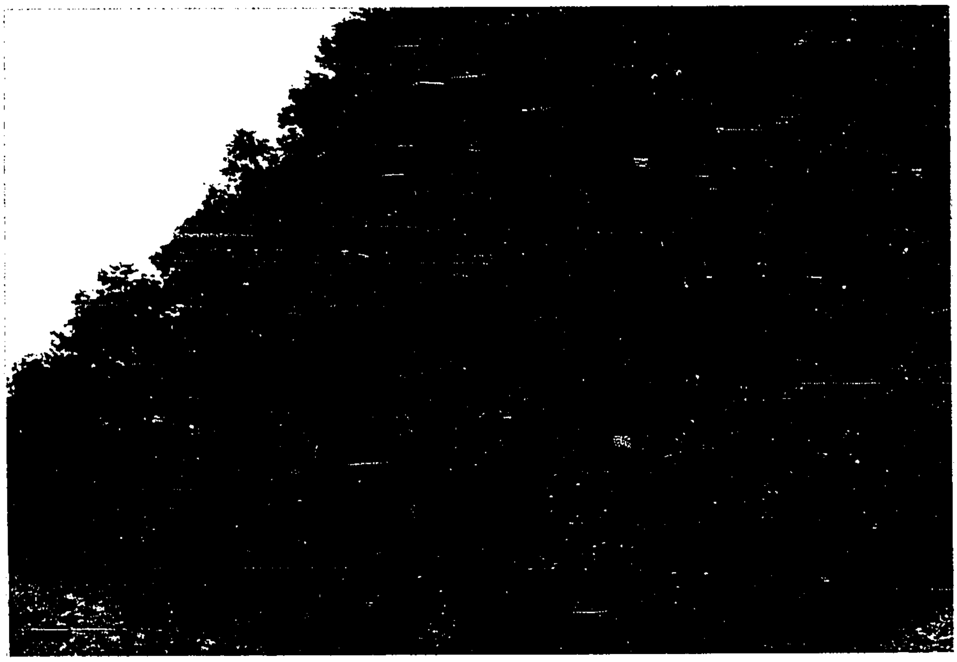
The Corryville Formation is overlain by a thin, nodular-bedded facies known as the *Mt. Auburn Formation*. The "Mt. Auburn or *Platystrophia lynx* Beds" were also defined by Nickles (1902, pp. 85-86) as follows: "Their thickness is about 20 feet. The lower five to twelve feet contain an abundance of the large Orthid, *Platystrophia lynx* [now *P. ponderosa*, var. *auburnensis*], known in common parlance as double-headed Dutchman; . . . The beds are mainly blue shale, though sometimes yellowish in exposure, with some rather irregularly bedded limestone." Again, Nickles' original description is adequate enough to distinguish this facies both lithologically and paleontologically from the overlying Sunset Formation and the underlying Corryville Formation. His original description includes total thickness, faunal content, the presence of abundant "blue shale" (olive gray shale comprises 37 percent of the unit), and most importantly, the presence of nodular-bedded limestones ("irregularly bedded"). Thus, I propose that the Name "Mt. Auburn Formation" be used to designate the nodular-bedded facies which occurs stratigraphically between the Corryville Formation and the Sunset Formation. As before, the vertical extent of Nickles' "Mt. Auburn Beds" may not coincide exactly with this new formation, but the lithology he described can be easily recognized in outcrop. Furthermore, the name "Mt. Auburn" has priority. This conclusion was first discussed by Krumpolz (1980) who believed that the Mt. Auburn facies should be given "member" status, primarily because of its thinness (5.1 meters at Blue Rock Road). However, the unit does meet the requirements of a formation as defined by the Code of Stratigraphic Nomenclature (i.e., distinctive lithologic character, mappability, usefulness in interpretation), and therefore should be given formational status.

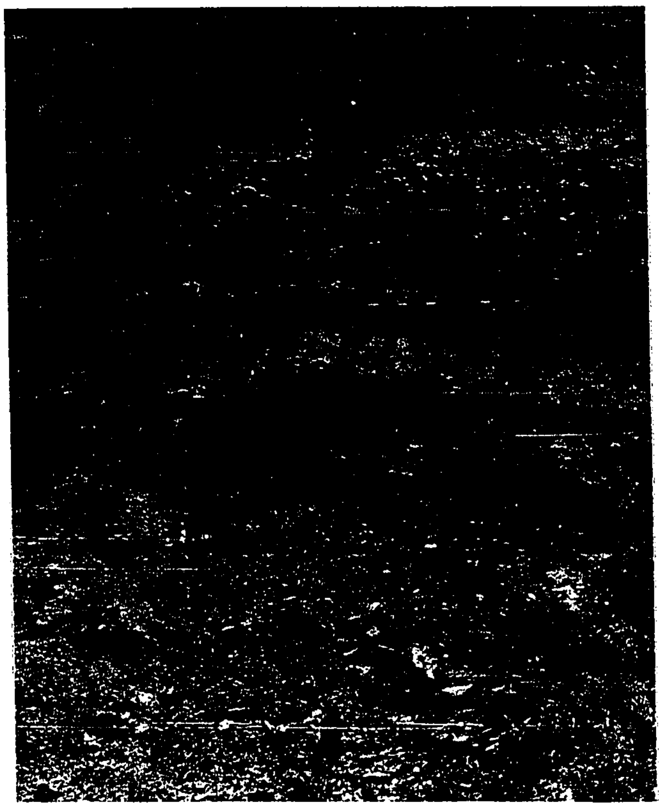
The Mt. Auburn Formation is a thin-bedded facies composed of very thin (2 cm), fissile shales (37 percent), and abundant, thin-bedded (4 cm) nodular limestone (63 percent). Limestones are dominated by two different varieties: fine-grained argillaceous packstones and wackestones, and grainstones. Although fossils are abundant and varied, the thick-shelled brachiopod, *Platystrophia ponderosa*, var. *auburnensis*, is characteristic of the formation. A typical outcrop exposure of the Mt. Auburn Formation is shown in Figure 60.

The lower contact of the Mt. Auburn Formation is redefined as the first (lowermost) horizon in which its nodular-bedded limestone occurs. On weathered outcrops, this horizon is easily recognized by a pronounced break in slope (see Figure 59). Similarly, the upper contact of the Mt. Auburn Formation is redefined as the uppermost occurrence of nodular-bedded limestone. This horizon is generally marked by the first occurrence of the thick, even-bedded limestones and shales of the overlying Sunset Formation (see Appendix 3; Blue Rock Road, Middletown, and Rumpke Landfill sites).

Figure 59: Field exposure of the Corryville and Mt. Auburn formations, Middletown locality. The Jacob's staff marks the contact between the shale-rich, planar-bedded Corryville Formation and the shale-poor, nodular-bedded Mt. Auburn Formation.

Figure 60: Field exposure of the Mt. Auburn Formation, Middletown locality. Note the discontinuous, nodular bedding. The Jacob's staff marks the Corryville-Mt. Auburn contact.





The "Mt. Auburn Beds" were originally described from exposures in the Mt. Auburn neighborhood of Cincinnati, and include the Price Hill and Clifton Heights localities (Nickles, 1902, p. 85). Because these outcrops are no longer exposed, a new type section should be defined. Perhaps the Blue Rock Road locality should be used for this purpose since it is the closest complete exposure of the Mt. Auburn Formation to the original type area. Additional reference localities may be observed at the Middletown and Rumpke locations. The Mt. Auburn Formation is persistent throughout the field area, occurring at least 20 miles east, northeast, and north of Cincinnati. In addition, the unit has also been observed along the eastern and western flanks of the Cincinnati Arch in Kentucky (Nickles, 1905). However, the Mt. Auburn Formation pinches out in a northwesterly direction between the Cincinnati area and Brookville, Indiana. At the Brookville Dam locality, the Corryville Formation is directly overlain by the Sunset Formation. The absence of the Mt. Auburn Formation in southeastern Indiana has also been noted by Cumings (1908, p. 636) between Weisburg and Guilford, 20 miles south of Brookville (the "Tanner's Creek section"). However, Cumings later mentioned the presence of a 6- to 10-inch-thick layer of strata at this locality which contains occasional specimens of *Platystrophia lynx*, and which he believed was equivalent to the Mt. Auburn Bed of Cincinnati (1908, p. 669). Furthermore, Felton (1982, pers. comm.) has observed a 4-foot-thick layer of phosphatic, shelly limestone containing *P. ponderosa maysvillensis* between the Corryville and Sunset formations along Route 421 at Madison, Indiana.

The next lithofacies in this sequence is the *Sunset Formation*. Nickles (1902) originally used the name "Warren or *Homotrypa bassleri*

Beds" to describe the interbedded limestones and shales which lie above the "Mt. Auburn Beds." This sequence roughly correlates with the Sunset and Oregonia facies described in Caster, Dalvé and Pope (1961). Nickles (1902, p. 86) described the lower part of the "Warren Beds" (i.e., Sunset) as follows: "Limestone is not very abundant in the beds under consideration, whose thickness is about 80 feet. The intercalated shales are of a dark bluish color, rather marly." Nickles (1902, p. 86) also noted that, "Toward the top of this division, the layers, both limestone and shale, especially the latter, become rough and nodular, indicating a marked change in the sedimentation." This nodular-bedded facies roughly corresponds to the Oregonia Formation. The term "Warren Beds" was later replaced by the name "Arnheim Bed" after the town of Arnheim, in Brown County, Ohio (Foerste, 1905b). Foerste also noticed the lithologic distinction between the planar-bedded facies below and the nodular-bedded facies above. Accordingly, Foerste (1910) subdivided the Arnheim into two divisions, the lower "Sunset Division" (after Sunset, Kentucky), and the upper "Oregonia Division" (after Oregonia, Ohio). Later, Foerste (1912a) gave the "Arnheim Bed" formational status. Hence, later workers assumed the Sunset and Oregonia divisions to be of member status. However, because Foerste's "Arnheim Formation" contains two rock facies having distinctive lithologic identities, it is deemed inappropriate for use in modern stratigraphic nomenclature. Hence, I propose that the term "Arnheim" be discontinued, and that the terms "Sunset" and "Oregonia" be reinstated as valid rock-stratigraphic units having formational status.

The Sunset Formation is herein redefined as the planar-bedded limestone and shale facies that occurs stratigraphically between the underlying

Mt. Auburn Formation (or, in Indiana, the Corryville Formation) and the overlying Oregonia Formation. The Sunset Formation is a medium-bedded facies containing nearly equal amounts of interbedded limestone (48 percent) and shale (52 percent). This formation is composed of medium-to-thin (6 cm), closely spaced, planar-bedded limestones interbedded with medium-thick (8 cm) shales. Limestones are dominated by packstones and wackestones, and shales are mostly mudstones.

The Sunset Formation is laterally persistent throughout the entire field area. Parts of the formation may be seen at the following localities: Aiken High School, Rumpke Landfill, Blue Rock Road, and Middletown (see Appendix 3). The only complete exposure of the Sunset Formation occurs at the Brookville Dam locality, where it reaches a total thickness of 13.5 meters (44 feet). Perhaps this locality should also serve as a type section for the new formation.

The lower boundary of the Sunset Formation is herein redefined as the lowermost occurrence of its medium-thick, planar-bedded lithology. This horizon coincides with the redefined upper Corryville Formation contact (in Indiana only), and elsewhere with the redefined top of the Mt. Auburn Formation (see preceding discussion). The top of the formation is redefined as the uppermost occurrence of its characteristic medium-thick, planar-bedded limestone and shale. This horizon is marked by the first (lowermost) occurrence of the nodular-bedded limestone typical of the overlying Oregonia Formation.

The uppermost facies in this sequence is the *Oregonia Formation*. As mentioned earlier, this facies was originally defined by its paleontologic *and* lithologic characteristics, and the name "Oregonia" has priority.

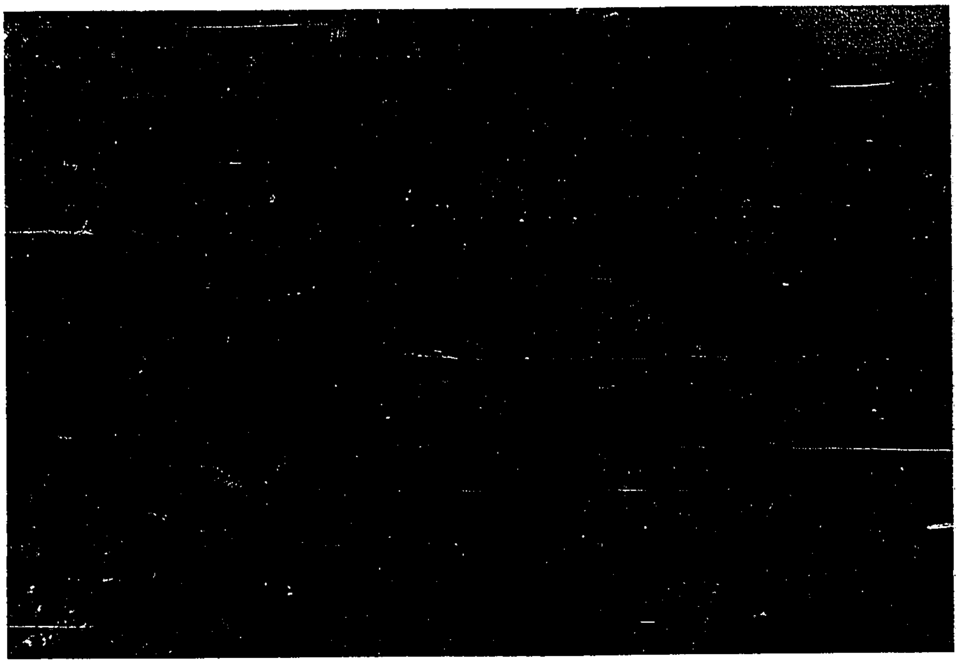
Thus, I propose that the nodular-bedded strata which occur stratigraphically between the Sunset Formation and the overlying Waynesville Formation represent a valid rock-stratigraphic unit and should be renamed the Oregonia Formation. This formation is a thin unit (7 meters thick at the Brookville Dam locality) composed of thin (4 cm), discontinuous, fissile shales interbedded with thin (4 cm), light gray, argillaceous limestone nodules and some wavy-to-planar limestone beds. The characteristic thin, nodular bedding is quite distinctive from the planar-bedded units above and below (see Figure 61). Furthermore, the shale content is lower than that of the underlying and overlying formations (44 percent).

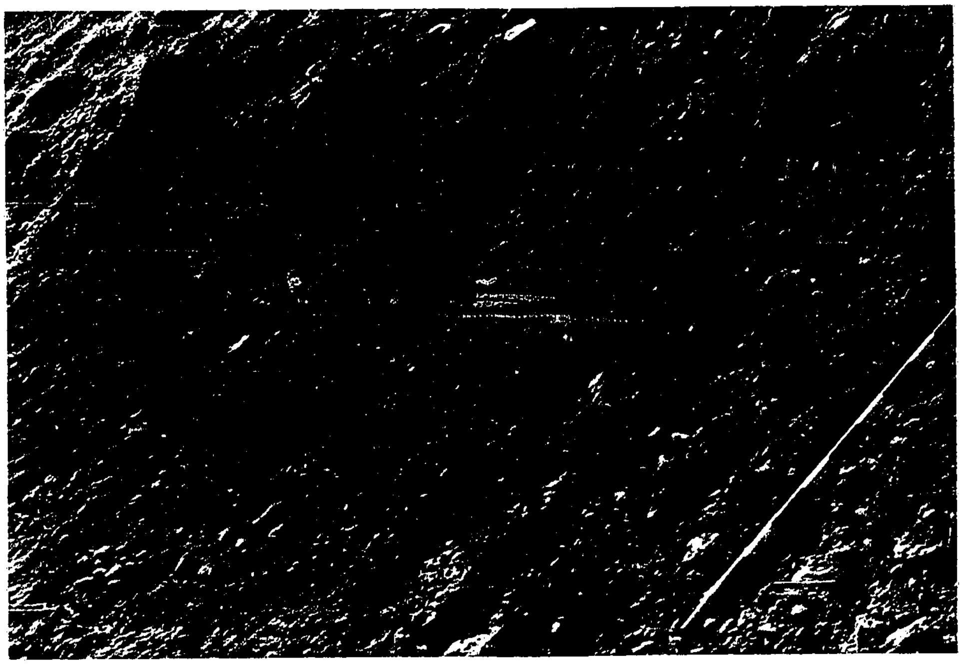
The lower contact of the Oregonia Formation coincides with the top of the Sunset Formation (see preceding discussion). The top of the Oregonia Formation is abrupt, and is redefined as the uppermost occurrence of its nodular- and wavy-bedded strata. This horizon is marked by an abrupt change from thin, nodular limestone to thick, planar beds of shale and limestone (see Appendix 3, Brookville Dam locality, and Figure 61).

The only complete exposure of the Oregonia Formation occurs at the Brookville Dam locality. Perhaps this exposure should serve as the redefined type section of the formation. Only two other exposures of the Oregonia Formation were described in this study: the Aiken High School locality (Appendix 3) and the Caesar Creek locality (see Figures 61 and 62A). In addition, the formation is exposed just west of the intersection of the Miami River and I-71, 5 miles southwest of Caesar Creek (Felton, 1982, pers. comm.). Hence, the Oregonia Formation is laterally persistent throughout the field area.

Figure 61A: Field exposure of the Oregonia Formation, Caesar Creek locality. Jacob's staff marks the Oregonia-Waynesville contact.

Figure 61B: Profile of the Oregonia Formation, Caesar Creek locality. Note the characteristic "rubble" produced upon weathering.





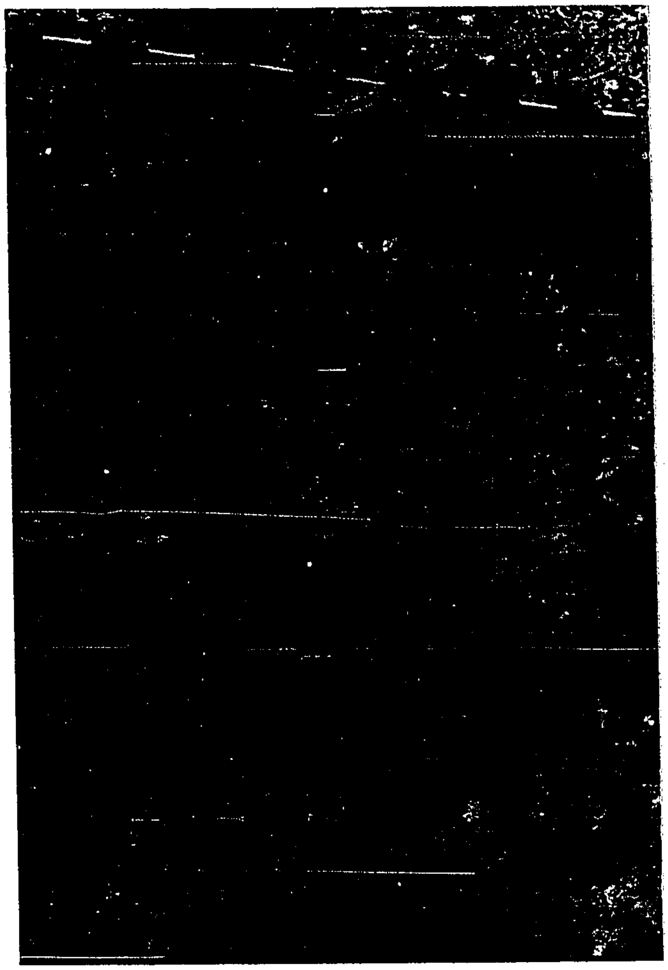


Figure 61C: Close-up view of the Oregonia Formation, Caesar Creek locality. Note the characteristic nodular bedding.

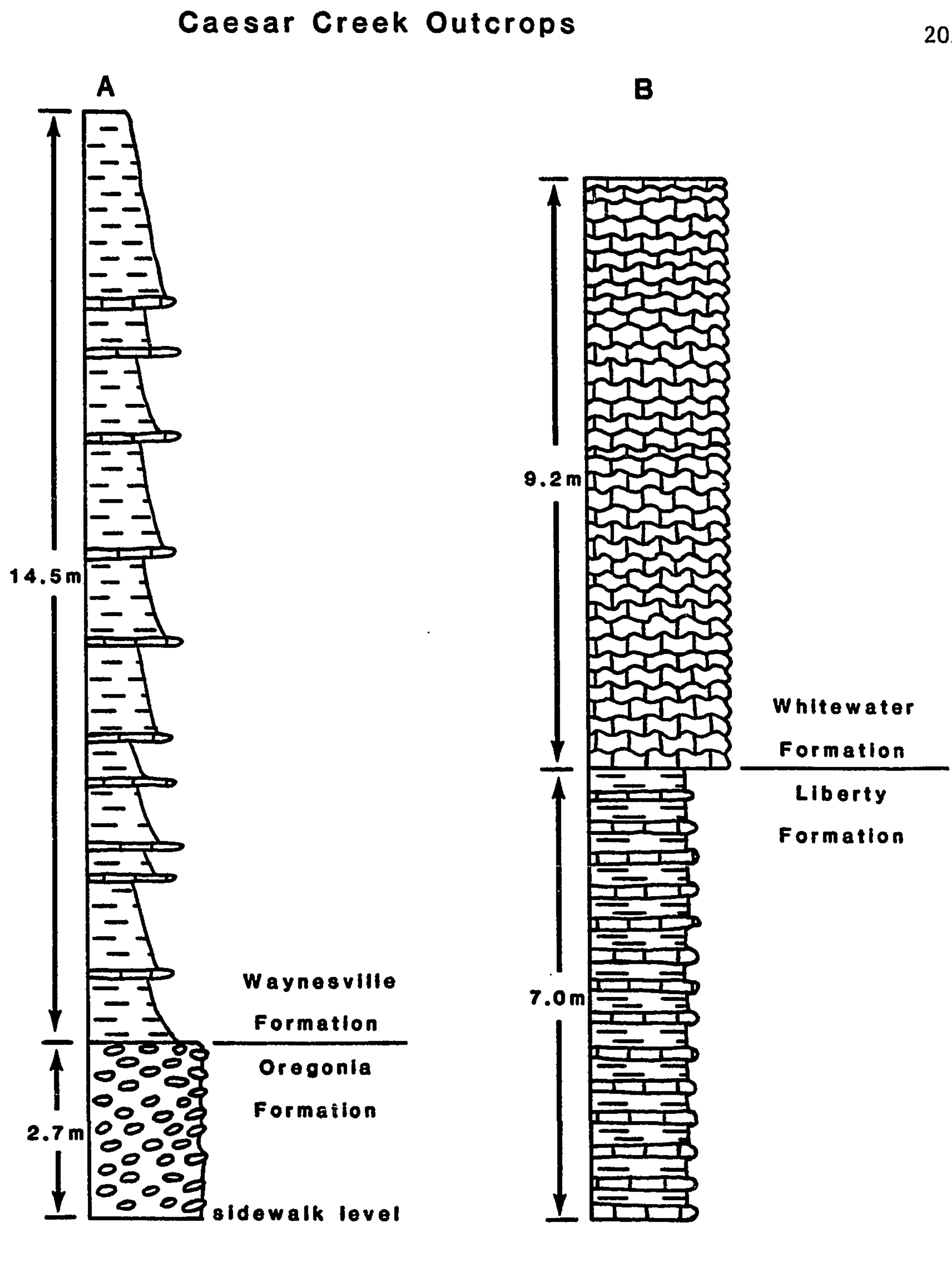


Figure 62: Caesar Creek outcrops.

In summary, previous workers have revised the stratigraphy of the middle third of the Cincinnatian Series without regard to the rules of priority established by the American Commission on Stratigraphic Nomenclature (1961), and without regard to the facies concept. Accordingly, four valid rock-stratigraphic units are herein proposed for future stratigraphic work on the Cincinnatian Series: the Corryville Formation, the Mt. Auburn Formation, the Sunset Formation, and the Oregonia Formation. This stratigraphic revision is believed to be more useful than previous revisions for the following reasons: (1) The reinstated names have priority, and are well known. (2) The newly defined units are laterally persistent throughout the field area. (3) These new formations are thinner, and are described in more detail than the thick, undifferentiated formations previously used. Hence, lateral trends and intertonguing relationships may now be accurately described. (4) All of the new formations introduced in this study represent contemporaneous ancient lithotopes, and therefore are genetically related. Thus, this new classification is more useful sedimentologically, because it conforms to the facies concept discussed earlier.

Sedimentology

The lowermost rock facies in this sequence is the *Corryville Formation*. This formation is thick (23 meters or 76 feet) and is composed of interbedded shales (64 percent) and carbonates (36 percent). Bedding is planar, moderately continuous, and moderately thick (averaging 8 cm). Shale beds are twice as thick as carbonate beds (10 cm vs. 5 cm). In addition, Corryville megacycles are thick and abundant (see Figure 43 and

Table 12). Sedimentary structures are also abundant and well preserved, including symmetric and asymmetric ripples, planar and cross lamination, tool marks, flute marks, gutter casts, rare ball and pillow structures (Stonelick Creek locality), and oriented fossils (aligned cephalopods, brachiopods, and crinoids--see Meyer et al., 1981--and imbricate brachiopods).

All eight of the "recurrent carbonate rock types" discussed earlier can be found in the Corryville Formation, but packstones and siltstones are most abundant. The percentages of each of these recurrent rock types follow: packstones (60 percent), wackestones (5 percent), micstones (2 percent), siltstones (13 percent), poorly washed grainstones (5 percent), coarse grainstones (5 percent), fine grainstones (7 percent), and calcisiltites (3 percent). The ratio of coarse grainstones to fine grainstones is low (0.71).

Shales in the Corryville Formation contain more silt than shales in the overlying units. Three of the four thin-section samples examined are mudstones. The "average" Corryville shale is a mudstone (QF_{39} CM_{42} CD_{19}) having a silt/clay ratio of 1.05 (the largest of any formation in the Cincinnatian Series) and a grain size of 28 microns.

The overlying *Mt. Auburn Formation* is a thin unit (5.1 meters) composed of nodular-bedded limestones (62 percent) and lumpy, fissile shales (38 percent). Three types of bedding exist: nodular bedding (73 percent), wavy bedding (8 percent), and planar bedding (19 percent). At the Middletown locality, the planar bedding occurs in a zone, 0.7 meters thick, in the middle of the formation. This planar-bedded zone is lithologically similar to the Sunset Formation, and may represent a lateral extension (tongue) of that unit (see Appendix 3). Overall, bedding is very discontinuous and thin (averaging only 4 cm). Limestones average 4 cm in thickness, and shales average 3 cm in thickness. Megacycles are absent in the Mt. Auburn Formation, and sedimentary structures are limited to planar and cross lamination, oriented fossils, and load structures.

Six of the eight "recurrent carbonate rock types" are present in the Mt. Auburn Formation, including packstones (39 percent), wackestones (27 percent), poorly washed grainstones (19 percent), coarse grainstones (9 percent), fine grainstones (5 percent), and calcisiltites (1 percent). The coarse grainstone to fine grainstone ratio is 0.67. About 35 percent of the packstones and wackestones are light gray, argillaceous or silty nodules which, upon microscopic examination, prove to be either (1) fine, silty or argillaceous grainstones, or (2) fine-grained (< 1 mm), silty or argillaceous packstones containing very well-sorted bioclast grains having a high degree of breakage (textural inversions). Most of the carbonate rocks in the Mt. Auburn Formation are phosphate rich. Phosphate, in the form of amorphous collophane, occurs as conodonts, as an internal pore filler (e.g., bryozoan zoecia, gastropod casts), and as a skeletal replacement feature (crinoid ossicles). Collophane is most abundant in limestones of the Mt. Auburn Formation, ranging from 1 to 52 percent of the rock volume, and averaging 12 percent.

Shales in the Mt. Auburn Formation are thin, fissile, discontinuous, and usually fossiliferous, impeding sample collection and thin section processing. Hence, shales were not examined microscopically. However, Krumpolz (1980, pp. 38-44) described three Mt. Auburn shale samples petrographically. According to his data (table 5, p. 41), the average

Mt. Auburn shale is a dolomitic claystone, having a composition of QF_{10} CM_{74} CD_{16}. These shales are very fossiliferous (16 percent bioclasts) and include a combination of fine-grained fragments (< 40 microns) and coarse-grained fragments (> 100 microns). The average silt/clay ratio is 0.14, and grain size averages 30 microns.

The overlying *Sunset Formation* is a medium-thick unit (13.5 meters or 44 feet) composed of interbedded limestones (48 percent) and shales (52 percent). Bedding is planar, moderately continuous, and medium thick (averaging 7 cm). In addition, shale beds are slightly thicker than limestone beds (8 cm vs. 6 cm). Sunset megacycles are slightly thinner than those in the Corryville Formation, averaging 1.02 meters in thickness. As in the Corryville Formation, sedimentary structures are abundant and occur in a variety of forms.

All eight of the "recurrent carbonate rock types" can be found in the Sunset Formation, but packstones dominate. The percentages of each of these recurrent rock types follow: packstones (60 percent); wackestones (5 percent), micstones (trace), siltstones (8 percent), poorly washed grainstones (8 percent), coarse grainstones (7 percent), fine grainstones (6 percent), and calcisiltites (6 percent). The ratio of coarse grainstones to fine grainstones is higher than that of the Corryville and Mt. Auburn formations (1.17).

Shales in the Sunset Formation are less silty than shales in the Corryville Formation. Although both of the shale thin sections examined are mudstones (QF_{41} CM_{59} CD_0), the silt/clay ratio is low, averaging 0.69. Average grain size is 41 microns.

The uppermost facies in this sequence, the *Oregonia Formation*, is a thin unit (7.3 meters) composed of nodular- and wavy-bedded limestones (56 percent) and thin, discontinuous, fissile shales (44 percent). Limestones and shales both average 4 cm in thickness. Overall, bedding is very discontinuous and thin (4 cm). As in the Mt. Auburn Formation, three types of bedding are present: nodular bedding (55 percent), wavy bedding (35 percent), and planar bedding (10 percent). Megacycles are absent in the Oregonia Formation, and sedimentary structures are limited to planar and cross lamination, ripples, and gutter casts.

All eight of the "recurrent carbonate rock types" are present in the Oregonia Formation, including packstones (36 percent), wackestones (9 percent), micstones (1 percent), siltstones (2 percent), poorly washed grainstones (8 percent), coarse grainstones (15 percent), fine grainstones (25 percent), and calcisiltites (4 percent). The coarse grainstone to fine grainstone ratio is low (0.60). About 30 percent of the packstones and wackestones in this facies are light gray, argillaceous or silty nodules similar to those described in the Mt. Auburn Formation. In addition, collophane content is high in Oregonia limestones, ranging from 4 to 28 percent, and averaging 11 percent.

As in the Mt. Auburn Formation, shales are thin, fissile, discontinuous, and usually fossiliferous, impeding sample collection and thin section processing. Thus, only one shale sample was examined in thin section: a mudstone having a composition of QF_{39} CM_{52} CD_9. The silt/clay ratio is nearly the same as that of the underlying Sunset Formation (0.74), and grain size is 27 microns.

In summary, the upward vertical succession of facies in the Corryville to Oregonia shoaling-upward sequence is reflected most strongly by the following trends: (1) a decrease in facies thickness, (2) a decrease in bedding thickness and lateral continuity, (3) a vertical change from planar bedding to nodular and wavy bedding, (4) a decrease in shale content, (5) a decrease in shale bedding thickness, (6) a decrease in the silt content of shales, (7) a decrease in siltstone content, and (8) an increase in the percentage of grainstones.

Paleontology

In situ limestones (packstones and wackestones) in the basal *Corryville Formation* contain a diverse, open-marine faunal assemblage dominated by bryozoans, brachiopods, trilobites, crinoids, gastropods, and pelecypods. Minor amounts of ostracods and conodonts also appear. These beds have an average generic diversity of 4.6 and a petrographic diversity of 6.3. Edrioasteroids, although rare in the Corryville Formation, are sometimes very abundant within a given stratum (Meyer et al., 1981).

The most common brachiopod genera in the Corryville Formation are *Rafinesquina* (*R. ponderosa* and *R. nasuta*), *Onniella*, and *Zygospira*. The first two genera have wide, thin, flat shells. Other, less common brachiopod genera are *Hebertella* and *Platystrophia* (*P. laticosta* mostly), which have large, inflated shells with coarse, detailed ornamentation. Bryozoans in the Corryville Formation are small and delicate. The most common genera (*Batostomella gracilis*, *Dekayia*, and *Chiloporella*) are small branching forms with smooth surfaces. Another common bryozoan, *Hallopora ramosa*, is a branching form having high, sharp monticules or monticules fused into ridges. Rare examples of *Monticulipora*, a large mound-shaped bryozoan, occur near the base of the formation, but are common at some locations in the middle of the formation. Other typical Corryville fossils include the gastropods *Cyclora*, *Loxoplocus bowdeni*, and *Cyclonema* (*C. humerosum* and *C. simulans*), the pelecypod *Ambonychia*, and the trilobite *Flexicalymene*. In addition, several examples of well-preserved echinoderm-Lagerstatten have been discovered in the Corryville Formation (Meyer et al., 1981). All body fossils are unabraded and well preserved.

Trace fossils are abundant in the Corryville Formation, and include the following varieties: *Chondrites*, color mottling, vertical tubes (possibly escape structures), *Trichophycus*, *Paleophycus*, *Diplocraterion*, and gastropod trails. These trace fossils belong primarily to the *Cruziana* ichnofacies.

In situ limestones (packstones, some poorly washed grainstones and coarse grainstones) in the overlying *Mt. Auburn Formation* also contain a diverse, open-marine faunal assemblage. Dominant fossils include brachiopods, bryozoans, trilobites, pelecypods, crinoids, and gastropods. Secondary amounts of ostracods and conodonts also exist. These beds have a slightly higher generic diversity (4.8) and petrographic diversity (6.8) than the underlying Corryville Formation.

The most common brachiopod genera in the Mt. Auburn Formation are *Rafinesquina*, *Zygospira*, and *Platystrophia* (*P. ponderosa* var. *auburnensis*). Other genera include *Hebertella*, *Onniella*, and *Leptaena*. *Platystrophia* and *Hebertella* are inflated, thick-shelled, highly ornamented brachiopods, whereas *Rafinesquina* and *Onniella* are flat, thin-shelled forms with delicate ornamentation. The most common bryozoan genus is *Homotrypa*, a larger, more robust organism than those in the underlying Corryville Formation. Other typical fossils are the gastropods *Cyclora*, *Cyclonema*, and *Lophospira*.

Although body fossils in the Mt. Auburn Formation exhibit a variety of preservational states, abrasion, boring, and encrustation effects are high. For example, specimens of the brachiopod *Platystrophia ponderosa* are occasionally preserved whole and unabraded. However, Krumpolz (1980) has shown that *P. ponderosa* is most commonly preserved as disarticulated valves showing some degree of abrasion (ranging from the simple abrasion of growth lines to the total abrasion of growth lines and plications). Furthermore, Meyer et al. (1981, fig. 36) show that highly abraded and bored shells of *P. ponderosa* occur within a thin zone near the top of the Mt. Auburn Formation at the Blue Rock Road locality (see Appendix 3). Encrustation is another common feature of Mt. Auburn fossils. Analysis of epizoans on *P. ponderosa* reveal frequent bryozoan encrustation overlapping the commissure of articulated specimens (Krumpolz, 1980).

Trace fossils are abundant in the Mt. Auburn Formation. The following varieties are known to exist: *Chondrites*, *Trichophycus*, *Paleophycus*, vertical tubes, color mottling, and possible hardgrounds (the tops of a few limestones beds exhibit a red-to-black stain, in addition to some possible biogenic borings; see Rassman, 1981, for a discussion of probable Cincinnatian hardgrounds). In addition, Krumpolz (1980, p. 20) has described a wackestone horizon near the base of the Mt. Auburn Formation from which symmetrical, cone-shaped structures (oriented apex-down) protrude into the underlying shale (see Figure 63). Krumpolz noted that these unknown structures extend from 2-8 cm below the bed and are composed of jumbled fossil fragments. Krumpolz concluded that these structures ". . . represent the filling of some sort of excavation of an organism." I have located and examined these structures at the Blue Rock Road and

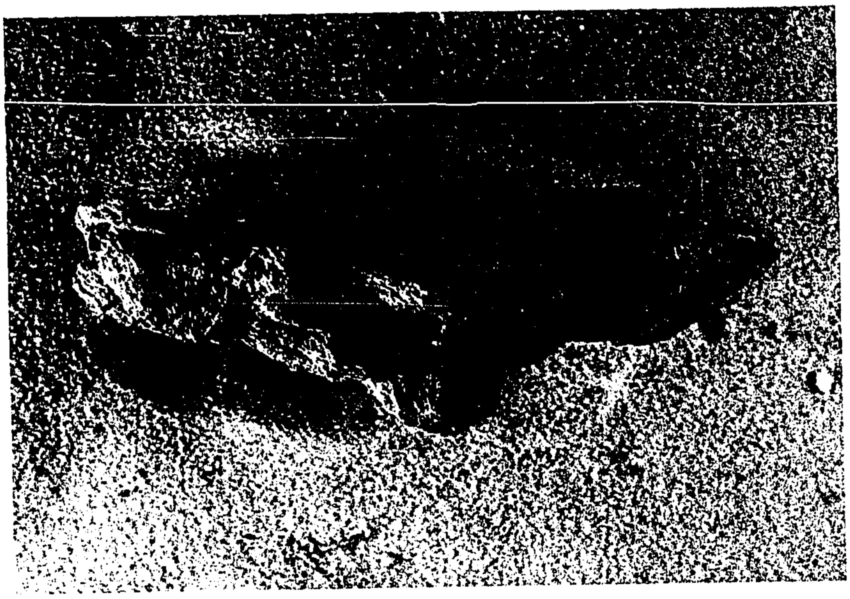


Figure 63: Conical trace fossils in the Mt. Auburn Formation (sample taken from the Blue Rock Road locality).

Middletown localities, and have also noted that in about 30 percent of the cases, *two* closely spaced, downward pointing cones are present. Usually, one of the cones is about twice as large as the other. I agree with Krumpolz' conclusion that these structures are biogenic in origin. These structures may in fact represent the resting traces or dwelling traces of sea anemones. The abundance of double cones may represent clustering or perhaps the close association of a juvenile (small cone) and an adult (large cone). Frey (1970) described recent anemone burrows (*Paranthus rapiformis*) in shallow water off the coast of North Carolina (slightly above the low tide mark). These burrows are similar to those found in the Mt. Auburn Formation. They have a conical shape (7-8 cm long), and have either a blunt or tapered end. Ancient examples of conical structures produced by anemones are *Bergaueria perata* (Moore, 1962, pp. 186-187; Ordovician) and *Kulindrichnus langi* (Hallam, 1960; Jurassic).

In situ limestones in the overlying *Sunset Formation* also contain a diverse, open-marine assemblage of fossils dominated by brachiopods, bryozoans, trilobites, crinoids, gastropods, and pelecypods. Secondary amounts of ostracods, conodonts, and graptolites are also present. These beds have an average generic diversity of 5.3 and a petrographic diversity of 6.5.

The most common brachiopod genera in the Sunset Formation are *Zygospira* and *Rafinesquina*. A dramatic change in the shell morphology of *Rafinesquina* occurs within this unit. Limestones in the bottom half of the Sunset Formation contain flat specimens of *Rafinesquina*, whereas limestones in the upper half of the formation contain "concavo-convex" (slightly curved) and "geniculate" (highly curved) specimens. [Note: According to Alexander (1975), the curvature of *Rafinesquina* is a morphologic adaptation to high sedimentation rates. However, Alexander also demonstrated with flume experiments that the "concavo-convex" and "geniculate" geometries are hydraulically more stable than the "flat" geometry. Hence, they may also represent an adaptaion to turbulent-water environments.] Less common brachiopod genera in the Sunset Formation include *Strophomena*, *Onniella*, *Leptaena*, and *Trematis*. Rare examples of *Platystrophia cypha* occur near the top of the formation. The dominant bryozoan genus in the Sunset Formation is *Homotrypa*, a larger, more robust form than those in the Corryville Formation. Other typical Sunset fossils include the trilobite *Flexicalymene*, and the gastropods *Cyclora* and *Cyclonema* (*C. bilix lata*). Body fossils in the Sunset Formation are generally well preserved.

Trace fossils are very common in the Sunset Formation, and include the following varieties: *Rhizocorallium*, *Diplocraterion*, vertical tubes, color mottling, *Trichophycus*, *Chondrites*, and horizontal gastropod trails. These trace fossils represent a mixed *Skolithos/Cruziana* ichnofacies.

In situ limestones in the uppermost facies, the *Oregonia Formation* also contain a diverse, open-marine assemblage of fossils dominated by brachiopods, trilobites, gastropods, pelecypods, bryozoans, crinoids, and ostracods. Gastropods, pelecypods, and ostracods are more abundant in this formation than in the underlying units. Minor amounts of scolecodonts and conodonts are also present. These beds have the highest average generic diversity (6.1) and petrographic diversity (6.7) in the entire shoaling-upward sequence.

The most common brachiopod genera include *Zygospira*, *Rafinesquina*, *Leptaena*, and *Retrorsirostra carleyi*. The last two genera have coarse, well-defined ornamentation, and *R. carleyi* is inflated. Furthermore, *Rafinesquina* specimens exhibit the "geniculate" geometry previously discussed. Occasional specimens of *Onniella* are also present. Other typical Oregonia fossils include the trilobites *Flexicalymene* and *Isotellus*, the gastropod *Cyclora*, and the pelecypods *Ambonychia* and *Modiolopsis*. Bryozoan encrustation, boring, and shell abrasion is commonplace in the Oregonia Formation.

Trace fossils in the Oregonia Formation include *Diplocraterion*, unknown vertical and inclined tubes, rare unnamed conical structures (similar to those in the Mt. Auburn Formation), *Chondrites*, *Paleophycus*, and *Trichophycus*. Again, this assemblage represents a mixed *Skolithos/Cruziana* ichnofacies.

In summary, both the body fossils and trace fossils characteristic of the Corryville to Oregonia shoaling-upward sequence are very abundant and highly diverse. However, the upward vertical succession of rock facies is accompanied by several faunal changes, including (1) an increase in faunal diversity; (2) an increase in the amount of abrasion, boring, and encrustation of shells; (3) an upward change from a dominantly *Cruziana* ichnofacies to a mixed *Skolithos/Cruziana* ichnofacies; (4) an upward change from small, thin, delicate fossils to larger, thicker, more robust fossils, (5) an upward morphological change in the brachiopod genus *Rafinesquina* from flat shells to "geniculate" shells, and (6) a slight increase in the amount of gastropods, pelecypods, and ostracods. These vertical trends are summarized in Table 15.

Interpretation

Following the deposition and progradation of the underlying Kope to Bellevue sequence, a major, rapid transgression of the Ordovician sea

FORMATION	DIVERSITY		DOMINANT FOSSIL ASSEMBLAGE	BRACHIOPOD MORPHOLOGY	BRYOZOAN MORPHOLOGY	FOSSIL PRESERVATION	ICHNO-FACIES
	Generic	Petro-graphic					
OREGONIA	6.1	6.7	brachiopods trilobites gastropods pelecypods bryozoans crinoids ostracods (open marine)	Coarse, rounded, thick shells with coarse ornamentation (Retrorsirostra) Smaller, flat shells (Rafinesquina, Leptaena); Rafinesquina is curved.	Mostly encrusting	Bryozoan encrustation, boring, and abrasion are common	Skolithos
SUNSET	5.3	6.5	brachiopods bryozoans trilobites crinoids gastropods pelecypods (open marine)	Mixture of types (Rafinesquina, Zygospira, Strophomena, Onniella, Leptaena, Trematis, Platystrophia); upward increase in curvature of Rafinesquina shells	Large, robust branching forms (Homotrypa)	Well preserved	Mixed Skolithos/ Cruziana
MT. AUBURN	4.8	6.8	brachiopods bryozoans trilobites pelecypods crinoids gastropods (open-marine)	Large, rounded, thick shells with coarse ornamentation (Platystrophia, Hebertella) Some flat, thin-shelled forms (Rafinesquina, Onniella, Leptaena)	Large, robust branching forms (Homotrypa)	High degree of abrasion, micritization, boring, and bryozoan encrustation	Mixed Skolithos/ Cruziana
CORRYVILLE	4.6	6.3	bryozoans brachiopods trilobites crinoids gastropods pelecypods (open marine)	Small, thin-shelled, flat, and finely ornamented (Onniella, Rafinesquina) Rare, large, rounded shells (Platystrophia, Hebertella)	Small, delicate, branching forms (Batostomella, Chiloporella, Dekayia) Rare massive forms (Monticulipora)	Well preserved	Cruziana

Table 15: Autecological comparison of rock facies in the Corryville to Oregonia shoaling-upward sequence.

occurred. This event is marked by the sharp unconformable contact between the Bellevue Limestone (a shallow-water facies) and the overlying Corryville Formation (a deeper water facies). The subsequent renewal of carbonate and shale sedimentation at this time resulted in the deposition of the Corryville to Oregonia sequence. The facies in this sequence are believed to represent deposition on the inner part of a gently sloping ramp, primarily in the transition zone to upper shoreface setting.

The Corryville to Oregonia sequence represents a typical shoaling-upward shelf cycle containing facies A, B, and C of the "idealized" model (see Figure 47). Facies A is represented by the *Corryville Formation*. I believe that this facies was deposited in the lower transition zone to upper offshore position for several reasons: (1) The relative abundance of shale (64 percent), the relatively high silt content and thickness of shale beds, and the relative abundance of siltstones (13 percent) all indicate low-energy deposition, mostly below wave base. (2) The excellent preservation of sedimentary structures and trace fossils indicates a low level of wave erosion. (3) The dominant carbonate rock type in this facies is a packstone (60 percent), suggesting deposition below wave base in quiet water. (4) Most of the body fossils in this facies are small and fragile, suggesting that these organisms lived in a protected, low-energy environment, mostly below wave base. (5) The lack of abrasion, boring, and micritization of fossils suggests a deeper shelf setting. (6) Trace fossils mostly belong to the *Cruziana* ichnofacies, representative of shallow shelf environments.

Facies B of this sequence is represented by the *Sunset Formation*. I believe that this facies was deposited in shallower water than the

Corryville Formation, probably in the transition zone to lower shoreface position. The following vertical trends suggest that Sunset sediments accumulated in shallower water than Corryville sediments: (1) the relative decrease in shale content (52 percent) and siltstone content (8 percent); (2) the lower silt content and bedding thickness of shales; (3) the change from a dominantly *Cruziana* trace fossil assemblage to a mixed *Skolithos/ Cruziana* assemblage; (4) the relative increase in grainstone content (27 percent vs. 20 percent); (5) the relative increase in larger, more robust fossils; and (6) the morphologic change in the brachiopod *Rafinesquina* from flat shells (in the Corryville and lower Sunset formations) to "geniculate" shells (in the upper Sunset Formation).

Facies C of this sequence is represented by the *Mt. Auburn Formation* and the *Oregonia Formation*. Both formations represent deposition in the shoreface zone (probably upper shoreface). High-energy shoreface deposition is indicated by the following data: (1) The relatively low shale content in both formations suggests high-energy deposition above wave base (37 percent in the Mt. Auburn Formation and 44 percent in the Oregonia Formation). (2) Trace fossils are a mixture of the *Skolithos* and *Cruziana* ichnofacies, suggestive of an inner shelf setting. (3) Both formations contain conical structures which are possibly the resting or dwelling traces of sea anemones. As mentioned earlier, modern sea anemones burrow in the intertidal zone. (4) The higher percentage of grainstones in these two facies (34 percent in the Mt. Auburn Formation and 52 percent in the Oregonia Formation) plus the abundance of textural inversions suggest high wave energy. (5) The presence of nodular bedding in both formations suggests shallow subtidal to intertidal conditions. This type of bedding is very similar to the "lenticular bedding with isolated lenses" described by Reineck and Wunderlich (1968b). Such bedding is believed to originate in shallow-water environments where the supply of (carbonate) sand is low. In such cases, thin layers of carbonate sand are reworked by waves and currents into the form of incomplete or isolated ripples ("starved ripples") on a pre-existing shale substrate. These isolated ripples are subsequently covered by another layer of shale, preserving them as "lenses" or "nodules." Repetition of this process produced the characteristic nodular bedding of both formations. Furthermore, uneven compaction of sediments may have contributed to the rounded, ovoid shape of these carbonate nodules (see McCrossan, 1958). (6) Most of the body fossils in these two formations are large, robust forms capable of withstanding a high degree of water turbulence. (7) The abundance of abrasion, boring, and encrustation of shells indicates a turbulent, shallow-water environment in which shell material was exposed to varying amounts of reworking, degradation, and encrustation for a considerable length of time before final burial. (8) The abundance of phosphate (collophane) suggests a shallow-water environment having low sedimentation rates and abundant bioturbation.

The Mt. Auburn and Oregonia facies probably represent shallow-water carbonate shoals which were flanked by deeper water, muddy-bottom subtidal environments into which shell material was periodically deposited. The "Oregonia shoal" was most likely a broad zone shoreward of the Sunset lithotope, whereas the "Mt. Auburn shoal" was probably a series discontinuous, isolated offshore bars seaward of the Sunset lithotope (see Figure 64).

Although the Kope to Bellevue and Corryville to Oregonia sequences are similar in appearance and were both deposited in similar environmental

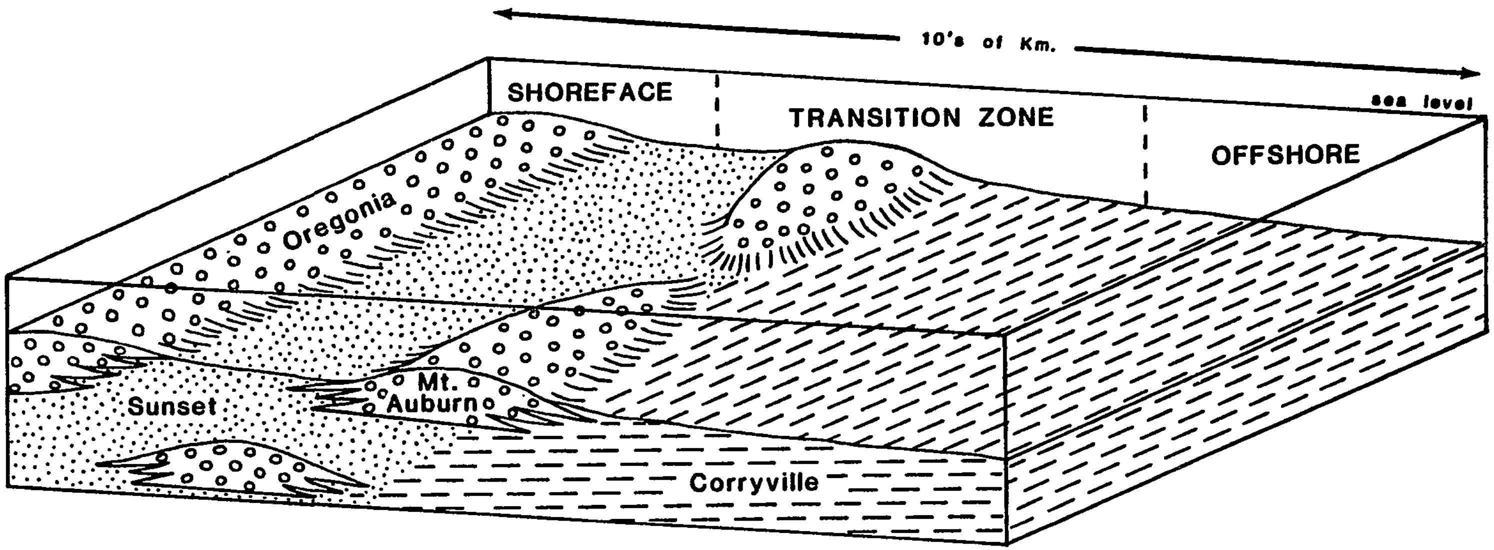


Figure 64: Interpretation of the Corryville, Mt. Auburn, Sunset, and Oregonia lithotopes. Vertical scale is highly exaggerated.

settings, several fundamental differences exist. First, the Corryville to Oregonia sequence was probably deposited in slightly shallower water than the Kope to Bellevue sequence. This conclusion is supported by the following observations: (1) The Corryville to Oregonia sequence is about half as thick as the Kope to Bellevue sequence. (2) It contains less shale, but more grainstones than the Kope to Bellevue sequence. (3) The degree of fossil abrasion is higher in the Mt. Auburn and Oregonia formations than it is in the Bellevue Limestone. (4) *Skolithos* trace fossils are more abundant in the Corryville to Oregonia sequence. (5) Possible sea anemone burrows are present in the Corryville to Oregonia sequence, suggestive of shallow subtidal to intertidal conditions.

The second major difference between these two sequences is that the process of gravity-induced transportation of fine-grained material downslope was apparently not as efficient during Corryville to Oregonia time as it was during Kope to Bellevue time. The relative abundance of fine-grained carbonates and shales in facies C of the Corryville to Oregonia sequence indicates that fine-grained sediments were retained closer to shore.

Finally, the sea floor may have been steeper during Kope to Bellevue time than it was during Corryville to Oregonia time. This conclusion is supported by the following evidence: (1) Fine-grained carbonates are concentrated in facies C of the Corryville to Oregonia sequence (i.e., closer to shore), suggesting that the sea floor was not inclined enough to enable gravity flows to transport sediment downslope. (2) Convolute lamination is found only in the Kope to Bellevue sequence. (3) Ball and pillow structures commonly occur in the upper Kope and Fairview formations along the eastern edge of the outcrop belt, but are present at only one locality (Stonelick Creek) in the Corryville Formation. (4) The lithologic differences (i.e., shale content, bedding thickness, rock types, etc.) between facies A and facies B are much greater in the Kope to Bellevue sequence. Because these differences are largely controlled by bathymetry, the difference in water depth (and hence, slope) was probably much greater between the Kope and Fairview lithotopes than it was between the Corryville and Sunset lithotopes.

Regional Comparison

A fairly detailed regional comparison was made for three of the four formations in this sequence. The lowermost unit, the Corryville Formation, is exposed in three areas: in Indiana (Brookville Dam), in the Cincinnati area (Blue Rock Road, Middletown, and Rumpke Landfill localities), and at the Georgetown, Ohio, locality. Four west-to-east lithologic trends were detected: (1) Shale content decreases toward the east (67 percent at Brookville, 57 percent in the Cincinnati area, and 45 percent at Georgetown). (2) Average shale bedding thickness decreases to the east (17 cm at Brookville, 7 cm in the Cincinnati area, and 6 cm at Georgetown). (3) Although the percentages of packstones and grainstones are nearly equal in the Brookville and Cincinnati areas, grainstones are more abundant (32 percent vs. 11 percent), and packstones are less abundant (38 percent vs. 64 percent) in the Georgetown area. (4) The proportion of inflated, thick-shelled brachiopods (*Hebertella* and *Platystrophia*) to flat, thin-shelled brachiopods (*Onniella* and *Rafinesquina*) increases to the east.

The Sunset Formation is exposed in the Brookville, Indiana, area (Brookville Dam), and in the Cincinnati area (Aiken High School, Blue Rock

Road, Middletown, and Rumpke Landfill localities). Five lithologic trends were observed in this unit: (1) Shale content decreases toward the east (from 52 percent to 45 percent). (2) Average shale bedding thickness decreases to the east (from 7 cm to 6 cm). (3) Grainstones increase toward the east (38 percent vs. 18 percent) while packstones decrease toward the east (50 percent vs. 69 percent). (4) The inflated, thick-shelled brachiopod *Platystrophia* is present only in the Cincinnati area. (5) Possible hardground surfaces are more common in the Cincinnati area.

Finally, the characteristics of the Oregonia Formation in the Brookville, Indiana, area (Brookville Dam) and at the Caesar Creek locality (50 miles to the east) were compared. Four lithologic trends were detected: (1) Shale content decreases toward the east (from 44 percent to 34 percent). (2) Average shale bedding thickness decreases to the east (from 4 cm to 3 cm). (3) Average limestone bedding thickness increases to the east (from 4 cm to 5 cm). (4) The inflated, thick-shelled brachiopod *Platystrophia* is present only at Caesar Creek.

In summary, four common west-to-east lithologic trends were detected in the Corryville to Oregonia sequence, including (1) a decrease in shale content, (2) a decrease in average shale bedding thickness, (3) an increase in the amount of grainstones, and (4) a change from flat, thin-shelled brachiopods to inflated, thick-shelled brachiopods. In addition, hardground surfaces and the Mt. Auburn lithofacies are absent toward the west. These trends indicate that deposition occurred in slightly shallower, more turbulent environments in the eastern part of the field area than in the west, and may reflect a gradual lowering of sea level as lithofacies prograded eastward across the shallow carbonate ramp.

Waynesville to Saluda Sequence

Stratigraphy

Unconformably overlying the Corryville to Oregonia sequence is a thicker sequence of strata composed of four rock facies which roughly correspond to the following traditional biostratigraphic units: "Waynesville," "Liberty," "Whitewater," and "Saluda" (see Figure 4). As mentioned earlier, previous lithostratigraphers have ignored these "traditional" units in favor of thick, undifferentiated formations such as the Dillsboro Formation (Brown and Lineback, 1966), the Tanner's Creek Formation (Hatfield, 1968), and the Bull Fork Formation (Peck, 1966).

Because the traditional biostratigraphic divisions of this sequence have distinctive lithologies which can be correlated laterally and recognized in the original descriptions, they are herein reinstated as valid rock-stratigraphic units. In this section, the following names are proposed for four lithogenetically related rock facies (from bottom to top): the *Waynesville Formation*, the *Liberty Formation*, the *Whitewater Formation*, and the *Saluda Formation*. The uppermost facies in this sequence, the Saluda Formation, occurs only in southeastern Indiana. This unit may be laterally equivalent to the *Elkhorn Formation* (Cumings, 1908), and/or the *Preachersville Member* of the *Drakes Formation* (Weir, Greene, and Simmons, 1965). Each unit will be described using modern terminology and redefined in accordance with the rules of the Code of Stratigraphic Nomenclature.

The lowermost facies in this sequence is the *Waynesville Formation*. The "Waynesville or *Bythopora meeki* Beds" were named after the town of

Waynesville, Ohio, by Nickles (1903). Nickles' original description (pp. 205-206) follows:

> They contain some good limestone layers, two to five inches thick, suitable for ordinary building purposes, and a large amount of clay and clay shale . . . . The thickness of this division is about fifty feet. The clay is often of an intense blue, or greenish blue color. The limestones are rather of a dove color than blue, though there is considerable variation in the matter of color.

Nickles has adequately described a 50-foot-thick, shale-rich facies composed of interbedded dove-gray limestones and greenish-blue shales. Although this description is incomplete by modern standards, Nickles' "Waynesville Beds" can be easily distinguished from the underlying nodular-bedded Oregonia Formation, and hence, should be considered as a valid rock-stratigraphic unit. Lee (1974) was the first to recognize that this interval has its own lithologic identity, and proposed that the Waynesville facies be considered a member of the Bull Fork Formation. Similarly, Hay et al. (1981) have proposed that the term "Waynesville Shale Member" (of the "Brookville Formation") be accepted for usage as a lithostratigraphic mapping unit. However, I disagree with both proposals for two reasons: (1) The Waynesville facies meets all the requirements of the Code of Stratigraphic Nomenclature for *formational* status (i.e., distinctive lithologic characteristics, internal lithologic homogeneity, mappability, usefulness in interpretation). (2) The "Brookville Formation" and the "Bull Fork Formation" are thick, undifferentiated units composed of at least six different rock facies. Because they lack the "degree of internal lithologic homogeneity" required by the Code (Article 6a), they should not be considered as valid formations.

Accordingly, the Waynesville Formation is herein proposed as a new lithostratigraphic unit. The Waynesville Formation is a thick-bedded, shale-rich facies (67 percent) composed of thin (5 cm), widely spaced, planar-bedded limestones and thick (11 cm), flaggy shale interbeds. The dominant limestones are mud rich (packstones and wackestones) and contain a thin-shelled, open-marine fauna. Shale beds are dominantly composed of dolomitic mudstone. The Waynesville Formation is the thickest unit in this sequence, reaching a maximum of 36 meters (118 feet) in the Brookville, Indiana, area. Figure 65 is a typical outcrop exposure of the Waynesville Formation.

The upper and lower contacts of the Waynesville Formation were not defined by Nickles. Thus, in accordance with modern stratigraphic procedures, the lower contact of the Waynesville Formation is herein defined as the lowermost extent of its characteristic shale-rich, planar-bedded strata. This contact is marked by the abrupt vertical transition from the nodular bedding of the underlying Oregonia Formation to the planar bedding of the Waynesville Formation (see Appendix 3, Brookville Dam). This contact is quite noticeable on weathered outcrops because the abrupt increase in shale content produces a distinct break in slope. Similarly, the upper contact of the Waynesville Formation is defined as the uppermost extent of its shale-rich, planar-bedded strata. This contact is marked by the first (lowermost) appearance of the shale-poor, planar-bedded strata of the overlying Liberty Formation.

Nickles (1903) did not define a specific type section for the Waynesville Formation. However, he did refer to Waynesville, Ohio, as a representative area. The only complete exposure of the Waynesville Formation at the present time is the Brookville Dam locality (see Appendix 3). Perhaps this outcrop should serve as a new type section for future study. Additional reference sections may be found at the Caesar Creek locality (see Figure 62) and on roadcuts along Ohio Rt. 42, north of Waynesville, Ohio.

The Waynesville Formation is overlain by a thinner sequence of strata herein referred to as the *Liberty Formation*. Nickles (1903, p. 207) originally described the "Liberty or *Strophomena planumbona* Beds" from exposures near Liberty, Indiana:

> The strata of this subdivision consist of even-bedded limestones averaging three inches in thickness, prevailingly blue in color, with clayey and shaley layers intervening, which are also usually blue in color . . . . The thickness of this subdivision is about thirty-five feet.

Again, such a lithologic description is poor by modern standards, but is adequate for distinguishing this facies from those above and below. Nickles has described a 35-foot-thick sequence of interbedded limestone and shale in which limestones, averaging three inches in thickness (7.6 cm), predominate. Although most lithostratigraphers in the past have ignored this lithofacies, Hay et al. (1981) have recognized that it has a characteristic lithology, and have proposed that the Liberty facies be designated as a member of the "Brookville Formation." However, the same argument for raising the Waynesville facies to formational status also applies to the Liberty facies.

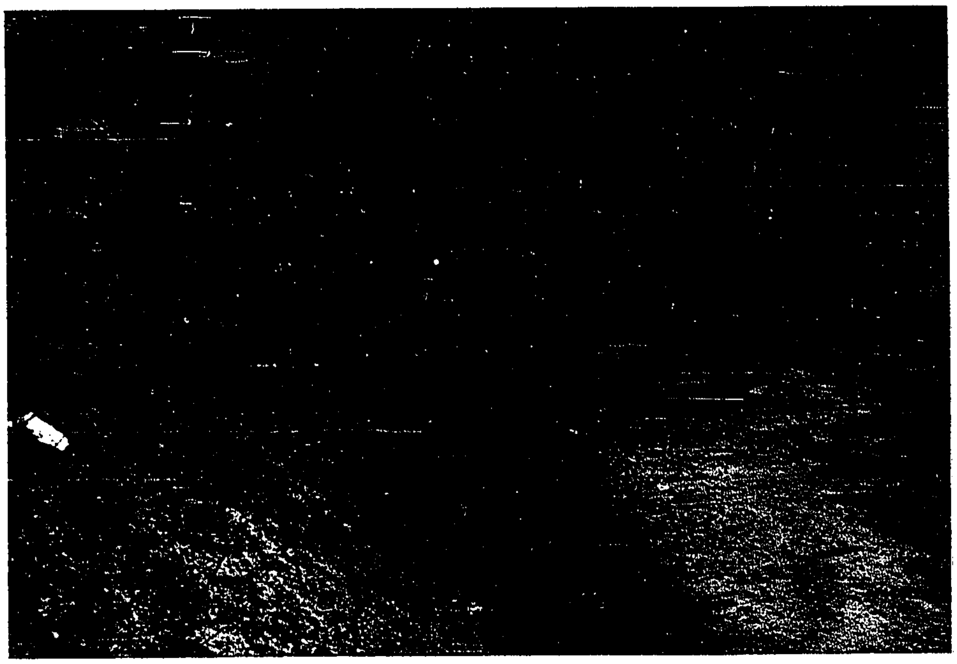
Therefore, the Liberty Formation is herein proposed as a new rock-stratigraphic unit which occurs in Ohio and Indiana. The Liberty Formation is a medium- to thick-bedded facies composed of closely spaced, planar-bedded limestones (55 percent) and shales (45 percent). Limestone beds are thicker than those in the Waynesville Formation (8 cm) and shales are thinner (8 cm). The most abundant limestone types are packstones and grainstones, containing an open-marine fossil assemblage. Shale beds are dominantly composed of dolomitic mudstone. The Liberty Formation is thinner than the Waynesville Formation, reaching a total thickness of 19 meters (62 feet) in the Brookville, Indiana, area. Figure 66 is a typical outcrop exposure of the Liberty Formation.

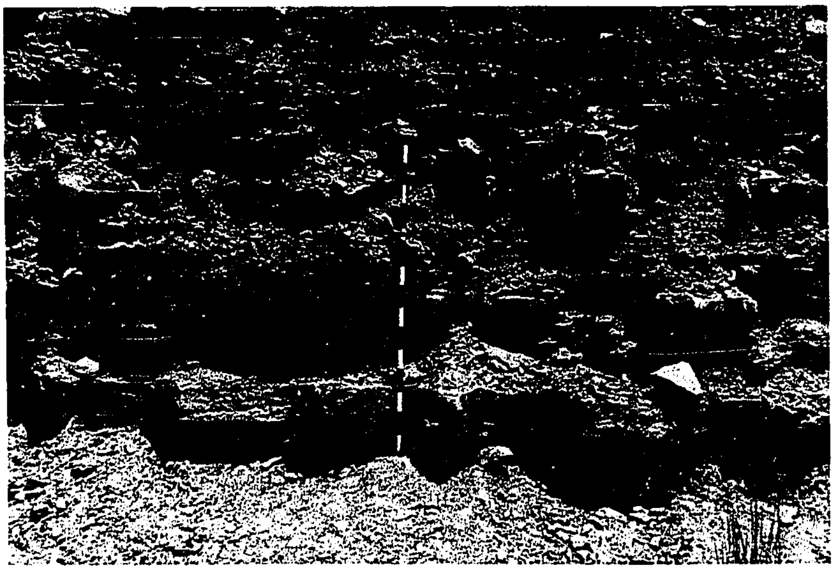
Because the boundaries of the Liberty Formation were not described by Nickles (1903), they are herein defined as the uppermost and lowermost extent of the planar-bedded, mixed carbonate and shale strata characteristic of the Liberty facies. The lower contact coincides with the newly defined upper Waynesville contact and is easily distinguished by the first appearance of thick, closely spaced limestone beds (see Appendix 3) In profile, it appears as a distinct break in slope (see Figure 65). The upper contact of the Liberty Formation is marked by the first appearance of the thin, wavy-bedded strata of the overlying Whitewater Formation. In the Brookville, Indiana, region, the Liberty Formation is directly overlain by thick-bedded, poorly fossiliferous, dolomitic wackestones of the Saluda Formation. In such cases, the upper contact of the Liberty Formation is instead marked by the first appearance of Saluda rocks.

Nickles (1903) did not define a specific type section for the Liberty Formation. However, he did refer to the following exposures as representative sections: Silver Creek in Liberty, Indiana; the Whitewater River south of Richmond, Indiana; the Dayton, Ohio area; and Cowan's Creek in Clinton County, Ohio. At the present time, the best exposures of the Liberty Formation may be found at the Brookville Dam, Brookville North, and Caesar Creek localities (see Appendix 3 and Figure 62). Although no complete, uninterrupted exposure of the Liberty Formation is known to exist,

Figure 65: Field exposure of the Waynesville Formation, Brookville Dam locality. The Waynesville-Liberty contact occurs at the break in slope near the top of the hill (photo courtesy of Paul E. Potter).

Figure 66: Field exposure of the Liberty Formation, Brookville North locality. Note the characteristic thick, planar limestone beds.





the Brookville Dam and Brookville North localities together expose the entire formation. Perhaps these two outcrops should serve as a composite type section for this new formation.

The Liberty Formation is overlain by the third lithofacies in this sequence, the *Whitewater Formation*. The "Whitewater or *Homotrypa wortheni* Beds" were originally described from exposures along the banks of the Whitewater River in Richmond, Indiana, by Nickles (1903, p. 208):

> In this division the strata usually present a roughish, concretionary, nodular appearance, both the limestone and the shale. The color is usually brownish or yellowish, though at some localities bluish. The limestone layers, often more or less impure, are seldom over two inches thick and generally less. The thickness of this division is from forty-five to fifty feet.

Again, Nickles has adequately described a 50-foot-thick sequence of thin (< 5 cm), irregularly bedded (nodular-to-wavy), argillaceous limestones and shales. Nickles' description can easily be used to identify the Whitewater Formation in outcrop. Accordingly, Brown and Lineback (1966), Hatfield (1968), and Hay et al. (1981) have reinstated the name "Whitewater Formation" in a rock-stratigraphic sense, although there appears to be little agreement about the upper and lower contacts of the unit. I have observed that the Whitewater Formation directly overlies rocks of the Liberty Formation at the Madison, Indiana, and Caesar Creek localities as well as rocks of *part* of the Saluda Formation (at the Brookville North locality). This intertonguing relationship has been previously described by Caster, Dalvé, and Pope (1961) and Fox (1962). In order to avoid confusion over the exact nature of the upper and lower boundaries of this formation, I propose that they be redefined as the uppermost and lowermost extent of the thin, limestone-rich, wavy-bedded strata typical of the Whitewater Formation, regardless of contiguous formations. Good exposures of the Whitewater Formation may be observed at the Richmond and Madison localities in Indiana (see Figure 1), at the Caesar Creek locality in Ohio (see Figure 62), and at the Cowan Lake Spillway section of Lee (1974).

The Whitewater Formation is the thinnest facies in this sequence, reaching a maximum of 11 meters (36 feet) in Indiana. It is composed of thin (4 cm), discontinuous, wavy-bedded limestones (86 percent) and thin (2 cm), fissile shales (14 percent). Grainstone is the dominant carbonate rock type (83 percent). Shales are thin, fissile, and silt poor. Figure 67 is a typical outcrop exposure of the Whitewater Formation.

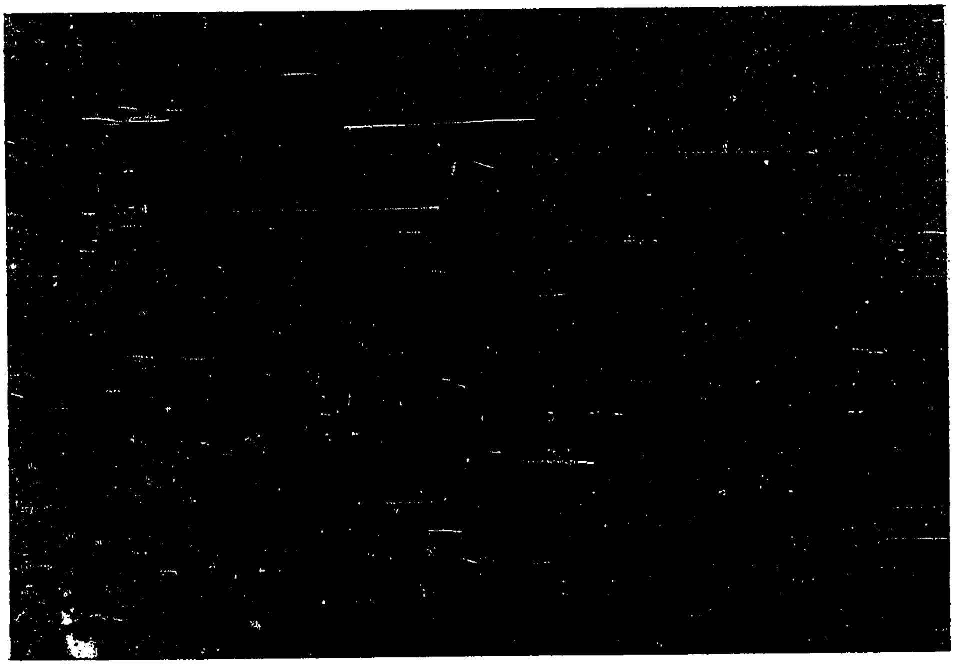
The uppermost unit in this sequence is represented by three different lithofacies: the Saluda Formation (Indiana), the Elkhorn Formation (between Richmond, Indiana, and Cincinnati), and the Preachersville Member of the Drakes Formation (along the eastern edge of the outcrop belt in Ohio). The *Saluda Formation* or "Upper Richmond Bed" was originally described by Foerste (1903, pp. 342-343) in a lithologic sense:

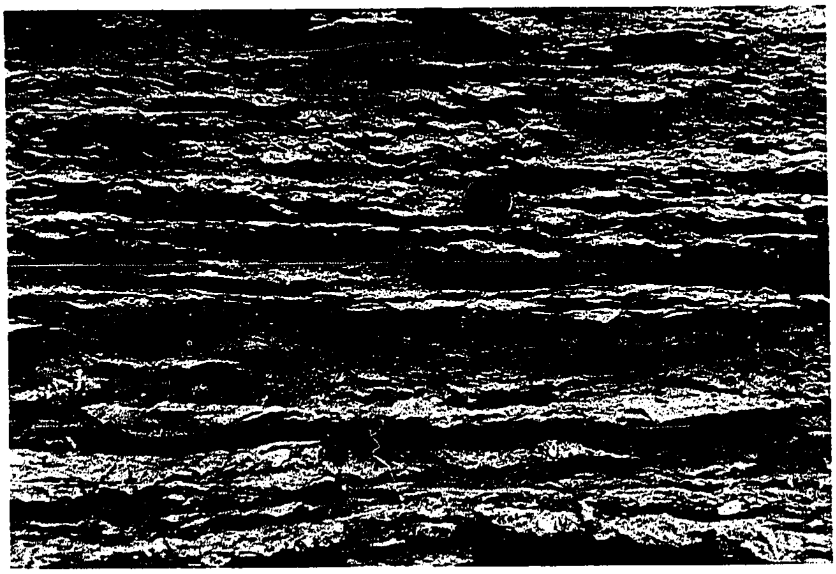
> The separation of the Upper Richmond from the Middle Richmond must usually be effected by lithological means. The Middle Richmond consists of a series of richly fossiliferous limestones interbedded with richly fossiliferous clays. The Upper Richmond consists of much less fossiliferous material, varying geographically from soft clay to clay rock and to massive beds of argillaceous limestone, fairly homogenous throughout the greater part of the vertical section.

Foerste (1903, pp. 343-347) goes on to describe three divisions of the Saluda Formation (from bottom to top): (1) a lower division consisting of soft, clayey and shaley rocks containing two conspicuous coral layers (*Favistella stellata* and *Tetradium minus*); (2) a middle division

Figure 67A: Field exposure of the Whitewater Formation, Caesar Creek locality.

Figure 67B: Close-up view of the Whitewater Formation, Richmond locality. Note the characteristic thin, wavy bedding.



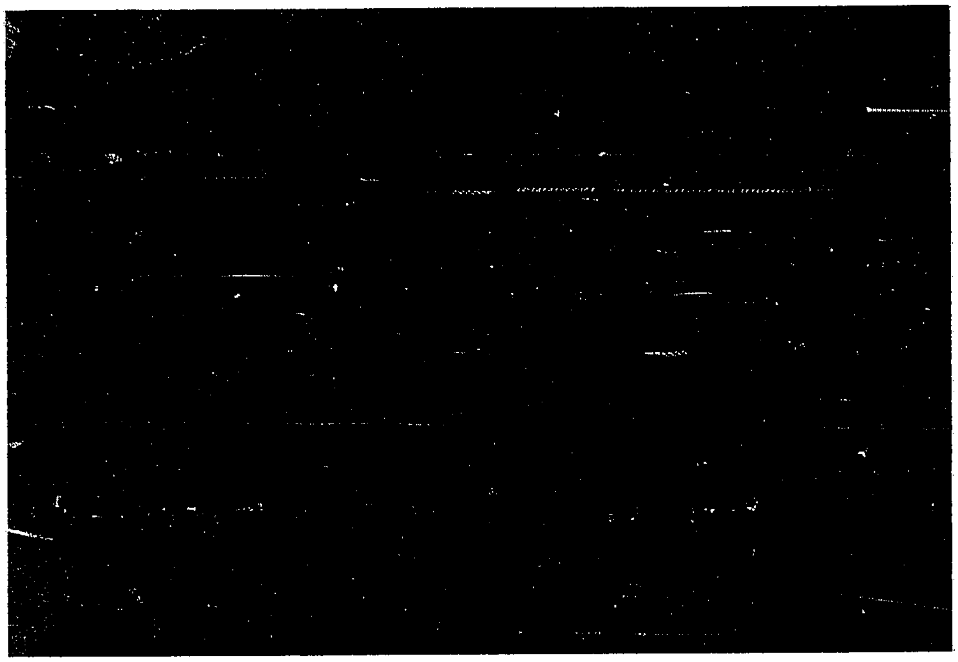


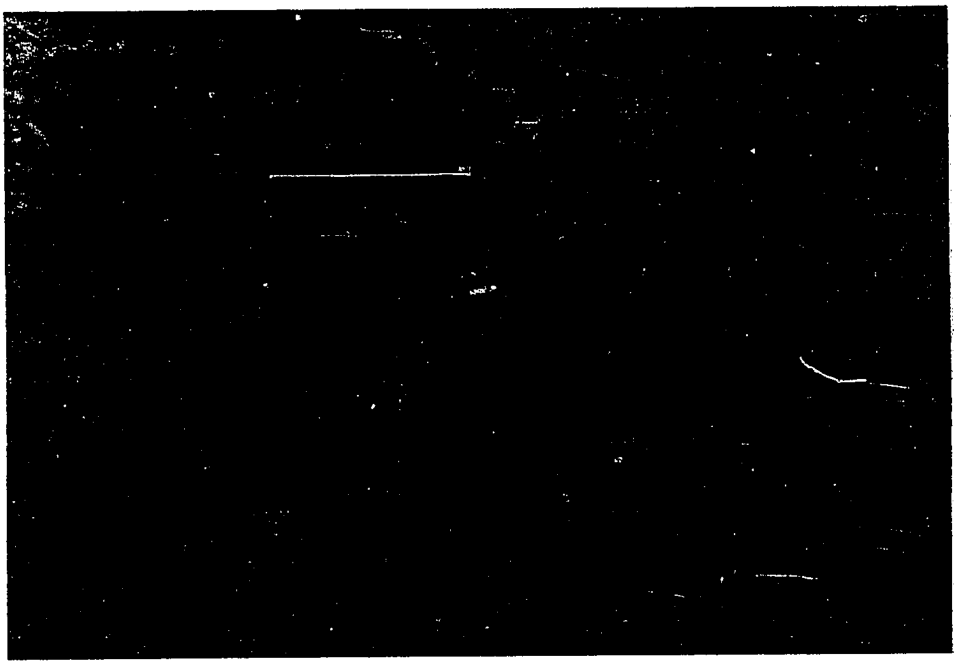
consisting of massive, unfossiliferous, "banded" limestone that is highly resistant to erosion--rocks in this division contain ripple marks and "suncracks"; (3) an upper division consisting of "rubbly," mottled, fine-grained limestone and fossiliferous clay. Rocks in this division contain the characteristic fossils *Lophospira hammelli* and *Cyrtocerina madisonensis*. This upper division was referred to as the "Hitz Bed," after Hitz hill in West Madison, Indiana. These three divisions were also recognized by Cumings (1922), but were not given proper names (with the exception of the Hitz Bed). More recent stratigraphic analyses of the Saluda Formation include Fox (1962), Brown and Lineback (1966), Hatfield (1968), Gray (1972), Oldroyd (1978), and Hay et al. (1981). In addition, Kepferle (1976) mapped the Hitz lithology in the Fishersville, Kentucky, area, 40 miles south of Madison, Indiana. Although Foerste's subdivisions have been recognized in some of these studies, they have never been described in a modern sedimentological sense, nor have they been assigned to member status. Furthermore, there is little agreement on the exact nature of upper and lower boundaries.

I believe that the Saluda Formation should be redefined according to modern stratigraphic procedures and described sedimentologically in its *original* type area (Madison, Indiana). I recognize that Foerste's subdivisions are lithologically distinctive and are genetically related. Thus, I propose that the Saluda Formation be redefined as a unit containing primarily dolomites and other dolomitic rocks, and having three members which are roughly equivalent to Foerste's subdivisions (see Figures 68 and 69): (1) The *Lower Saluda Member* is a medium- to thick-bedded, shale-bearing facies composed of thick (12 cm), planar-bedded limestones

Figure 68A: Field exposure of the Saluda Formation (Lower Member), Madison locality. Note the *Tetradium* horizon in the middle of the photograph.

Figure 68B: Close-up view of the Saluda Formation (Lower Member), Madison locality.





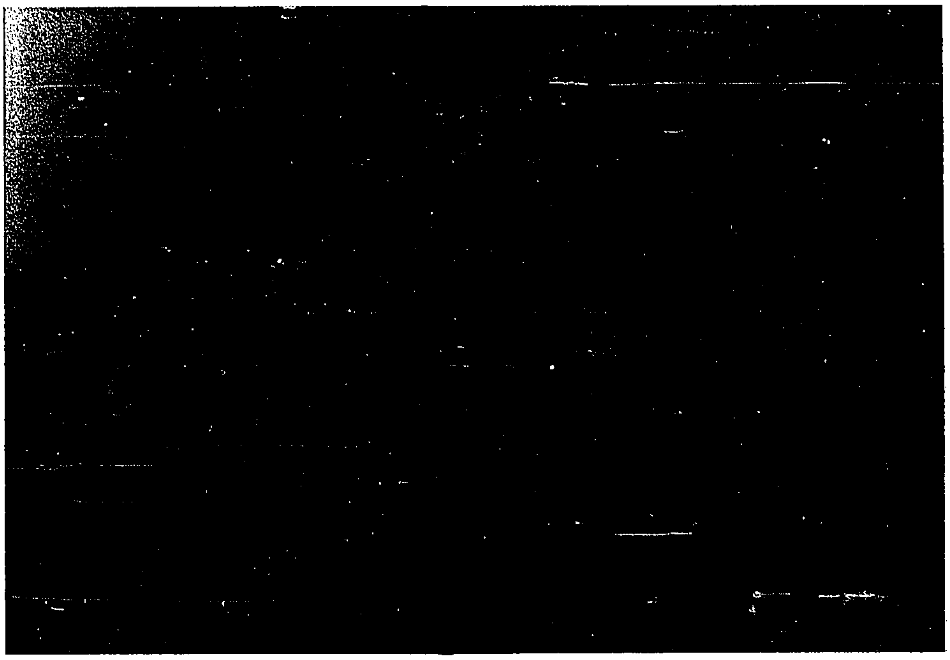


Figure 68C: Field exposure of the Saluda Formation (Middle Member), Madison locality. Note the characteristic "banded" appearance.

MADISON, IND. OUTCROP

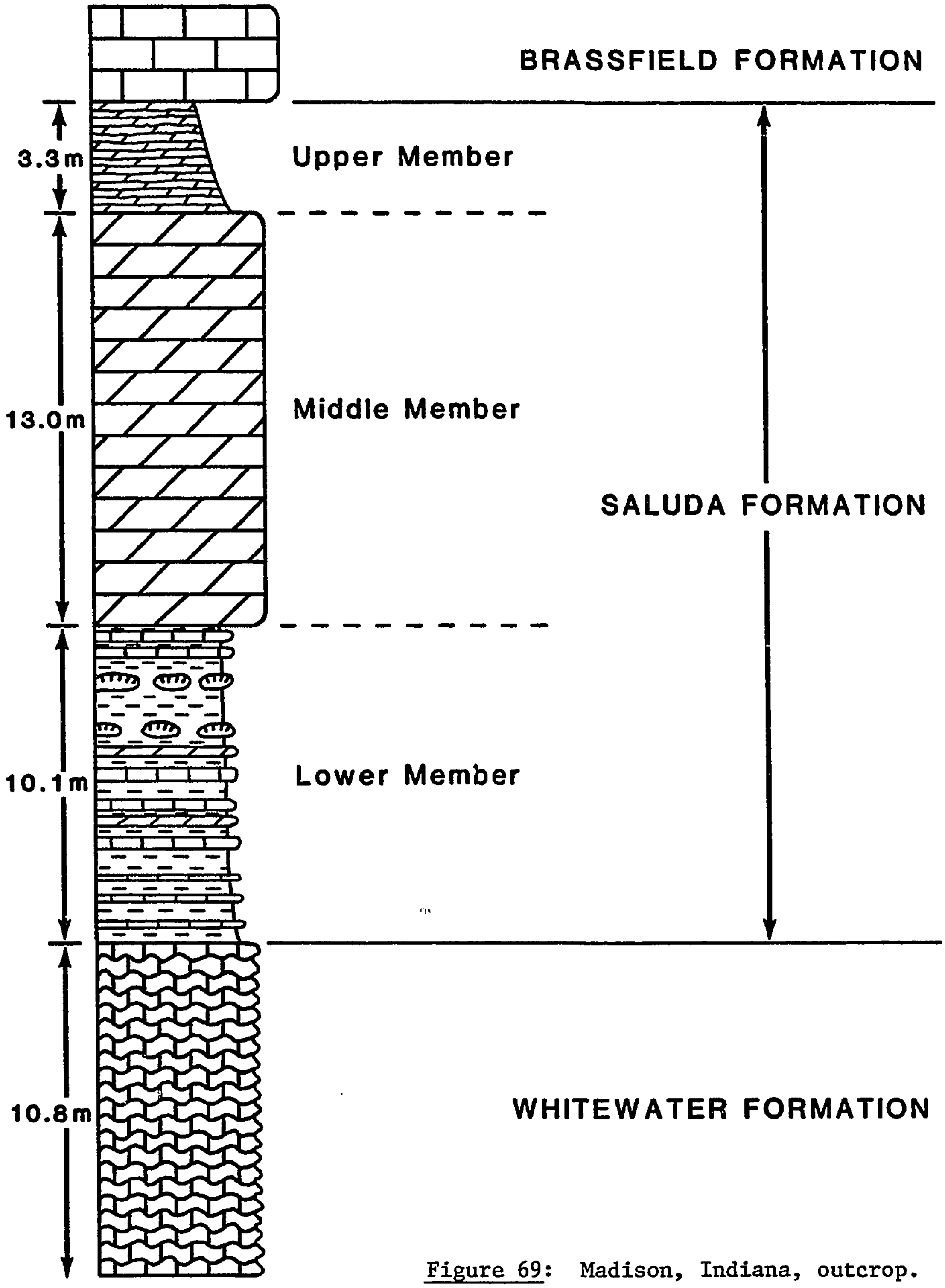


Figure 69: Madison, Indiana, outcrop.

and thin (4 cm) shale interbeds. Shale content decreases upward from about 80 percent in the lower three meters to about 10 percent near the top. Limestones are primarily dolomitic wackestones and micstones containing a restricted-marine fossil assemblage dominated by gastropods and ostracods. This facies contains two massive coral horizons (*Tetradium* and *Favistella*) which occur at the Madison and Brookville North localities. The Lower Saluda Member is thickest at its type section (10.1 meters or 33 feet), and thins to 4.3 meters (14 feet) at the Brookville North locality. The boundaries of this member are defined as the uppermost or lowermost extent of the interbedded shales and dolomitic wackestones or micstones characteristic of this unit. At the type section, the lower contact is marked by the vertical transition from the thin, wavy-bedded, shale-poor strata of the underlying Whitewater Formation to the thicker, shale-bearing, dolomitic rocks of the Saluda Formation. At the Brookville North locality, the Lower Saluda Member directly overlies similarly interbedded limestones and shales of the Liberty Formation. Here, the contact is more gradational and is represented by a vertical change from very fossiliferous grainstones and poorly washed grainstones to poorly fossiliferous, silty or argillaceous wackestones and micstones (see Appendix 3). The upper contact is marked by a vertical transition to massive, laminated, dolomitic rocks of the overlying member. However, at the Brookville North locality this member is overlain by Whitewater strata. (2) The *Middle Saluda Member* is a medium-thick (13.0 meters or 43 feet), massively bedded unit containing unfossiliferous, silty-to-sandy, sucrosic dolomites and dolomitic limestones in poorly defined beds. Planar lamination, cross lamination, ripples, mudcracks, rip-up clasts and omission surfaces are characteristic.

This member is highly resistant to erosion and stands out in relief on weathered outcrops. Shale is absent in this member. Occasional layers of pelletal glauconite and calcite spar-filled vugs are present. The boundaries of this member are defined as the uppermost and lowermost extent of its characteristic lithology. (3) The *Upper Saluda Member* is a thin unit (3.3 meters or 11 feet) composed of very light gray, poorly fossiliferous, color mottled, sucrosic dolomites that occur in very thin (< 2 cm), irregular bedding planes. These dolomites contain abundant, elongate pyrite lumps (1-3 cm in length) that are oriented vertically and horizontally. This facies is unlaminated and contains no sedimentary structures. In addition, the dolomites are soft and non-resistant to weathering. The boundaries of this member are defined as the uppermost and lowermost extent of its characteristic lithology. The lower contact is marked by the vertical transition from massive, resistant, sandy dolomites of the Middle Saluda Member to the soft, thin-bedded dolomites of the upper member. Similarly, the upper contact is very sharp, and is marked by the first occurrence of the massive dolomites of the overlying Brassfield Formation (Silurian).

The uppermost strata of the Cincinnatian Series have also been assigned to the *Elkhorn Formation*. This formation was poorly described by Cumings (1908) from outcrops along Elkhorn Creek southeast of Richmond, Indiana. Cumings later described the formation in more detail (1922, p. 438):

> . . . at the top is a bed of soft clay-shale four feet thick, underlain by six feet of hard brownish limestone layers abounding in the brachiopods *Platystrophia moritura* and *Hebertella sinuata*. Below this come twenty-five feet of blocky, arenaceous limestone, underlain in turn by fifteen feet of very soft, blue,

> barren shale. Beneath this occur the lumpy Whitewater limestones abounding in *Rhynchotrema dentata*.

Caster, Dalvé, and Pope (1961) have reported the Elkhorn Formation in Ohio as far east as Manchester, where the unit contains a characteristic "red facies." Hay et al. (1981) have described this unit from the Elkhorn Creek locality and have designated it as a member of the Whitewater Formation. However, I examined the type section of the Elkhorn Formation (Elkhorn Creek) in the Fall of 1981 and found it to be covered by a thick layer of soil and vegetation. Although a few *in situ* limestone beds, which contain the brachiopod *Platystrophia moritura*, are still projecting from the creek bank, the outcrop is virtually unmeasurable in its present state. Because the "Elkhorn Formation" is no longer exposed in outcrop, I recommend that its use as a rock-stratigraphic unit be discontinued until further exposures become available for study. Perhaps core descriptions may be used to define this facies in the future.

In contrast, the uppermost facies of the Cincinnatian Series is well exposed along the eastern edge of the outcrop belt in Adams County, Ohio. A series of outcrops along Route 41, north of West Union, expose a shale-rich interval of strata at least 12.7 meters (42 feet) thick that directly underlie the Silurian Brassfield Formation (see Figure 70). This interval has been assigned to the *Preachersville Member* of the *Drakes Formation* by Lee (1974). The Preachersville Member was originally described by Weir, Greene, and Simmons (1965) for strata outcropping in south-central Kentucky (30 miles south of Lexington) as follows (p. D18):

> . . . contains 10 to 20 percent argillaceous, fine-grained dolomite or dolomitic limestone in resistant beds, a few inches to a few feet thick; commonly, the thicker beds are near the base of the member.

WEST UNION OUTCROP

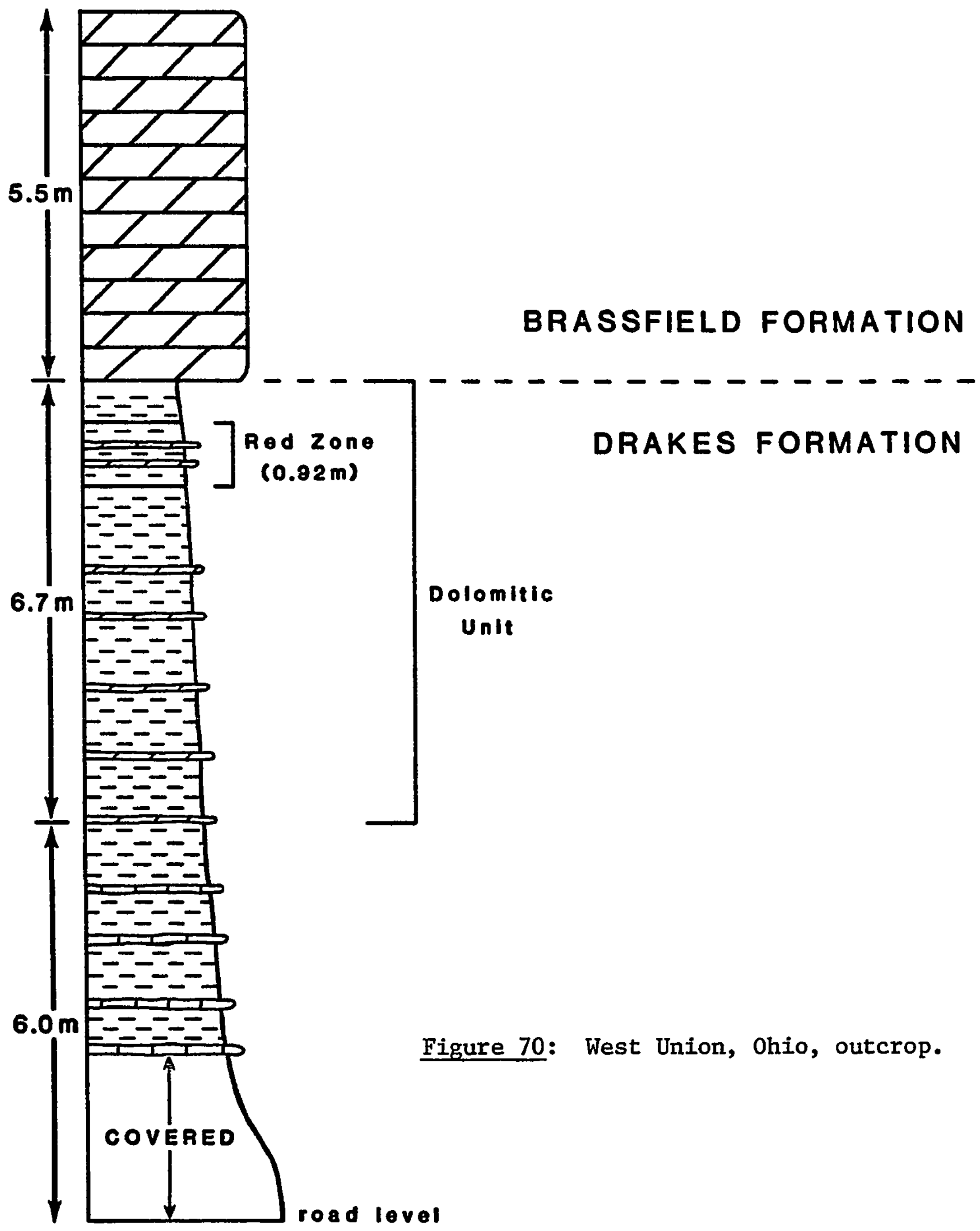


Figure 70: West Union, Ohio, outcrop.

The authors believed that this unit was probably correlative with the Liberty and Whitewater formations undivided, although they did not attempt to trace the unit northward into Ohio. Peck (1966, p. 22) believed that the rocks outcropping in the Maysville, Kentucky, area (18 miles southeast of the West Union outcrops) were a "northern extension of the upper part of the Preachersville Member in the type area." Finally, Lee (1974) extended this nomenclature to the West Union area.

I described three outcrops of this interval just north of West Union, along Rt. 41 (see Figure 70). At this locality, the Preachersville Member is a shale-rich facies (87 percent) containing a few thin, widely spaced carbonate beds. These carbonates are primarily represented by unfossiliferous, dolomitic micstones, and some non-dolomitic limestones which contain an open-marine fauna. Furthermore, a thin layer (0.92 m thick) occurs near the top of the unit, which consists of dark red shales, siltstones, and limestones.

Because I have not described this unit in its type area, I can only follow the advice of Lee (1974) that the strata near West Union is a northern extension of the Preachersville Member, even though the two lithologic descriptions are somewhat different. However, the use of the term "Preachersville Member" in Ohio should be questioned for three reasons: (1) The lithologic descriptions of both field areas, although similar, are not identical. (2) The Drakes Formation is a thick, undifferentiated unit which may consist of numerous rock facies. Thus, it may no longer be advisable to use the term "Drakes Formation" as a valid rock-stratigraphic unit. (3) The shale-rich strata exposed in the West Union area may indeed prove to be equivalent to the "Elkhorn Formation." Caster, Dalvé, and

Pope (1961) referred to outcrops near Manchester, Ohio, (just south of the West Union area) as good exposures of the Elkhorn Formation, and noted the presence of a "red facies" in this area.

In summary, the following lithostratigraphic names are proposed for use in Ohio, Indiana, and northern Kentucky: the Waynesville Formation, the Liberty Formation, the Whitewater Formation, and the Saluda Formation. Furthermore, the Saluda Formation is divided into Lower, Middle, and Upper members. These formations are well known to stratigraphers, are laterally persistent throughout the field area, and represent contemporaneous ancient lithotopes. Hence, they are highly useful for interpretive purposes as well as for mapping. However, the existing stratigraphic nomenclature for the uppermost facies in this sequence (Saluda Formation, Elkhorn Formation, and Preachersville Member) is confusing. All three units roughly occupy the same stratigraphic position and have similar paleoenvironmental interpretations. Hence, all three may represent lateral variations of the *same* lithosome, or they may represent *different* lithosomes. Hopefully, future workers will be able to address these two possibilities by studying the stratigraphic relationships of all three units, perhaps by using a combination of outcrop and subsurface data.

Sedimentology

The lowermost rock facies in this sequence is the *Waynesville Formation*. This formation is thick (36 meters or 118 feet), and is composed of interbedded shales (67 percent) and carbonates (33 percent). Bedding is planar, moderately continuous, and moderately thick (averaging 9 cm). Shale beds are more than twice as thick as carbonate beds (11 cm vs. 5 cm).

In addition, Waynesville megacycles are thick (averaging 1.18 meters) and abundant (see Figure 43 and Table 12). Furthermore, megacycles thin upward stratigraphically, averaging 1.54 meters in thickness in the lower half of the formation and 0.95 meters in the upper half. In addition, sedimentary structures are abundant and well preserved, including symmetric and asymmetric ripples, planar lamination, cross lamination, tool marks, flute marks, gutter casts, shale clasts, and imbricate brachiopods.

All eight of the "recurrent carbonate rock types" discussed earlier can be found in the Waynesville Formation, but packstones are most abundant. The percentages of each of these recurrent rock types follow: packstones (73 percent), wackestones (6 percent), micstones (1 percent), siltstones (6 percent), poorly washed grainstones (3 percent), coarse grainstones (5 percent), fine grainstones (6 percent), and calcisiltites (trace). The ratio of coarse grainstones to fine grainstones is low (0.83).

Shales in the Waynesville Formation contain a moderate amount of silt. Four of the seven thin-section samples examined are mudstones. The "average" Waynesville shale is a dolomitic claystone (QF_{31} CM_{58} CD_{11}) having a silt/clay ratio of 0.61 and a grain size of 20 microns.

The overlying *Liberty Formation* is a medium-thick unit (19 meters or 62 feet) composed of interbedded limestones (55 percent) and shales (45 percent). Bedding is planar, moderately continuous, and medium thick (averaging 8 cm). In addition, shale beds are slightly thicker than limestone beds (9 cm vs. 7 cm). Liberty megacycles are thinner than those in the Waynesville Formation (averaging 0.85 meters), but also thin upward stratigraphically. Megacycles in the lower half of the formation average

0.99 meters in thickness and those in the upper half average 0.42 meters in thickness. As in the Waynesville Formation, sedimentary structures are abundant and occur in a variety of forms.

All eight of the "recurrent carbonate rock types" can be found in the Liberty Formation, but packstones and grainstones dominate. The percentages of each of these rock types follow: packstones (44 percent), wackestones (3 percent), micstones (2 percent), siltstones (8 percent), poorly washed grainstones (7 percent), coarse grainstones (14 percent), fine grainstones (18 percent), and calcisiltites (4 percent). Again, the ratio of coarse grainstones to fine grainstones is low (0.77). Shales in the Liberty Formation are silt rich. The average Liberty shale is a dolomitic mudstone (QF_{35} CM_{35} CD_{30}) having a silt/clay ratio of 1.02 and a grain size of 22 microns.

The overlying *Whitewater Formation* is a thin unit (11 meters or 36 feet) composed of wavy-bedded limestones (86 percent) and thin, discontinuous, fissile shales (14 percent). Limestones average 4 cm in thickness, and shales average 2 cm in thickness. Overall, bedding is very discontinuous and thin (3 cm). Three types of bedding are present: wavy bedding (82 percent), nodular bedding (3 percent), and planar bedding (15 percent). Megacycles are absent in the Whitewater Formation, and sedimentary structures are limited to planar lamination, cross lamination, ripples, and shingled brachiopods.

Four of the eight "recurrent carbonate rock types" are present in the Whitewater Formation, but grainstones dominate (83 percent). Carbonate rock types include packstones (17 percent), poorly washed grainstones (22 percent), coarse grainstones (39 percent), and fine grainstones (22 percent). The coarse grainstone to fine grainstone ratio is high (1.80).

As in other examples of facies C of the "ideal" shoaling-upward shelf cycle (the Bellevue, Mt. Auburn, and Oregonia formations), shales in the Whitewater Formation are thin, fissile, discontinuous, and sometimes fossiliferous, impeding sample collection and thin-section processing. Thus, only one shale sample was examined in thin-section, a claystone having a composition of QF_{15} CM_{84} CD_{1}. The silt/clay ratio of this claystone is the lowest in the Cincinnatian Series (0.17) and grain size is the lowest (16 microns).

The uppermost facies in this sequence is the *Saluda Formation*. As mentioned earlier, this formation is composed of three lithologically distinct members at the type section (Madison, Indiana). The *Lower Saluda Member* is a thin unit (10.1 meters or 33 feet) which directly overlies the Whitewater Formation (at the Madison locality) or the Liberty Formation (at the Brookville North locality). This member is a medium- to thick-bedded (10 cm), shale-bearing facies composed of thick (12 cm), planar- to wavy-bedded limestones and thin (4 cm) shale interbeds (see Figure 68). Shale content is 27 percent, but decreases upward from 80 percent (in the lower 3 meters of the member) to 10 percent (in the upper 7.1 meters). Shales are slabby, silt poor, dolomitic, and are heavily burrowed. Color mottling, horizontal tubes, and vertical tubes are abundant (see Figure 71). The basal 3 meters of this unit contain very thin (3 cm) grainstone beds (fine grainstones and grainstones having a bimodal grain size) in addition to lesser amounts of dolomitic packstones and wackestones (see Figure 71). Imbricate brachiopods are common. The upper 7.1 meters of the Lower Saluda Member also contain some fine grainstones (3 percent),

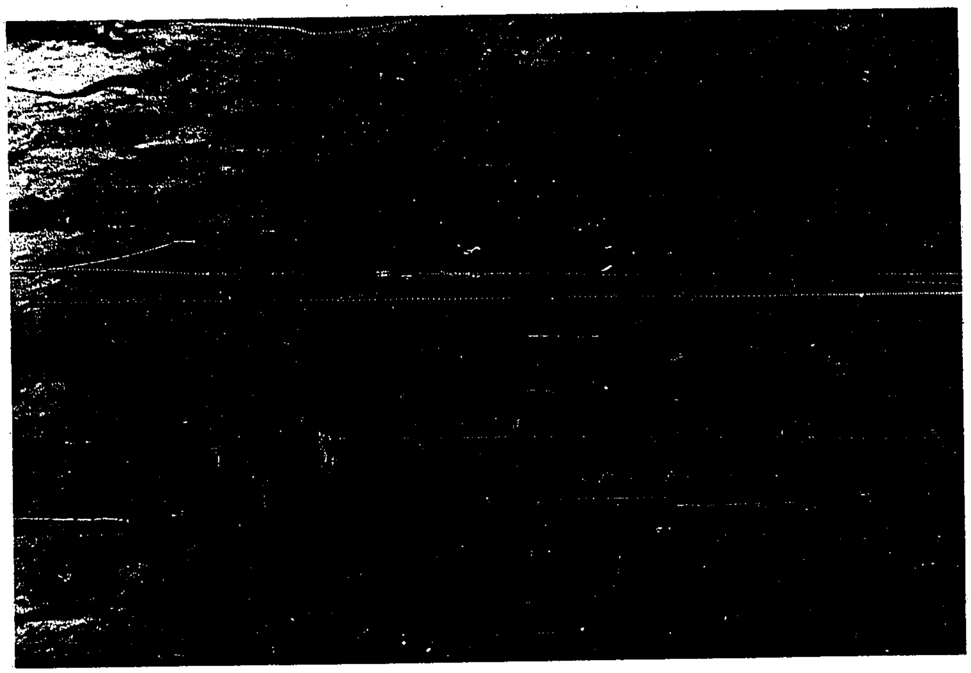


Figure 71A: Bioturbated shales in the Saluda Formation (Lower Member), Madison locality.

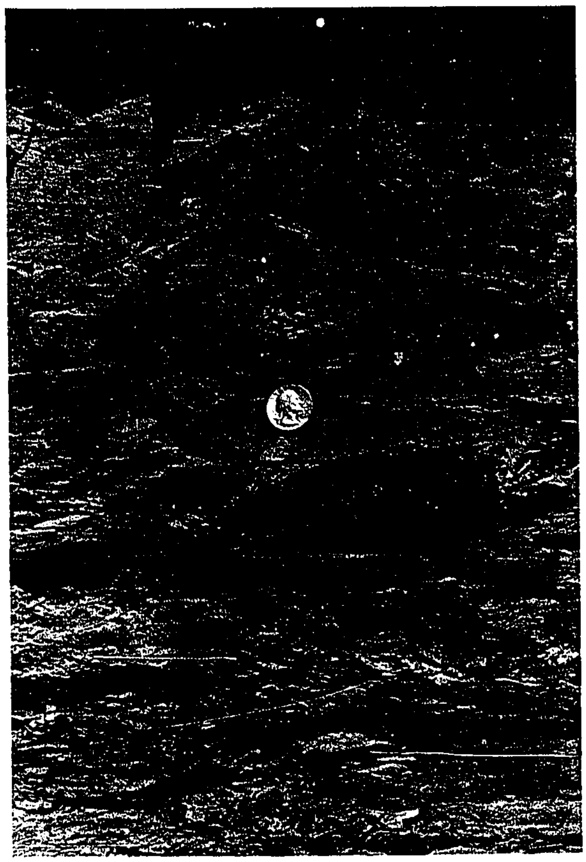


Figure 71B: Dolomitic shales in the Saluda Formation (Lower Member), Madison locality. Note the presence of a thin storm layer (coarse grainstone) in the middle of the picture.

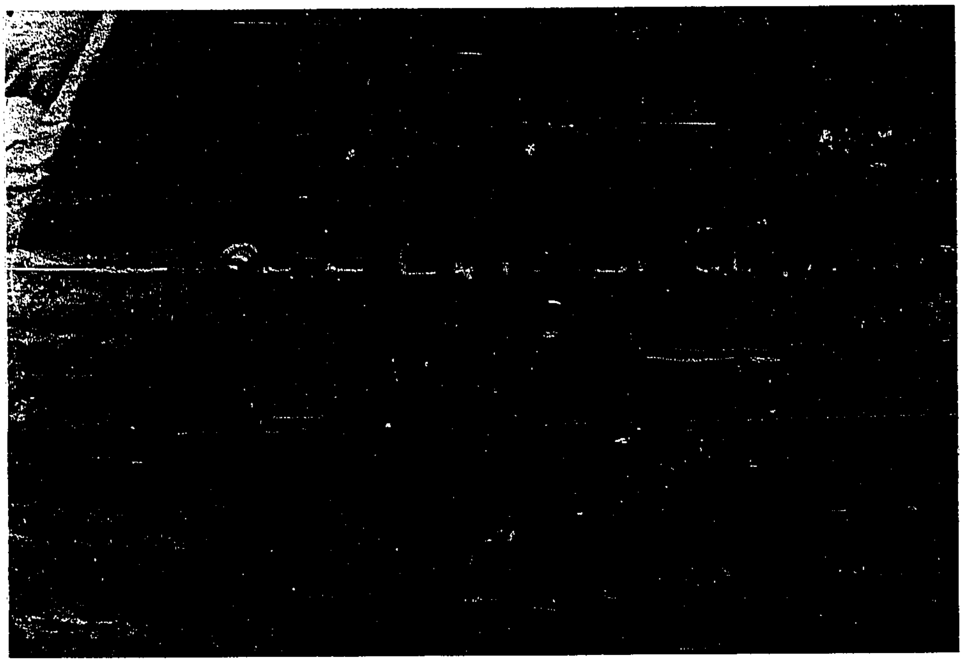
but the dominant rock types are dolomitic wackestones (76 percent), packstones (14 percent), and micstones (7 percent). Sedimentary structures in the Lower Saluda Member are sparse, but include planar lamination, imbricate brachiopods, and symmetric ripples. Megacycles are absent. As mentioned earlier, two massive coral horizons occur within this facies (see Figure 69).

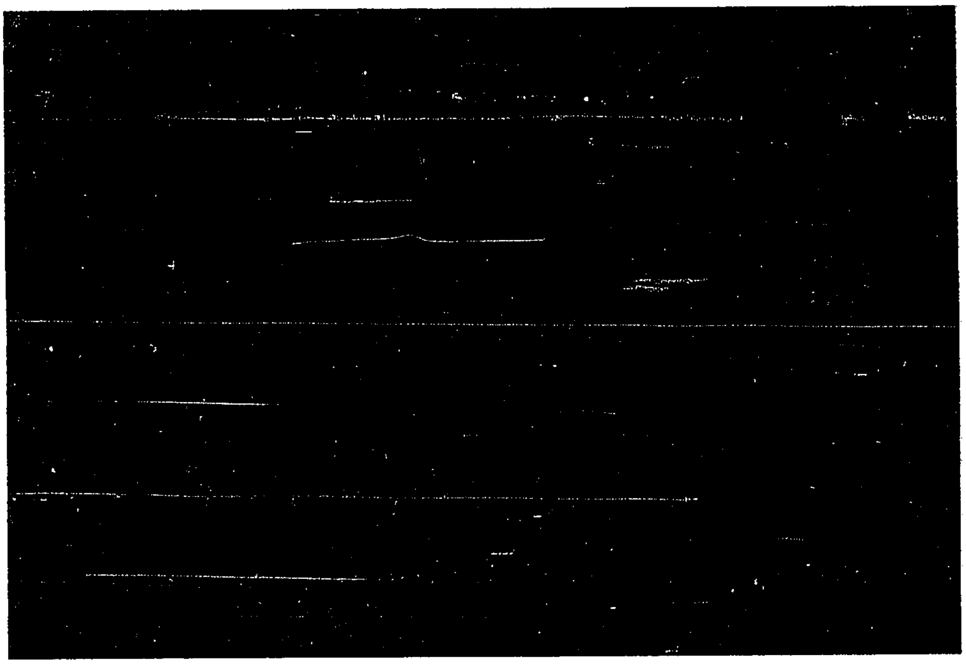
The *Middle Saluda Member* is a medium-thick (13.0 meters or 43 feet), massively bedded unit that stands out in relief on weathered outcrops (see Figure 68). This member consists of unfossiliferous, silty-to-sandy sucrosic dolomites (69 percent), dolomitic micstones (23 percent), and non-dolomitic fine grainstones (8 percent). Planar and cross lamination is very abundant, giving the unit a characteristic "banded" appearance. Other common sedimentary structures include ripples, mudcracks, flat-pebble rip-up clasts, birdseye structures, and omission surfaces (see Figure 72). Occasional layers of pelletal glauconite and calcite spar-filled vugs are also present. Shale is absent in this member.

The *Upper Saluda Member* is a thin unit (3.3 meters or 11 feet) composed of soft, light gray, irregularly bedded dolomites which are highly susceptible to weathering (see Figure 68). Bedding is thin (< 2 cm), wavy, very discontinuous, and poorly defined. The characteristic rock type in this member is a sucrosic dolomite, consisting of 94 percent ferroan dolomite, 4 percent fine-grained fossil fragments (brachiopods and crinoids), 2 percent quartz silt, and trace amounts of pyrite. These dolomites are heavily burrowed with distinct vertical and horizontal tubes as well as color mottling. Shales and sedimentary structures are absent in this member. However, this facies contains abundant, elongate pyrite

Figure 72A: Bedding characteristics of the Middle Saluda Member, Madison locality. Note the presence of planar lamination, ripple marks, and omission surfaces.

Figure 72B: Planar laminated dolomite in the Middle Saluda Member, Madison locality. Note the presence of omission surfaces (truncated burrows) in each light-colored lamination.





"lumps" (1-3 cm in length) that commonly have one bulbous end. These structures are oriented vertically and horizontally, and may represent burrows of unknown origin or perhaps dessication structures.

Along the eastern edge of the Ordovician outcrop belt in Ohio, the uppermost facies of the Cincinnatian Series is represented by shale-rich strata which have previously been assigned to the *Preachersville Member* of the *Drakes Formation*. This facies is at least 12.7 meters (42 feet) thick in the West Union area, and consists of interbedded shales (87 percent) and carbonates (13 percent). Bedding is planar, discontinuous, and thick (averaging 12 cm). Shale beds are nearly three times as thick as carbonate beds (13 cm vs. 5 cm). Megacycles are absent and sedimentary structures are limited to ripples, cross lamination, gutter casts, and imbricate brachiopods. Figure 70 is a representation of the West Union outcrop.

Carbonate beds in the bottom 6 meters of the West Union outcrop are composed of three rock types: (1) grainstones having large, whole fossils "floating" within a calcisiltite groundmass (53 percent); (2) silty, unlaminated micstones (11 percent); and (3) fragmental packstones containing an open-marine fauna (36 percent). Shales in this part of the outcrop are olive gray to medium bluish gray in color, and are composed of dolomitic mudstone.

The upper 6.7 meters of the West Union outcrop contain planar-bedded, unfossiliferous, dolomitic micstones and medium bluish gray (5B 5/1), very dolomitic shales (mudstones). Some of the dolomitic micstone beds exhibit mudcracks. In addition, a distinctive layer of dark red carbonates and shales (0.92 meters thick) occurs within the upper few meters of the unit (see Figure 70). Three varieties of shale occur within this reddish layer: (1) abundant blackish red (5R 2/2) and grayish red (5R 4/2), non-calcareous, unfossiliferous mudstones having abundant horizontal and inclined burrows; (2) occasional thin layers of dark yellowish brown (10 YR 4/2) and dusky yellowish brown (10 YR 2/2), calcareous mudstones that lack bioturbation and fossils; and (3) rare, discontinuous layers of bluish gray, dolomitic mudstone. Five varieties of carbonate rocks occur within this red zone: (1) grayish red (5R 4/2) siltstones; (2) grayish red, fine grainstones having rip-up clasts; (3) light olive gray (5Y 6/1), fine-grained, well-sorted, crinoidal grainstones; (4) fine-grained, olive gray packstones having parallel-oriented fossils and reddish rip-up clasts; and (5) silty, olive gray, fine-grained packstones.

The same shale-rich facies which is exposed in the West Union area is also known to occur 40 miles to the north in Highland County, Ohio. Examination of a core from the Ohio State Geological Survey (sample number 2499, Fairfield Township) revealed the presence of a 14-meter-thick (46 feet) facies at the top of the Ordovician which is composed of bluish, dolomitic shales and dolomitic limestone interbeds. Most of the shales exhibit wavy, "crinkly" lamination (< 2 mm thick) formed by the alternation of clay-rich layers and ferroan dolomite layers. In addition, the dolomite laminae contain very thin stringers of pyrite which are oriented parallel to the laminae. This interval also contains a thin layer of reddish shales and carbonates, just like the West Union outcrops.

In summary, the upward vertical succession of facies in the Waynesville to Saluda sequence is reflected most strongly by the following trends: (1) a decrease in facies thickness; (2) a decrease in bedding thickness and lateral continuity; (3) a vertical change from planar bedding in the Waynesville and Liberty formations to wavy bedding in the Whitewater Formation; (4) a decrease in shale content; (5) a decrease in shale bedding thickness (with the exception of the Preachersville Member); (6) a decrease in the silt content of shales; (7) a decrease in siltstone content; (8) an increase in the percentage of grainstones (especially coarse grainstones); and (9) a vertical change from non-dolomitic limestones containing an open-marine assemblage of fossils (Waynesville, Liberty, and Whitewater formations) to dolomites and poorly fossiliferous, dolomitic limestones containing a restricted-marine assemblage of fossils (Saluda Formation).

Paleontology

In situ limestones (packstones and wackestones) in the *Waynesville Formation* contain a diverse, open-marine faunal assemblage dominated by brachiopods, bryozoans, trilobites, crinoids, and gastropods. Lesser amounts of pelecypods, ostracods, conodonts, and scolecodonts also exist. These beds have an average generic diversity of 6.6 and a petrographic diversity of 7.7.

The most common brachiopod genera in the lower half of the Waynesville Formation are *Onniella*, *Rafinesquina*, and *Zygospira*. The first two genera have wide, thin, flat shells and the last has a rounded, but minute shell (< 5 mm). These same three brachiopods are also present in the upper half of the formation in addition to *Strophomena*, *Leptaena*, *Rhynchotrema*, *Hebertella*, *Platystrophia*, and *Lepidocyclas*. The last four of these brachiopods have inflated shells with coarse, detailed ornamentation. Bryozoans in the

Waynesville Formation are small, branching forms such as *Batostomella* and *Hallopora*, but fan-shaped forms are also present (*Homotrypa dawsoni*). Other typical Waynesville fossils include the trilobite *Flexicalymene*, the gastropods *Cyclora* and *Cyclonema*, the characteristic cricoconarid *Tentaculites*, and the pelecypods *Caritodens* and *Ambonychia*. All body fossils are unabraded and well preserved.

Trace fossils are abundant in the Waynesville Formation and include the following varieties: *Chondrites*, *Trichophycus*, *Paleophycus*, *Rusophycus*, and unnamed vertical tubes. These trace fossils belong to the *Cruziana* ichnofacies.

In situ limestones in the overlying *Liberty Formation* also contain a diverse, open-marine faunal assemblage. These rocks contain abundant brachiopods, bryozoans, trilobites, crinoids, corals, and gastropods. Lesser amounts of pelecypods, cephalopods, conodonts, and ostracods also occur. These beds have nearly the same generic (6.2) and petrographic (7.7) diversities as those in the underlying Waynesville Formation.

Some of the brachiopod genera in the Liberty Formation have large, inflated shells with coarse, detailed ornamentation, such as *Lepidocyclas*, *Platystrophia*, *Glyptorthis*, and *Rhynchotrema*. Others have smaller, flatter shells with less detailed ornamentation, such as *Holtedahlina*, *Strophomena*, *Onniella*, *Thaerodonta*, and *Rafinesquina*. Bryozoans in the Liberty Formation are either small and branching, such as *Hallopora* and *Homotrypa* (*H. flabellaris*), or fan-shaped, such as *Constellaria*. Other typical Liberty fossils include the gastropods *Cyclora*, *Cyclonema*, and *Lophospira*, the trilobite *Isotellus*, and the cup coral *Grewingkia*. All body fossils are unabraded and well preserved.

Trace fossils are also abundant in the Liberty Formation and include *Chondrites*, *Trichophycus*, inclined tubes, vertical tubes, and color mottling. These trace fossils represent a mixture of the *Cruziana* and *Skolithos* ichnofacies.

In situ limestones (packstones, poorly washed grainstones, and some coarse grainstones) in the overlying *Whitewater Formation* contain a diverse, open-marine fossil assemblage dominated by brachiopods, crinoids, bryozoans, trilobites, gastropods, pelecypods, and algae (both red and blue-green algae as isolated fragments and as onkoidal coatings). Lesser amounts of cephalopods, ostracods, and conodonts are also present. These beds have a higher average generic diversity (7.3) and petrographic diversity (8.2) than limestones in the underlying units.

Most of the brachiopods in the Whitewater Formation have large, inflated shells with coarse, detailed ornamentation, such as *Platystrophia* (*P. acutilirata*), *Hebertella*, *Lepidocyclas*, *Plaesiomys*, and *Rhynchotrema*. Others have smaller, flatter shells with less detailed ornamentation, such as *Holtedahlina*, *Leptaena*, and *Strophomena*. The minute brachiopod *Zygospira* is present in most beds. Similarly, bryozoans in the Whitewater Formation are large, massive forms with coarse, star-shaped monticules (such as *Constellaria polystomella*), with coarse, knob-like monticules (such as *Hallopora subnodosa*), or with sharp, pointed monticules (such as *Homotrypa wortheni*). Other typical Whitewater fossils include the gastropod *Cyclora*, the pelecypod *Ambonychia*, and the cup coral *Grewingkia*. The effects of boring, abrasion, bryozoan and algal encrustation, and micritization are relatively high in this unit. Trace fossils are less abundant in the Whitewater Formation than they are in the underlying units, and are limited to color mottling and unnamed vertical tubes (*Skolithos*).

As previously defined, the overlying Saluda Formation consists of three members. Limestones in the *Lower Saluda Member* contain a semi-restricted fossil assemblage dominated by gastropods, ostracods, and pelecypods. Less abundant fossils include bryozoans, brachiopods, crinoids, trilobites, corals, scolecodonts, cephalopods, and blue-green algae. Average generic diversity is low (3.7), but average petrographic diversity is fairly high (7.6). This discrepancy is the result of the presence of very fine-grained (< 100 microns) fossil fragments that can be seen only in thin section. [Note: These small, highly broken fragments were probably eroded from an adjacent high-energy lithotope and transported into the Saluda lithotope.] Thus, the average *generic* diversity (3.7) is probably most representative of the indigenous fauna of the Lower Saluda Member.

Genera in the Lower Saluda Member include the brachiopods *Lepidocyclas*, *Plaesiomys*, and *Zygospira*, and the corals *Tetradium* and *Favistella*. Bioturbation is abundant, but is limited to color mottling and vertical tubes (*Skolithos*). Body fossils are unabraded and well preserved.

Body fossils in the *Middle and Upper Saluda Members* are very sparse. No body fossils were observed in the Middle Member, and only a few very small crinoid and brachiopod fragments were observed in the Upper Member, although Foerste (1903) reported the presence of the gastropod *Lophospira* in the Upper Member ("Hitz Bed"). Trace fossils are abundant in both members, but are limited to vertical tubes and color mottling.

Although no exposures of the *Elkhorn Formation* are presently available for study, the characteristic fossils in this unit are included in this discussion, thanks to the work of Caster, Dalvé, and Pope (1961). These fossils include the corals *Tetradium*, *Favistina*, and *Labechia*, the cystoid *Lepadocystis*, the bryozoan *Homotrypa*, the pelecypod *Ischyrodonta*, and the brachiopod *Platystrophia* (*P. moritura*, a "winged" form, and *P. acutilirata*, also a "winged" form, but only occurring near the base of the unit).

Field observations of the *Preachersville Member* of the *Drakes Formation* reveal the presence of the brachiopods *Onniella*, *Platystrophia* (*P. acutilirata*), *Lepidocyclas*, and *Strophomena* (*S. vetusta*) in the lower 6 meters of the West Union outcrop. In the upper 6.7 meters of this outcrop, body fossils are limited to a few small inarticulate brachiopods (*Pseudolingula*) and the bryozoan *Bythorpora delicatula*. *B. delicatula* also occurs in the lower 6 meters of the outcrop and is a very small (< 1 cm), delicate, branching form. Trace fossils are limited to color mottling and vertical tubes.

In summary, the upward vertical succession of rock facies in the Waynesville to Saluda shoaling-upward sequence is accompanied by several faunal changes, including (1) an increase in faunal diversity from the Waynesville Formation to the Whitewater Formation, followed by a decrease in diversity in the overlying Saluda Formation; (2) an increase in the amount of abrasion, boring, and encrustation of shells (followed by a return to well-preserved fossils in the Saluda Formation); (3) an upward change from a *Cruziana* ichnofacies (Waynesville) to a mixed *Cruziana*/*Skolithos* ichnofacies (Liberty) to a *Skolithos* ichnofacies (Whitewater and Saluda); (4) an upward change from small, thin, delicate fossils (Waynesville and Liberty) to larger, thicker, more robust fossils (Whitewater), followed by a return to thin-shelled, delicate fossils (Saluda);

and (5) an upward change from an open-marine assemblage of fossils (Waynesville, Liberty, Whitewater) to a restricted-marine assemblage of fossils (Saluda). These vertical trends are summarized in Table 16.

Interpretation

Following the deposition and progradation of the underlying Corryville to Oregonia sequence, a second major transgression of the Ordovician sea occurred. This event is marked by the unconformable contact between the Oregonia Formation (a shallow-water facies) and the overlying Waynesville Formation (a deeper water facies). The subsequent renewal of carbonate and shale sedimentation at this time resulted in the deposition of the Waynesville to Saluda sequence. The facies in this sequence are believed to represent deposition on the inner part of a gently sloping ramp, primarily in the offshore to supratidal zones (see Figure 73). The top of the Waynesville to Saluda sequence is marked by the unconformable contact between the Saluda Formation and the overlying Brassfield Formation (Silurian). This contact represents a third major transgression of the sea that began at the close of the Ordovician period.

The Waynesville to Saluda sequence is the only *complete* example of the "idealized" shoaling-upward shelf cycle discussed earlier (see Figure 47). All four lithofacies in the idealized cycle are represented in this sequence. Facies A is represented by the *Waynesville Formation*. The following evidence suggests that this facies was deposited in the offshore zone: (1) The relative abundance of shales (67 percent) and siltstones (6 percent) indicates deposition in a non-turbulent environment, probably below wave base. (2) The excellent preservation of sedimentary structures

FORMATION	DIVERSITY		DOMINANT FOSSIL ASSEMBLAGE	BRACHIOPOD MORPHOLOGY	BRYOZOAN MORPHOLOGY	FOSSIL PRESERVATION	ICHNO-FACIES
	Generic	Petro-graphic					
SALUDA	3.7	7.6	gastropods ostracods pelecypods (restricted marine)	Not applicable	Not applicable	Well preserved	Skolithos
WHITEWATER	7.3	8.2	brachiopods crinoids bryozoans trilobites gastropods pelecypods algae (open marine)	Large, rounded shells with coarse, detailed ornamentation (Platystrophia, Hebertella, Lepidocyclas, Plaesiomys, Rhynchotrema)	Large, massive forms (Constellaria, Hallopora, Homotrypa)	High degree of abrasion, micritization, boring, algal encrustation, and bryozoan encrustation	Skolithos
LIBERTY	6.2	7.7	brachiopods bryozoans trilobites crinoids corals gastropods (open-marine)	Mixture of wide, flat shells (Rafinesquina, Strophomena, Onniella, Holtedahlina) and large, rounded shells (Platystrophia, Lepidocyclas, Glyptorthis, Rhynchotrema)	Small, branching forms (Hallopora, Homotrypa) and fan-shaped forms (Constellaria)	Well preserved	Mixed Skolithos/ Cruziana
WAYNESVILLE	6.6	7.7	brachiopods bryozoans trilobites crinoids gastropods (open marine)	Small, thin, flat shells in lower half (Rafinesquina, Onniella) Mixture of small shells and large shells in upper half (Strophomena, Rhyncotrema, Leptaena, Platystrophia, Hebertella, Lepidocyclas)	Small, delicate, branching forms (Batostomella, Hallopora) Some fan-shaped forms (Homotrypa)	Well preserved	Cruziana

Table 16: Autecological comparison of rock facies in the Waynesville to Saluda shoaling-upward sequence.

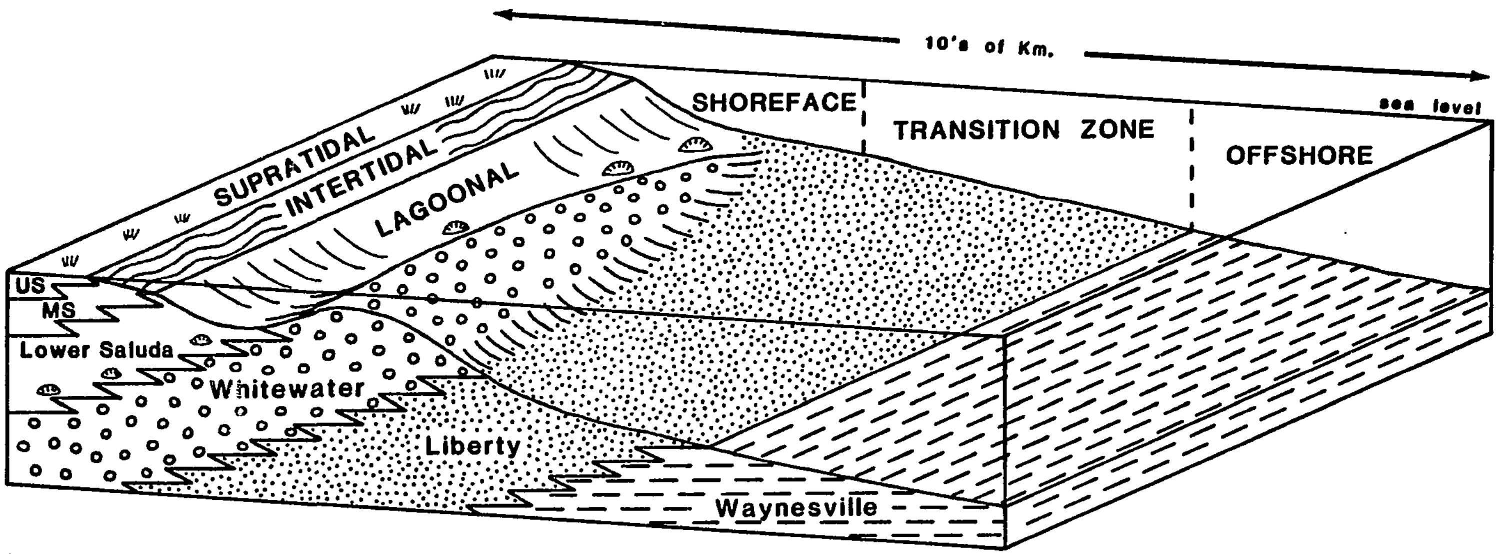


Figure 73: Interpretation of the Waynesville, Liberty, Whitewater, and Saluda lithotopes. Vertical scale is highly exaggerated. MS = Middle Saluda Member; US = Upper Saluda Member.

and trace fossils indicates a low level of wave erosion. (3) The dominant carbonate rock type in this facies is a packstone (73 percent) suggesting deposition below wave base in quiet water. (4) Body fossils in this facies are small and fragile, suggesting that these organisms lived in a protected, quiet-water environment. (5) The lack of shell abrasion, boring, encrustation, and micritization suggests a deeper shelf setting. (6) Trace fossils belong to the *Cruziana* ichnofacies, representative of inner- to outer-shelf environments. (7) The abundance of thick, moderately continuous, planar beds suggests a lack of wave erosion.

Facies B of this sequence is represented by the overlying *Liberty Formation*. This formation was deposited in shallower water than the Waynesville Formation, probably in the transition zone. The following vertical trends suggest that Liberty sediments accumulated in shallower water than Waynesville sediments: (1) a decrease in shale content (45 percent); (2) a decrease in shale bedding thickness; (3) a change from a dominantly *Cruziana* trace fossil assemblage to a mixed *Cruziana/Skolithos* assemblage; (4) an increase in grainstone content (from 14 percent to 43 percent) and a decrease in packstone content (from 73 percent to 44 percent); (5) an increase in the amount of larger, more robust fossils; and (6) a higher degree of micritized fossils (50 percent of the samples examined contain micritized fossils as opposed to only 33 percent in the Waynesville Formation).

Facies C of this sequence is represented by the *Whitewater Formation*. This facies was probably deposited in a high-energy shoreface setting for the following reasons: (1) The low shale content (14 percent), low silt content of shales, and thin, discontinuous shale bedding indicate that winnowing effects were high. (2) The characteristic wavy, discontinuous bedding is generated primarily in the shallow subtidal-to-intertidal zones (Reineck and Singh, 1973, pp. 99-102). (3) The poor preservation of sedimentary structures and trace fossils in this unit indicates that substrates were highly mobile and subject to wave erosion. (4) The trace fossils which are preserved in this formation belong to the *Skolithos* ichnofacies, indicative of shallow, inner-shelf environments. (5) The dominant carbonate rocks in the Whitewater Formation are grainstones (83 percent), indicating a high degree of winnowing. (6) Most of the body fossils are large, robust forms capable of withstanding a high degree of water turbulence. (7) Although a mixture of fossil preservational states exists in most beds, abrasion, boring, and encrustation of shells is most abundant in this formation. In addition, all of the limestones in this unit contain micritized fossils. Such preservation indicates a turbulent, shallow-water environment in which shell material was exposed to varying amounts of reworking, degradation, and encrustation for a considerable length of time before final burial. The Whitewater facies probably represents a shallow-water carbonate shoal which was located seaward of the Saluda lithotope. This shoal acted as a barrier to incoming wave energy, thereby allowing mud-rich, dolomitic sediments to accumulate in a quiet-water zone behind the barrier bar.

During Kope to Bellevue time, frequent storm activity resulted in the loss of fine-grained sediments from the shoreface zone (i.e., the Bellevue lithotope) into the deeper parts of the ramp (i.e., the Fairview and Kope lithotopes--see previous discussion). The following evidence suggests that this process was just as active during Waynesville to Saluda time:

(1) The thin, wavy, discontinuous bedding, the low shale content, and the thinness of the Whitewater Formation itself indicate a loss of indigenous sediments downslope via storm-induced gravity flows. (2) The presence of textural inversions in the Waynesville and Liberty formations indicates that fine-grained carbonate sediments originating from a nearby shallow-water source were periodically transported into the offshore and transition zones. (3) The high coarse grainstone to fine grainstone ratio and the absence of calcisiltites in the Whitewater Formation indicate a nearly continual loss of fine-grained sediments into deeper water. (4) The presence of fine grainstone and calcisiltite beds in the Waynesville and Liberty formations plus the low coarse grainstone to fine grainstone ratio in both units indicate that fine carbonate sediments originating in shallow water were periodically transported downslope into the offshore and transition zones.

Facies D of the ideal shoaling-upward shelf cycle is represented by the *Saluda Formation*. This unit was deposited in very shallow water, ranging from shallow subtidal (lagoonal) to supratidal. The *Lower Saluda Member* was deposited in a back-shoal, shallow subtidal (lagoonal) environment, based on the following evidence: (1) The abundance of mud-rich carbonate rocks (mostly wackestones), in addition to the presence of shale (27 percent), suggests a protected subtidal environment in which fine-grained sediments were able to accumulate shoreward of the "Whitewater shoal" (see Figure 73). (2) The presence of planar bedding, in contrast to the wavy bedding in the underlying Whitewater Formation, indicates a lack of wave erosion on bottom sediments. (3) The abundance of bioturbation (particularly *Skolithos*) indicates a shallow-water setting (primarily shoreface to intertidal). (4) The presence of thin, graded layers of fine grainstone, in addition to the presence of abundant shale interbeds (80 percent) in the bottom 3 meters of the unit, suggests that storms occasionally deposited terrigenous muds and carbonate sand (derived from the "Whitewater shoal") into the Lower Saluda lagoon, where they were trapped. (5) The abundance of gastropods, ostracods, and pelecypods in addition to the low generic diversity characteristic of this unit suggest a shallow-water, penesaline, lagoonal environment having restricted oceanic circulation. (6) The presence of intraclasts, pellets, and blue-green algae in carbonate rocks indicates a shallow, quiet-water setting.

The *Middle Saluda Member* was probably deposited in an intertidal setting, based on the following evidence: (1) The absence of body fossils indicates a stressful, restricted-marine environment which was inhospitable to most invertebrate life. (2) Vertical tubes and omission surfaces are abundant, suggesting an intertidal setting. (3) This member contains abundant ripples, mudcracks, flat pebble rip-up clasts, birdseye structures, lamination, dolomite, glauconite, and calcite spar-filled vugs, all of which are characteristic features of intertidal flats.

The *Upper Saluda Member* may represent an intertidal-to-supratidal environment. The abundance of dolomite, absence of fossils, abundance of vertical burrows, and the presence of possible desiccation structures indicate a very shallow water environment that was periodically exposed to the atmosphere.

Similarly, the *Preachersville Member* of the *Drakes Formation* also represents a shallow-water, lagoonal-to-intertidal setting, based on the following evidence: (1) The abundance of shale (87 percent) indicates a protected, quiet-water environment. (2) The abundance of dolomitic shales and carbonates suggests a tidal, penesaline environment. (3) The abundance of rip-up clasts, graded storm layers, possible algal lamination, mudcracks, and omission surfaces suggests a shallow subtidal-to-intertidal setting. (4) The abundance of bioturbation (particularly *Skolithos*) indicates a very shallow-water, inner-shelf setting. (5) The presence of a thin zone of red hematite-rich sediments (both in outcrops and cores) suggests periodic subaerial exposure.

Regional Comparison

A detailed west-to-east regional comparison of the Waynesville to Saluda sequence was inhibited by the lack of outcrop exposures in the field area. Although the sequence is completely exposed in Indiana, the only known outcrops in Ohio are those at the Caesar Creek locality, 50 miles east of Brookville, Indiana (see Figures 1 and 62). Only three of the four formations in this sequence occur at Caesar Creek. Furthermore, less than half of the total thickness of the Waynesville Formation and only one-third of the Liberty Formation is exposed at Caesar Creek. Hence, regional trends discussed in this section are tenuous and should be more completely investigated by future workers.

Three west-to-east trends were observed in this sequence: (1) a slight increase in shale content in the Whitewater Formation (from 14 percent to 23 percent); (2) a slight increase in average shale bedding thickness in the Waynesville Formation (from 11 cm to 13 cm); and (3) a change from shale-poor dolomitic rocks of the Saluda Formation (in Indiana) to shale-rich strata of the Preachersville Member (along the eastern edge of the outcrop belt). These trends indicate that the influx of terrigenous sediments during Waynesville to Saluda time was greater in the eastern part of the field area than it was in Indiana. Perhaps this situation was the result of a gradual increase in terrigenous sediment *supply* with the passage of time (and with the eastward progradation of facies across the ramp).

SUMMARY OF DEPOSITIONAL MODEL

The interbedded carbonate and shale strata of the Cincinnatian Series represents shallow-marine deposition on a gently sloping, storm-dominated carbonate ramp. Deposition occurred on the *inner* part of this ramp in sub-environments ranging from the offshore zone to the supratidal zone. This shallow-water ramp lay to the west of an elongate, deep-water turbidite basin which extended from Canada to the southeastern United States. This deep-water basin graded eastward into an elongate landmass (the "Taconic Highlands") which supplied terrigenous sands, silts, and clays to the ocean basin. Cincinnatian Series shales were ultimately derived from this source area.

The strata of the Cincinnatian Series is composed of interbedded shales, siltstones, limestones, and dolomites. The distribution, bedding characteristics, and proportions of each of these rock types were governed by the depositional environments in which they were deposited, and by the specific depositional processes that were active during Late Ordovician time. Two dominant modes of sedimentation were active during Cincinnatian time: *in situ accumulation* of carbonate sediments and *storm sedimentation*. *In situ* carbonate accumulation was a slow process which was periodically interrupted by storm events, and is represented in the rock record by matrix-rich packstones and wackestones. Storm sedimentation was manifested in several ways, including (1) the upslope transportation and deposition of terrigenous muds (represented by graded shale beds); (2) submarine erosion (represented by omission surfaces, irregular or scoured surfaces, rip-up clasts, truncated cross laminae, "Fossil-Lagerstatten," and abrupt changes in rock type or grain size); (3) winnowing of carbonate mud from bottom sediments (represented by poorly washed grainstones, coarse grainstones, and shell lag deposits); and (4) the transportation and redistribution of fine-grained carbonate sediments upslope, downslope, and parallel to slope. The transportation and redistribution of carbonate sediments is represented by textural inversions, graded calcisiltite and fine grainstone beds, and coarse, whole-fossil shell layers. Upslope transportation resulted from storm surge, and downslope transportation resulted from storm ebb or storm-induced gravity flows.

Cincinnatian strata are arranged in a cyclic pattern with at least three different levels of cyclicity represented, including storm cycles, megacycles, and shoaling-upward shelf cycles (see Figure 30). Storm cycles are thin (< 20 cm), fining-upward sequences of rocks (both limestone and shale) which represent the periodic deposition of sediments by hurricane events. The characteristic graded bedding is the result of deposition from suspension during a period of declining flow regime (i.e., as the storm is waning).

Megacycles are moderately thin (< 5 m) sequences of interbedded carbonates and shales in which carbonate-rich strata (the "carbonate hemicycle") grade upward into shaley strata (the "shale hemicycle"). These cycles represent a periodic shift from carbonate sedimentation to shale sedimentation, and probably reflect fluctuating terrigenous sediment supply. The supply of terrigenous sediments may have been controlled by global climatic fluctuations or by shifting source areas.

Shoaling-upward shelf cycles are thick sequences (49 m to 106 m) of strata that consist of four major rock facies (from bottom to top): *Facies A*, a thick, planar-bedded, shale-rich unit; *Facies B*, a moderately thick, planar-bedded unit containing nearly equal proportions of carbonate and shale; *Facies C*, a thin, wavy- to nodular-bedded, limestone-rich unit; and *Facies D*, a moderately thick unit composed of dolomites, dolomitic limestones, and dolomitic shales. Three examples of shoaling-upward shelf cycles are present in the Cincinnatian Series (see Figure 74 and Table 17). The superposition of rock facies within shoaling-upward shelf cycles was formed by the lateral progradation of consanguineous environments, ranging from offshore shelf (Facies A) to supratidal (Facies D). Hence, these cycles are regressive vertical sequences that can be explained by Walther's Law (see Figure 75).

A record of frequent storm activity during Late Ordovician time has been well preserved in the undeformed strata of the Cincinnatian Series. Many of the sedimentary characteristics of the Cincinnatian Series (bedding style, rock types, vertical sequences, sedimentary structures, etc.) are the direct result of frequent hurricane events. Because of the excellent preservation of these events, the Cincinnatian Series should be utilized by future workers as an example of an ancient *storm dominated* carbonate shelf. Accordingly, the following characteristics of the Cincinnatian Series may be used as criteria for recognizing storm domination in other examples of ancient carbonate shelf strata: (1) Thin, fining-upward storm sequences are abundant and occur in all rock facies. (2) A wide variety of storm sequences exists. (3) Rock facies representative of inner shelf environments are thinner and have a thinner, less continuous bedding style than facies representative of outer shelf environments.

(4) Winnowed, coarse-grained, shelly sediments (rudites) are most abundant in those facies representative of very shallow-water environments. (5) Clean, well-sorted, fine-grained limestone beds (fine grainstones and calcisiltites) occur in all facies, but are concentrated in deeper shelf facies. (6) Textural inversions are common. (7) A wide variety of carbonate rock types occur in all facies. (8) Vertical escape structures, omission surfaces, erosional (scoured) surfaces, mud clasts, ripples, cross bedding, and sole marks are common in all facies. (9) Well-preserved, *in situ* faunal communities are rarely preserved. (10) The tops of most carbonate beds contain a mixture of fossil preservational states.

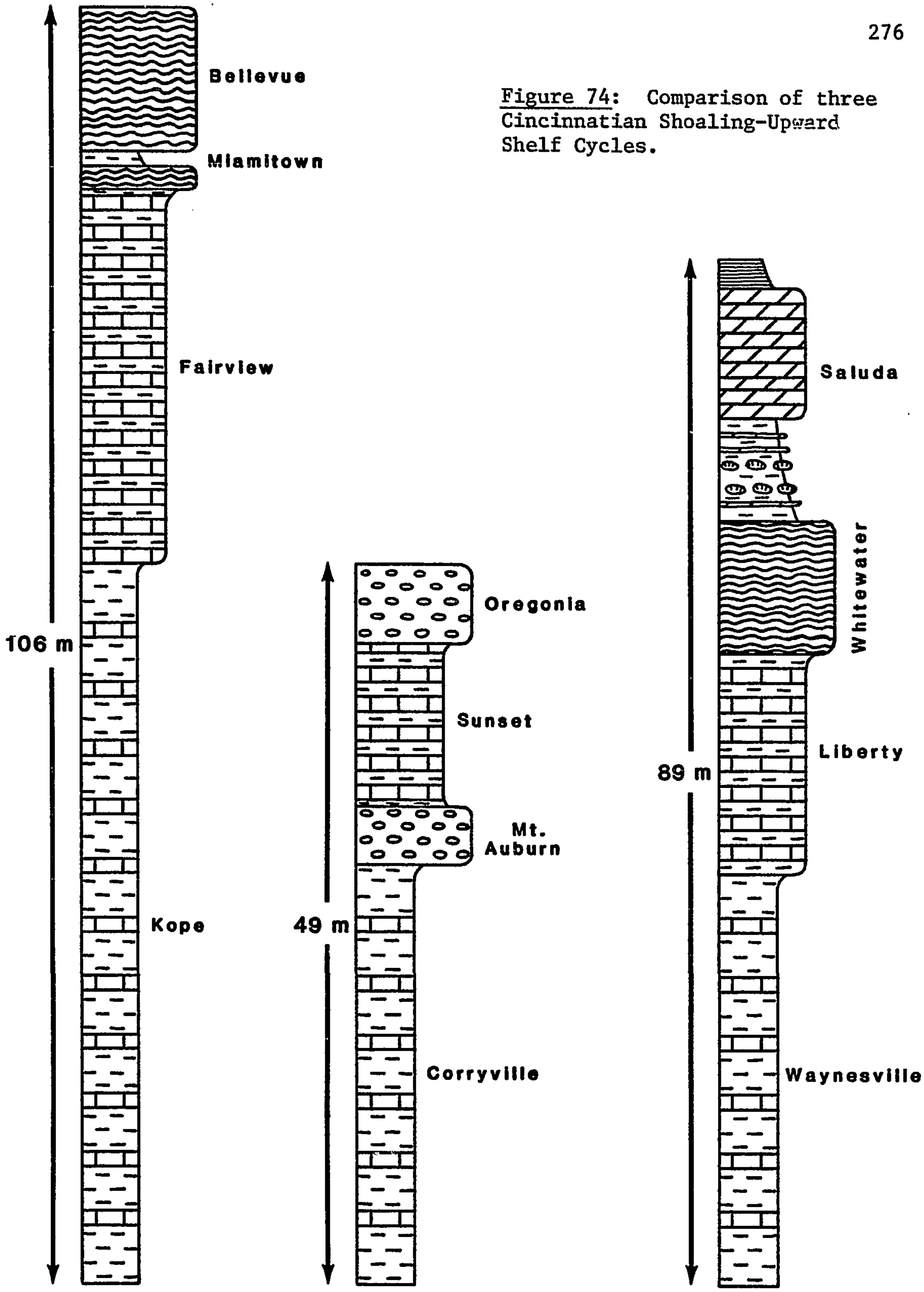
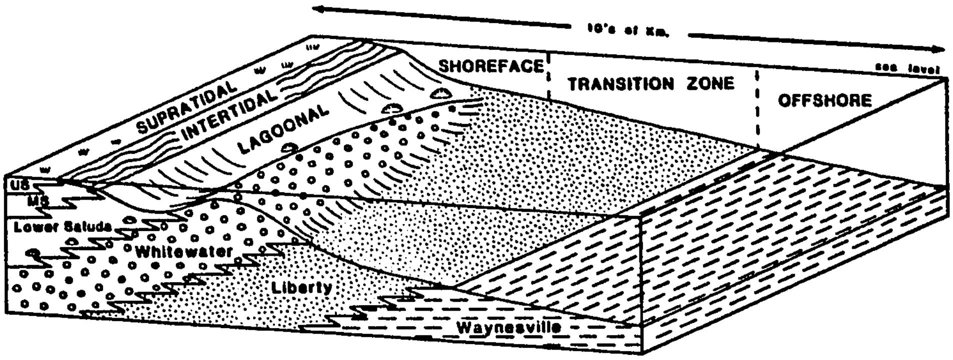


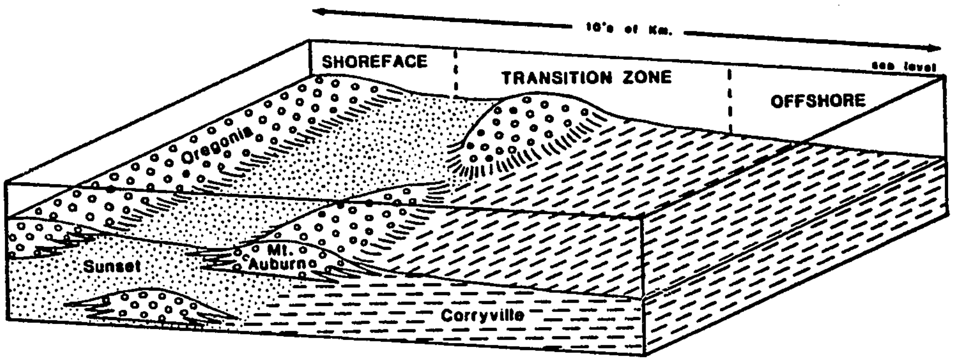
Figure 74: Comparison of three Cincinnatian Shoaling-Upward Shelf Cycles.

FACIES	SHOALING-UPWARD SHELF CYCLES		
	KOPE TO BELLEVUE	CORRYVILLE TO OREGONIA	WAYNESVILLE TO SALUDA
D	Absent	Absent	Saluda: Shale-poor (10%); bedding is massive, continuous; megacycles absent; dolomites, dolomitic limestones, and dolomitic shales; restricted-marine fossil assemblage; *Skolithos* trace fossils.
C	Bellevue: Shale-poor (18%); bedding is wavy, discontinuous, and thin (4 cm); megacycles absent; grainstones dominate (89%); shales are silt-poor (claystones); open-marine fossil assemblage; *Skolithos* trace fossils.	Mt. Auburn/Oregonia: Mod. shale content (40%); bedding is nodular and wavy, very discontinuous and thin (4 cm); megacycles absent; grainstones (43%) and packstones (37%) dominate; shales are silt-poor (claystones); open-marine fossil assemblage; *Skolithos* trace fossils.	Whitewater: Shale-poor (14%); bedding is wavy, discontinuous, and thin (4 cm); megacycles absent; grainstones dominate (83%); shales are silt-poor (claystones); open-marine fossil assemblage; *Skolithos* trace fossils.
B	Fairview: Mod. shale content (49%); bedding is planar, mod. continuous, and medium thick (8 cm); thin megacycles; packstones (53%) and grainstones (26%) dominate; shales are silty (mudstones); open-marine fossil assemblage; *Cruziana* trace fossils.	Sunset: Mod. shale content (52%); bedding is planar, mod. continuous, and medium thick (7 cm); thin megacycles; packstones (60%) and grainstones (27%) dominate; shales are silty (mudstones); open-marine fossil assemblage; *Skolithos/Cruziana* trace fossils.	Liberty: Mod. shale content (45%); bedding is planar, mod. continuous, and medium thick (8 cm); thin megacycles; packstones (44%) and grainstones (43%) dominate; shales are silt-rich (mudstones); open-marine fossil assemblage; *Skolithos/Cruziana* trace fossils.
A	Kope: Shale-rich (80%); bedding is planar, mod. continuous, and thick (12 cm); thick megacycles; packstones (45%) and siltstones (30%) dominate; shales are silt-rich (mudstones); open-marine fossil assemblage; *Cruziana* trace fossils.	Corryville: Shale-rich (64%); bedding is planar, mod. continuous, and medium thick (8 cm); thick megacycles; packstones (60%) and siltstones (13%) dominate; shales are silt-rich (mudstones); open-marine fossil assemblage; *Cruziana* trace fossils.	Waynesville: Shale-rich (67%); bedding is planar, mod. continuous, and thick (9 cm); thick megacycles; packstones dominate (73%); shales are silty (claystones); open-marine fossil assemblage; *Cruziana* trace fossils.

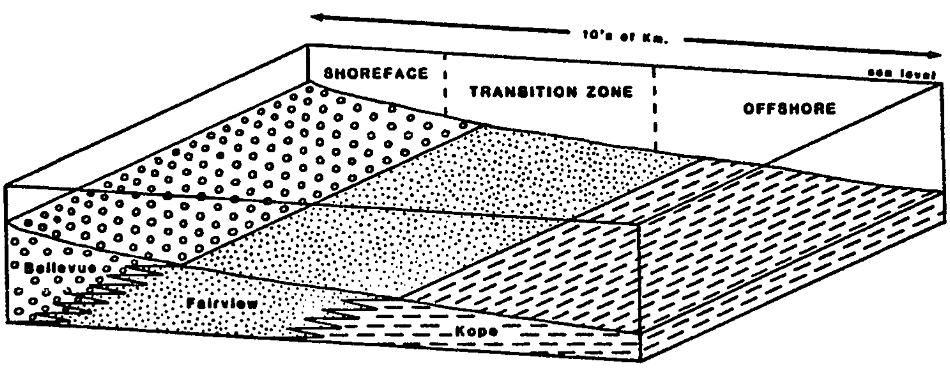
Table 17: Comparison of three Cincinnatian Shoaling-Upward Sequences.



Waynesville to Saluda Sequence



Corryville to Oregonia Sequence



Kope to Bellevue Sequence

Figure 75: Facies interpretation of three Cincinnatian Shoaling-Upward Shelf Cycles.

C O N C L U S I O N S

(1) Previous lithostratigraphers have disregarded the presence of numerous rock facies in the Cincinnatian Series which had *originally* been described and named by "biostratigraphers" as early as 1902. Because these rock facies have priority in description, are mappable, have distinctive lithologic characteristics, and conform to the facies concept, it is proposed that they be reinstated as valid formations.

(2) The strata of the Cincinnatian Series were deposited on the inner part of a gently sloping, unbarred, shallow-marine carbonate ramp. Deposition occurred in subenvironments ranging from the offshore zone to the supratidal zone. This shallow-water ramp lay to the west of an elongate, deep-water turbidite basin.

(3) The Cincinnatian Series is composed of interbedded carbonates and shales. Although some carbonate rocks are restricted to certain facies (e.g., dolomites occur only in the Saluda facies), eight varieties of carbonate rocks are repeatedly encountered throughout the Cincinnatian Series. These "recurrent" rock types include packstones, wackestones, micstones, siltstones, poorly washed grainstones, coarse grainstones, fine grainstones, and calcisiltites. The first three rock types represent *in situ* accumulation below wave base, whereas the last five represent high-energy storm deposition.

(4) Carbonate diagenetic processes include dolomitization, calcite spar cementation, recrystallization, partial silicification, phosphatization, pyritization, and limonite staining. Diagenetic minerals and textures in Cincinnatian limestones suggest that these rocks were subjected

to at least two diagenetic environments (the "mixing zone" and the "marine phreatic zone").

(5) Cincinnatian shales are olive gray in color, unfossiliferous, unlaminated, and dolomitic. The "average" shale is a dolomitic mudstone. Most shales are unburrowed and occur as graded "packages" ranging from several mm to several cm in thickness. Shales were ultimately derived from the Taconic Highlands (at least 350 miles to the east) and were rapidly deposited from suspension by storm events.

(6) Cincinnatian strata are arranged in a cyclic pattern. Three different levels of cyclicity are represented, including *storm cycles* (thin, fining-upward sequences that were deposited from suspension by storms); *megacycles* (moderately thin sequences that have an upper shale-rich hemicycle and a lower carbonate-rich hemicycle and represent fluctuating terrigenous sediment supply); and *shoaling-upward shelf cycles* (thick sequences of strata that grade upward from shale-rich facies to shale-poor facies and represent the lateral progradation of consanguineous environments, ranging from offshore shelf to supratidal).

(7) Three examples of shoaling-upward shelf cycles are present in the Cincinnatian Series: the *Kope to Bellevue* sequence, the *Corryville to Oregonia* sequence, and the *Waynesville to Saluda* sequence. Each sequence is bounded by unconformable upper and lower contacts.

(8) Tropical storms were responsible for the wide variety of carbonate rock types, and for most of the bedding features characteristic of the Cincinnatian Series. Storms contributed to sedimentation by transporting shales upslope onto the shallow-water carbonate ramp (thereby producing shale interbeds), by eroding sediments, by winnowing carbonate mud

from sediments (thereby producing poorly washed grainstones and coarse grainstones), and by transporting and redistributing carbonate sediments upslope, downslope, and parallel to slope (resulting in fine grainstone and calcisiltite beds).

(9) Tropical storms affected the paleoecologic record of the Cincinnatian Series by periodically interrupting the process of community succession, by obscuring evidence of community succession, by mixing benthic fauna from neighboring communities (resulting in the non-preservation of many *in situ* benthic communities), and by creating favorable conditions for the evolution and success of opportunistic species.

(10) Cincinnatian carbonate depositional rates were probably comparable to modern carbonate depositional rates. However, *calculated* depositional rate for the Cincinnatian Series is too slow by a factor of 100 to 1. This discrepancy is largely the result of the frequent interruption of carbonate sedimentation by Late Ordovician storms. Hence, the Cincinnatian Series is a record of rapid, but very discontinuous sedimentation.

(11) The Cincinnatian Series is a good example of an ancient, storm-dominated carbonate shelf. Storm-generated characteristics of the Cincinnatian Series may be used as criteria for recognizing storm domination in other examples of ancient carbonate shelf strata.

SUGGESTIONS FOR FUTURE WORK

One of the objectives of this study is to provide a plan for future research on the Cincinnatian Series. I believe that this research should focus on topics that will test the validity of the depositional model proposed in this study, and generate new ideas and information which may enhance the model. Perhaps this plan will help to avoid the random, unrelated studies of the Cincinnatian Series that have been so characteristic of the past. Accordingly, I recommend that the following topics be investigated by future workers:

(1) The diagenesis of Cincinnatian carbonate rocks should be more fully investigated. Modern analytical equipment such as the cathode luminoscope, scanning electron microscope, mass spectrometer, and electron microprobe can be used to enhance information obtained from stained thin sections, particularly with respect to isotopic and trace element composition of diagenetic minerals. Such research could yield valuable information about specific diagenetic processes, diagenetic environments, and the timing of diagenetic events (relative to each other and with respect to geologic time).

(2) The Cincinnatian Series should be studied from subsurface data. Core descriptions and well logs could provide valuable information about geographic areas in which little or no outcrop data is presently available. Such information may enable future geologists to correlate individual stratigraphic units and lithogenetic sequences in greater detail. Furthermore, if subsurface data could be used to trace the Cincinnatian Series away from the field area (i.e., into northern Ohio, eastern Ohio,

and central Indiana), the lateral extent and nature of the Late Ordovician carbonate ramp could be more accurately defined.

(3) Upper Ordovician strata in central Kentucky should be re-examined to determine if the revised stratigraphic nomenclature proposed in this study for the southwestern Ohio and southeastern Indiana region is applicable to the central Kentucky area. Furthermore, a depositional model should be developed for these rocks, based on modern sedimentologic and paleoecologic analyses, and compared to the model proposed in this paper for southwestern Ohio and southeastern Indiana.

(4) As previously mentioned, Cincinnatian megacycles exhibit a limited amount of homotaxial correlation over short distances (at least 6.5 miles). However, the maximum lateral extent of a given megacycle is unknown. Perhaps future workers will be able to trace megacycles regionally to determine their geometry, lateral extent, and stratigraphic relationship with adjacent units.

(5) As mentioned earlier, the paleogeographic and stratigraphic relationships between the Saluda Formation, Elkhorn Formation, and Preachersville Member of the Drakes Formation are unclear. Future stratigraphers should investigate these relationships by making a systematic search for new outcrop exposures in the area north of Cincinnati (between Brookville, Indiana, and Goes, Ohio--the northernmost exposure of the Preachersville Member), and by utilizing subsurface data, if available.

(6) The Miamitown Shale should be examined in greater detail to determine its lateral extent, thickening trend(s), and relationship to contiguous formations. This data could be used to determine if the Miamitown Shale represents a time line or a lithotope contemporaneous with the

Bellevue, Fairview, and Kope lithotopes (see discussion in "Kope to Bellevue Sequence").

(7) A detailed sedimentologic and biostratinomic comparison should be made between the Bellevue and Whitewater formations, and the Mt. Auburn and Oregonia formations. All four units are examples of Facies C of the idealized shoaling-upward shelf cycle. However, the first two formations are lithologically and faunally different from the last two formations, and may represent similar, but different paleoenvironments or paleoenvironmental conditions.

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APPENDIX 1

THICKNESS OF FORMATIONS DESCRIBED IN OUTCROP

Outcrop Locality	Formations and Thickness	Total Thickness
(A) Aiken High School, Cincinnati, OH	Sunset (6.0 m), Oregonia (2.0 m)	8.0 m
(BK) Bald Knob Hill, Cincinnati, OH	Kope (6.6 m), Fairview (0.6 m described)	7.2 m
(Ba) Batavia, OH	Kope (16.0 m)	16.0 m
(Bl) Blue Rock Road Cincinnati, OH	Corryville (1.0 m), Mt. Auburn (5.1 m), Sunset (2.5 m)	8.6 m
(BD) Brookville Dam, Brookville, IN	Corryville (13.8 m), Sunset (13.5 m), Oregonia (7.4 m), Waynesville (35.9 m), Liberty (15.4 m)	86.0 m
(BN) Brookville North, Brookville, IN	Waynesville (13.5 m), Liberty (18.3 m), Saluda (4.3 m), Whitewater (1.1 m)	37.2 m
(G) Georgetown, OH	Kope (8.9 m), Fairview (9.2 m), Bellevue (14.8 m), Corryville (5.0 m)	37.9 m
(I) I-275 East/KY Rt. 445	Kope (59.0 m)	59.0 m
(M) Middletown, OH	Corryville (5.0 m), Mt. Auburn (4.6 m), Sunset (2.4 m)	12.0 m
(Re) Reidlin Road, KY	Kope (8.5 m), Fairview (32.6 m), Bellevue (4.5 m), Miamitown (0.4 m)	46.0 m
(Ri) Rt. 27 North, Richmond, IN	Whitewater (7.0 m)	7.0 m
(Ru) Rumpke Landfill, Cincinnati, OH	Corryville (13.9 m), Mt. Auburn (5.2 m), Sunset (4.2 m)	23.3 m

APPENDIX 2

OUTCROP LOCATIONS IN THE FIELD AREA

Outcrop Locality	Location
(A) Aiken High School	Roadcut along driveway on the north side of the school. Access is from Belmont Avenue, College Hill.
(BK) Bald Knob Hill	Roadcut along driveway, 0.2 miles west of intersection of Lehman Road and State Avenue, Cincinnati.
(Ba) Batavia, Ohio	Roadcut along exit ramp from State Route 32 East, Batavia, Ohio. Outcrop is about 0.5 miles east of the East Fork of the Little Miami River.
(Bl) Blue Rock Road	Roadcut just past entrance ramp to Blue Rock Road, Cincinnati, Ohio. Outcrop is 0.3 miles southeast of intersection of I-275 and Blue Rock Road (Exit 31).
(BD) Brookville Dam	Spillway section south of Brookville Lake. Access is from Route 101 North, 1.5 miles north of Brookville, Indiana.
(BN) Brookville North	Roadcuts along both sides of Route 101, 5.0 miles north of Brookville, Indiana.
(G) Georgetown, Ohio	Composite section; Kope formation outcrops along banks of White Oak Creek south of Route 125. Remainder of section is a roadcut on Route 125 about 0.8 miles west of the Georgetown city limits.
(I) I-275 East/KY Route 445	Composite Kope section; lower Kope outcrops along roadcut at intersection of KY 445 and Route 8, Fort Thomas, Kentucky. Upper Kope outcrops along the north side of I-275, just west of the Ohio River
(M) Middletown, Ohio	Roadcut along Ohio Route 4, just south of bridge across Dicks Creek, and about 0.3 miles south of Route 73.

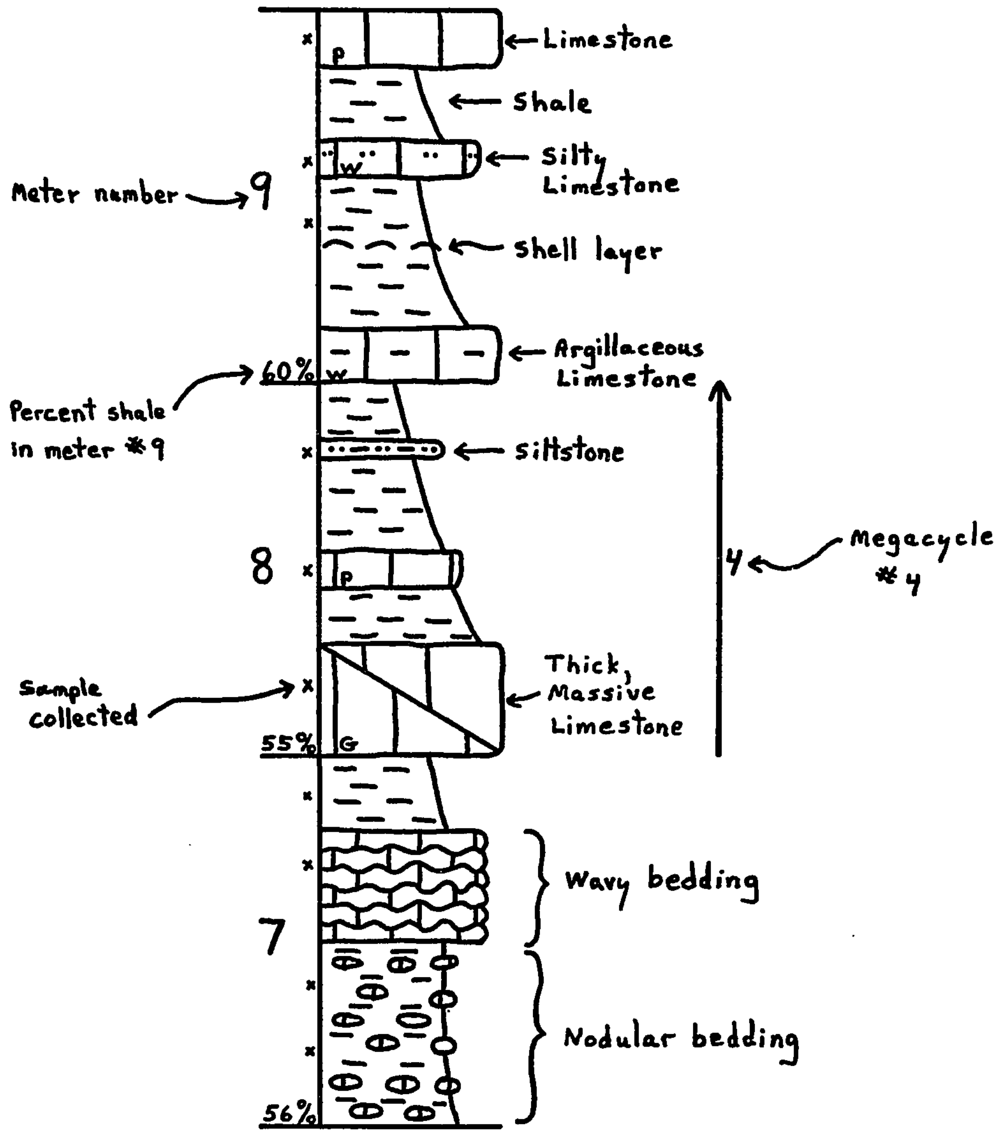
APPENDIX 2 (continued)

Outcrop Locality	Location
(Re) Reidlin Road, KY	Outcrop along Reidlin Road, just south of Covington, Kentucky. Access is from Route 16, 0.5 miles north of I-275 (Exit 79) and 0.6 miles south of Banlick Creek.
(Ri) Route 27 North, Richmond, Indiana	Roadcut along west side of Route 27, 1.0 mile south of Richmond, Indiana.
(Ru) Rumpke Landfill	Streamcut and landfill exposure in field east of Route 27 North (Colerain Avenue, Cincinnati), 1.5 miles north of I-275.

APPENDIX 3

Detailed Outcrop Descriptions

Key to Geologic Columns:



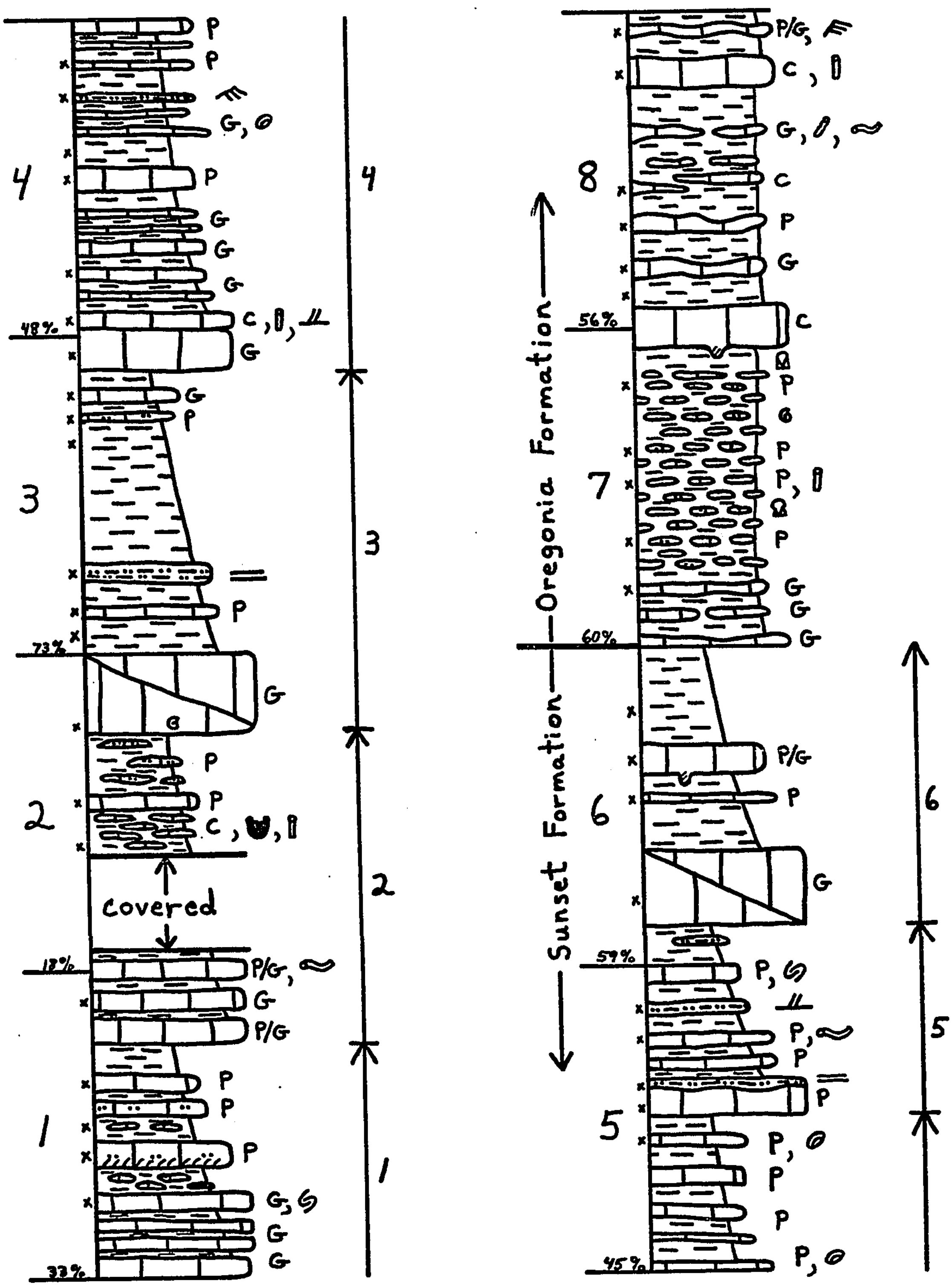
Key to Symbols:

- *Diplocraterion*
- *Paleophycus*, *Trichophycus*
- vertical tubes
- inclined tubes
- *Chondrites* (horizontal)
- *Chondrites* (vertical)
- color mottling
- slumping
- horizontal lamination
- cross lamination
- ripples
- imbricate shells
- gutter casts
- mud clasts
- hardground
- cone-in-cone
- onkoids
- corals
- ostracods
- trilobites
- gastropods
- pelecypods
- crinoids
- bryozoans
- brachiopods
- abrasion
- boring

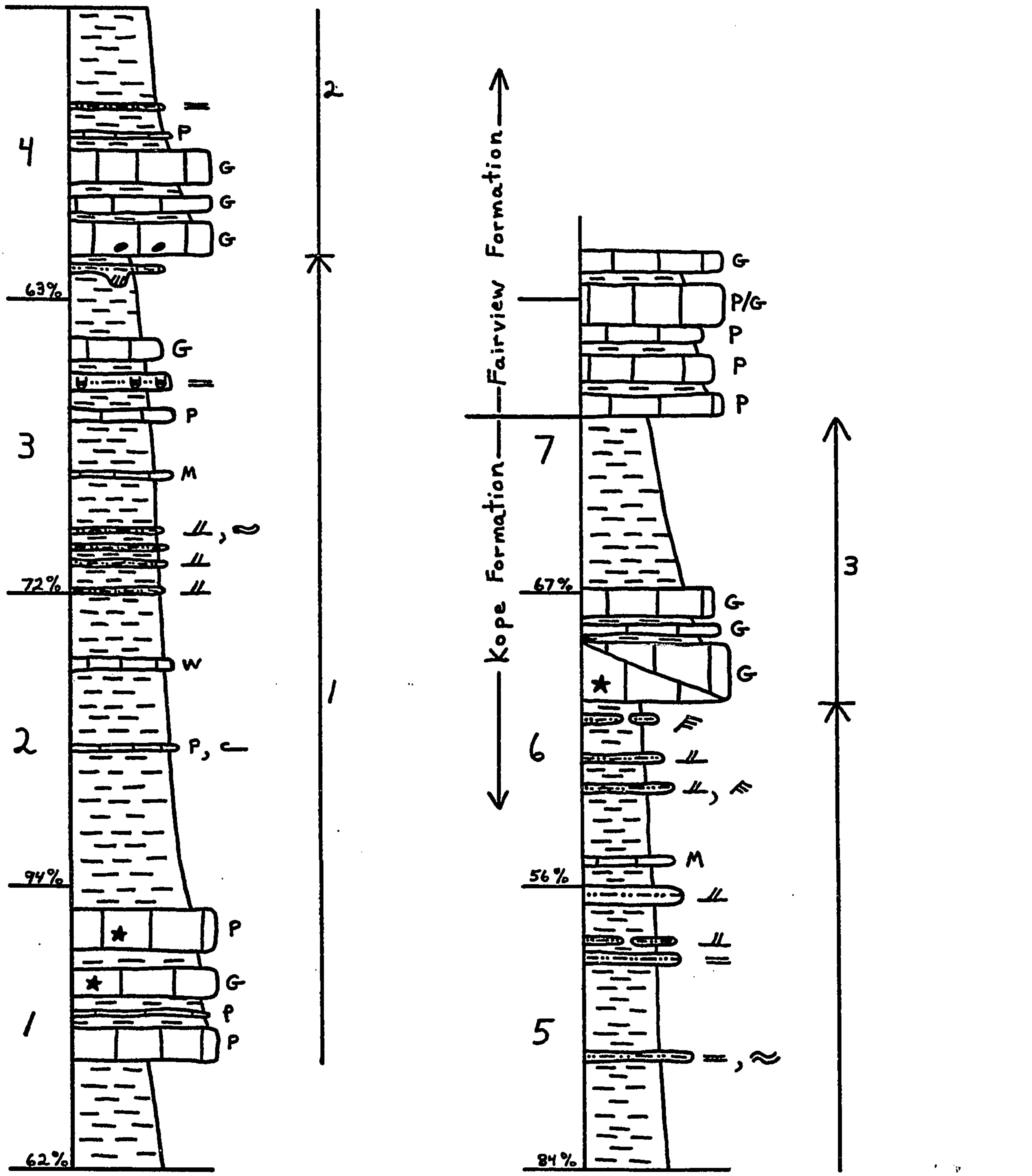
Rock Types:

P = packstone
W = wackestone
M = micstone
P/G = poorly washed grainstone
G = grainstone
C = calcisiltite

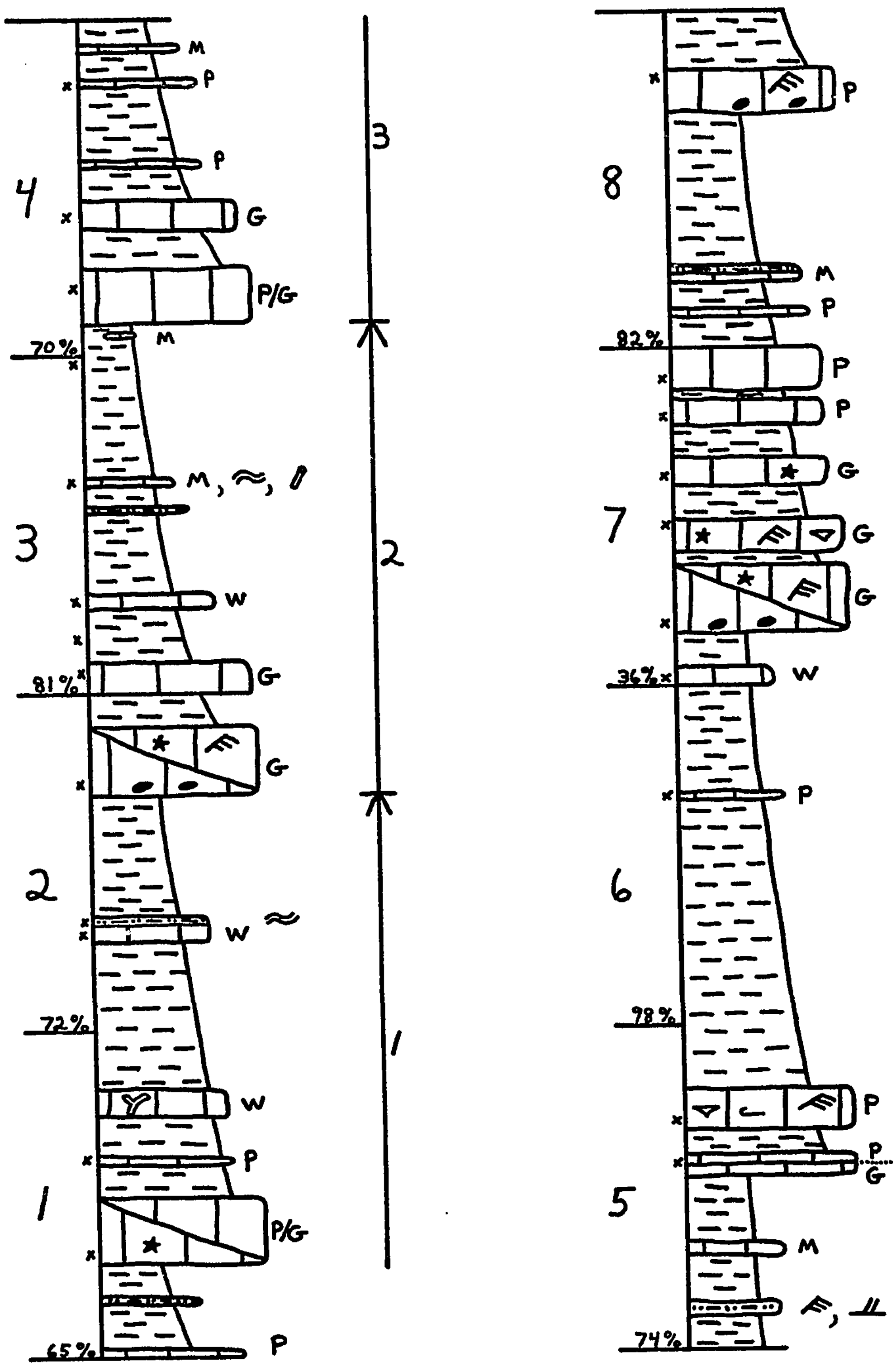
AIKEN HIGH SCHOOL



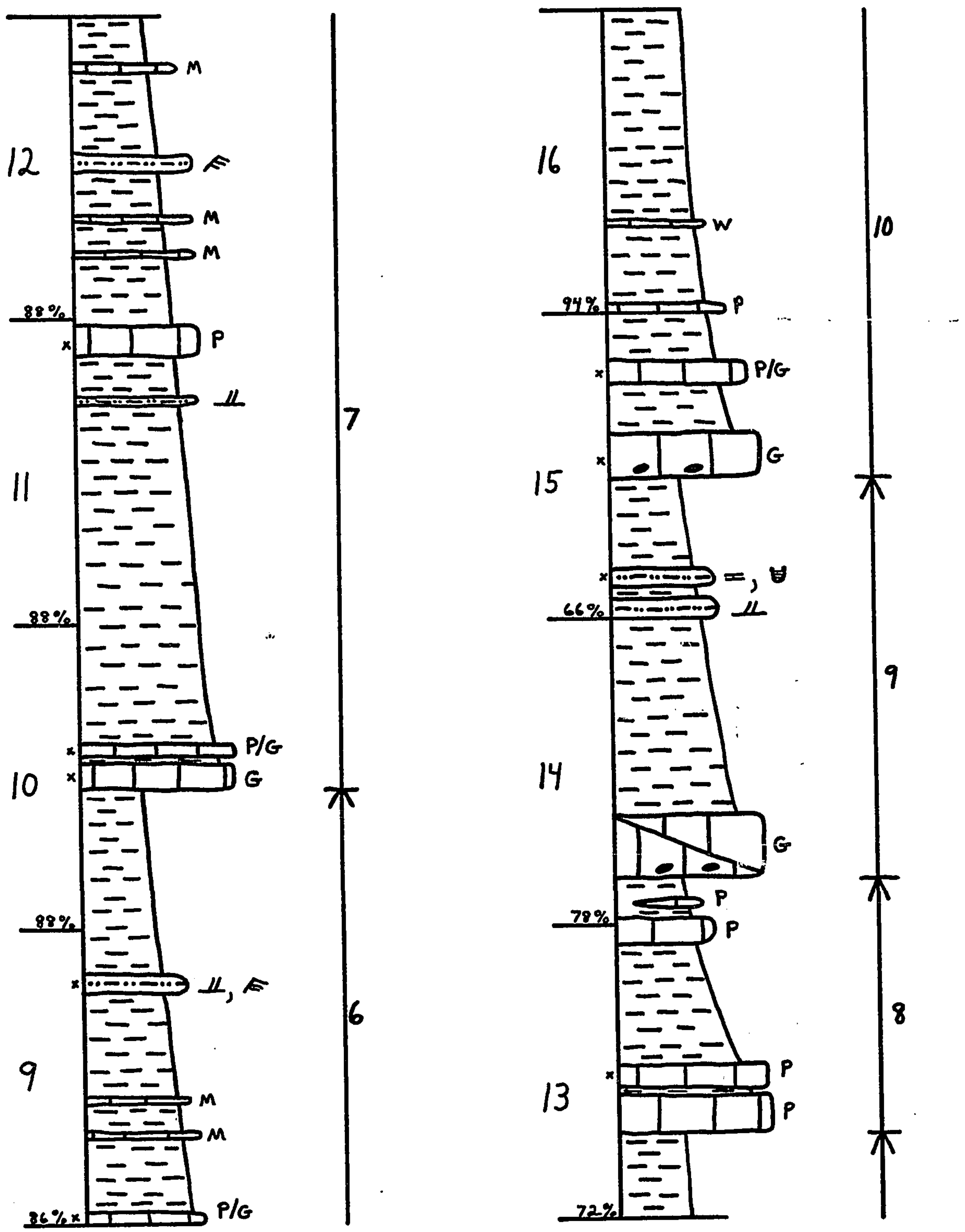
BALD KNOB HILL



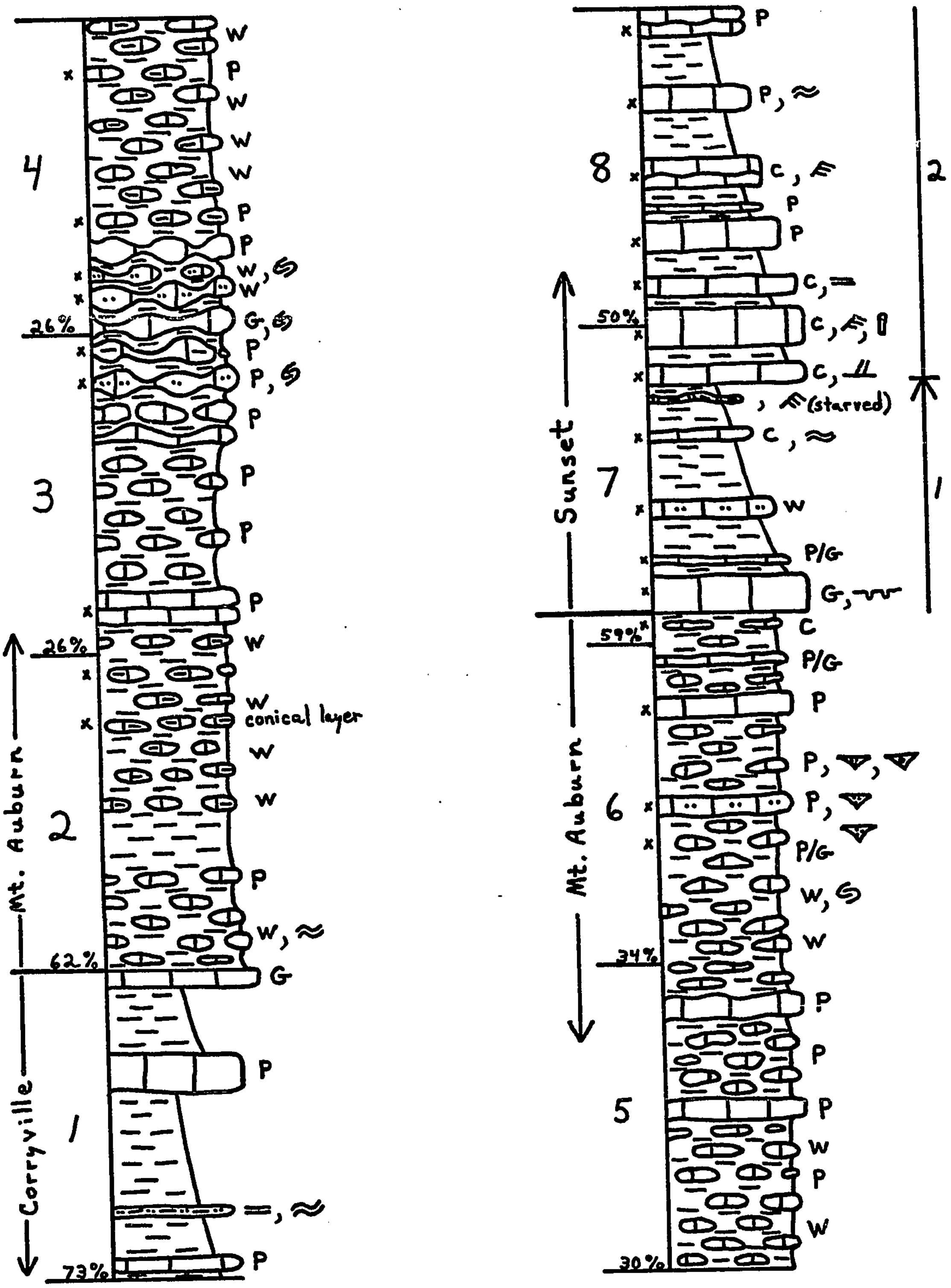
BATAVIA, OHIO (Kope Fm.)



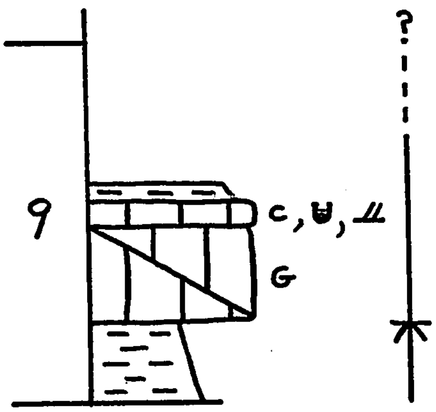
BATAVIA, OHIO (cont.)



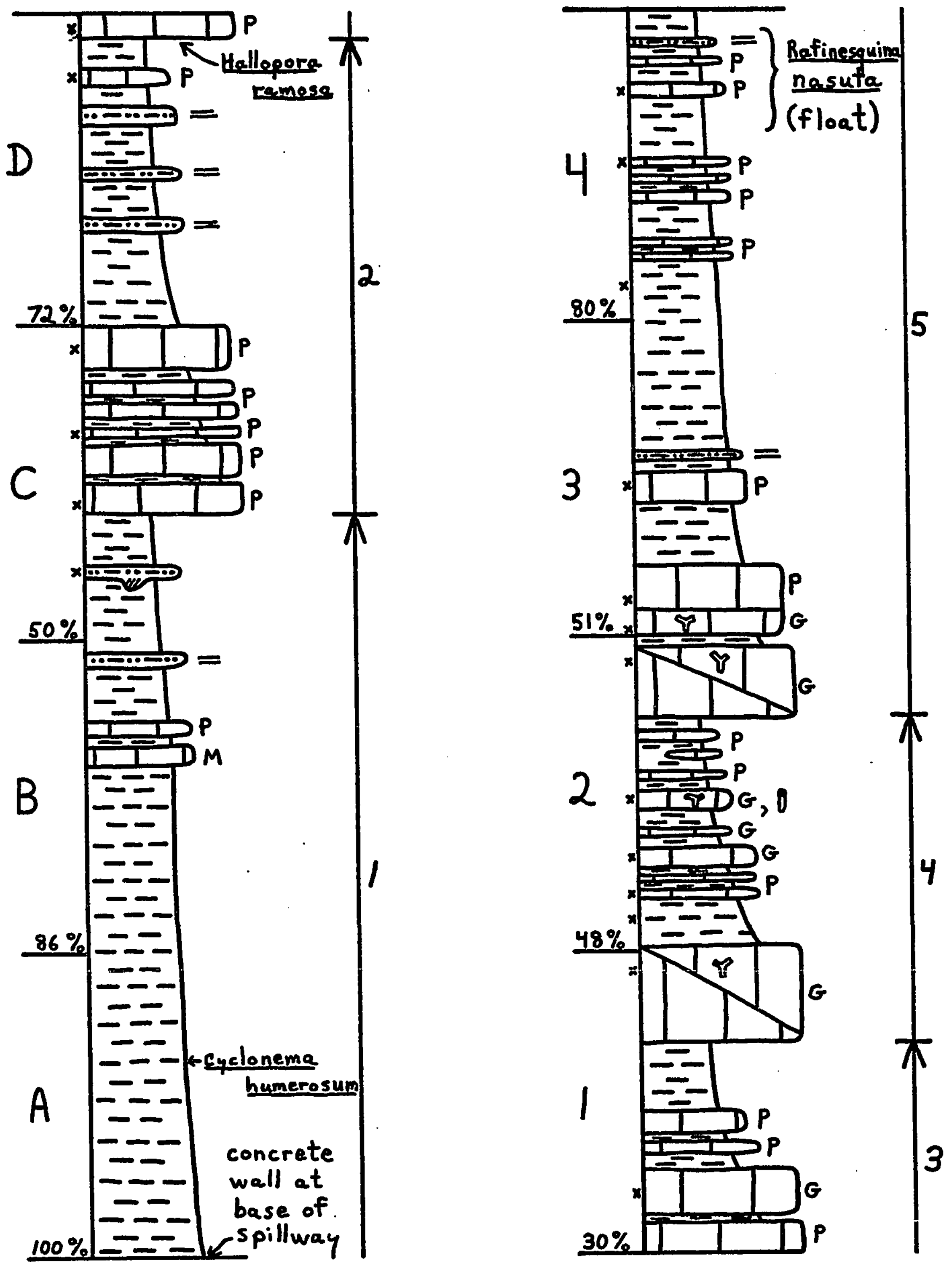
BLUE ROCK ROAD



BLUE ROCK ROAD (cont.)



BROOKVILLE DAM (Corryville Fm.)



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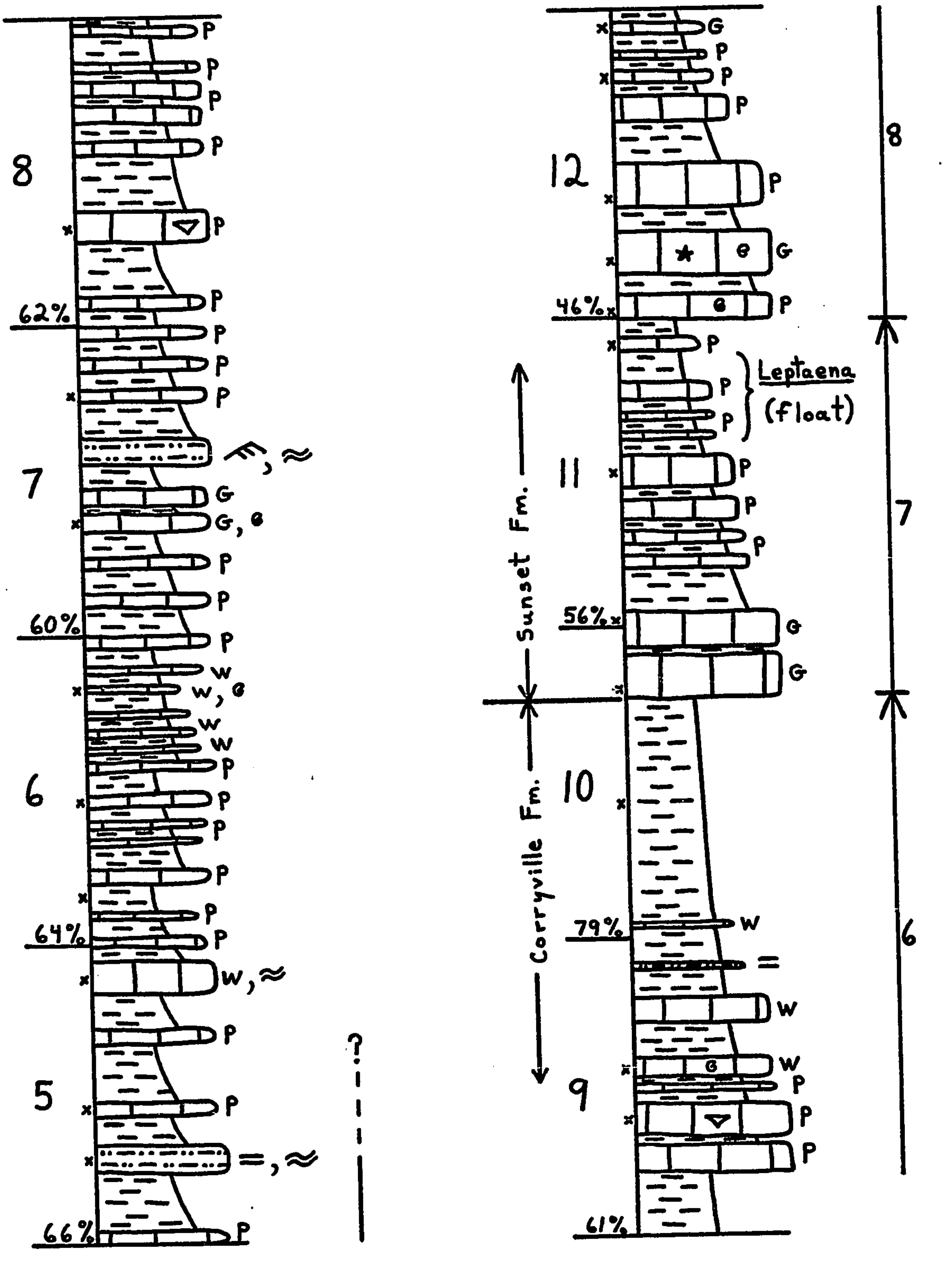

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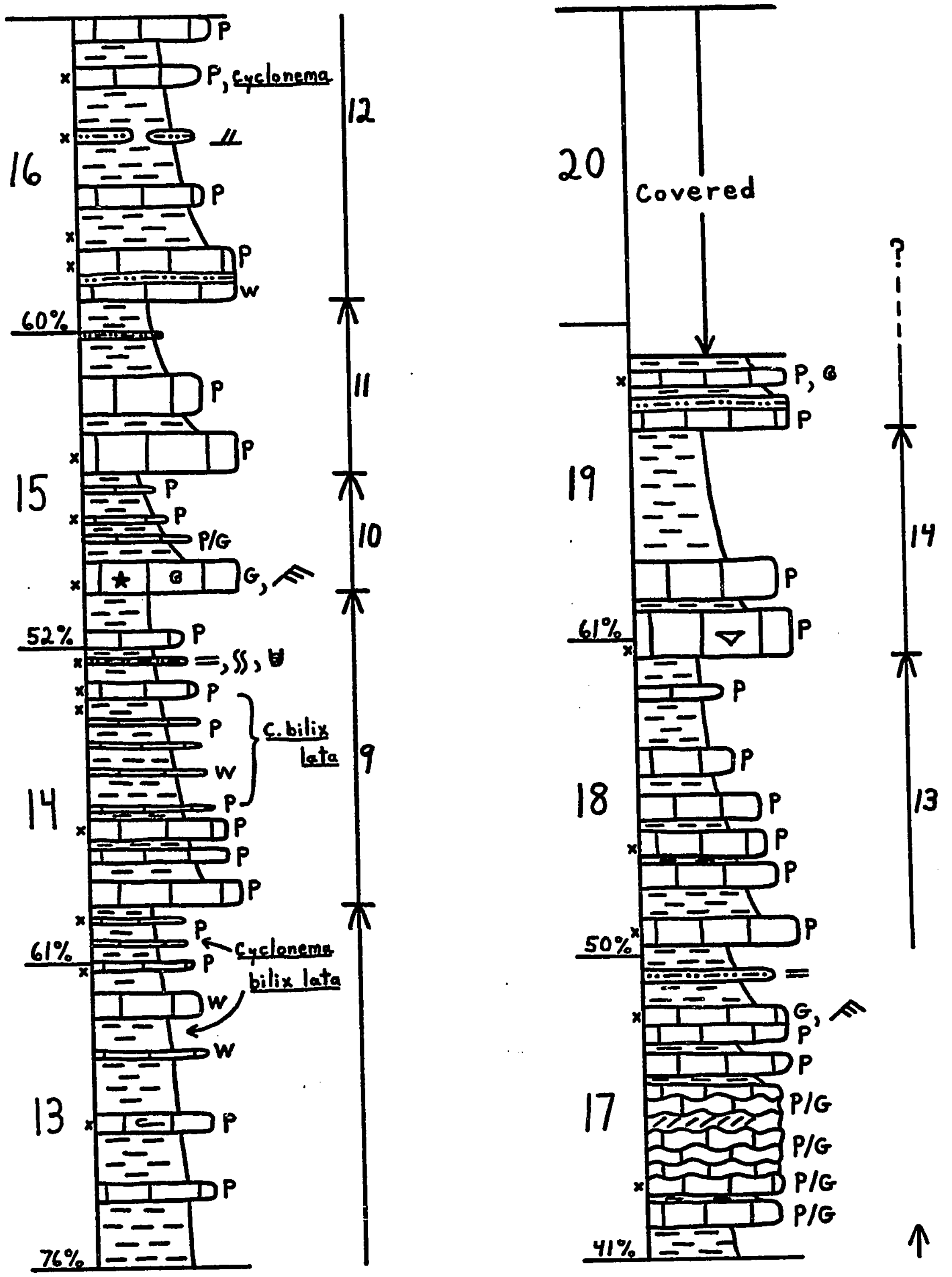

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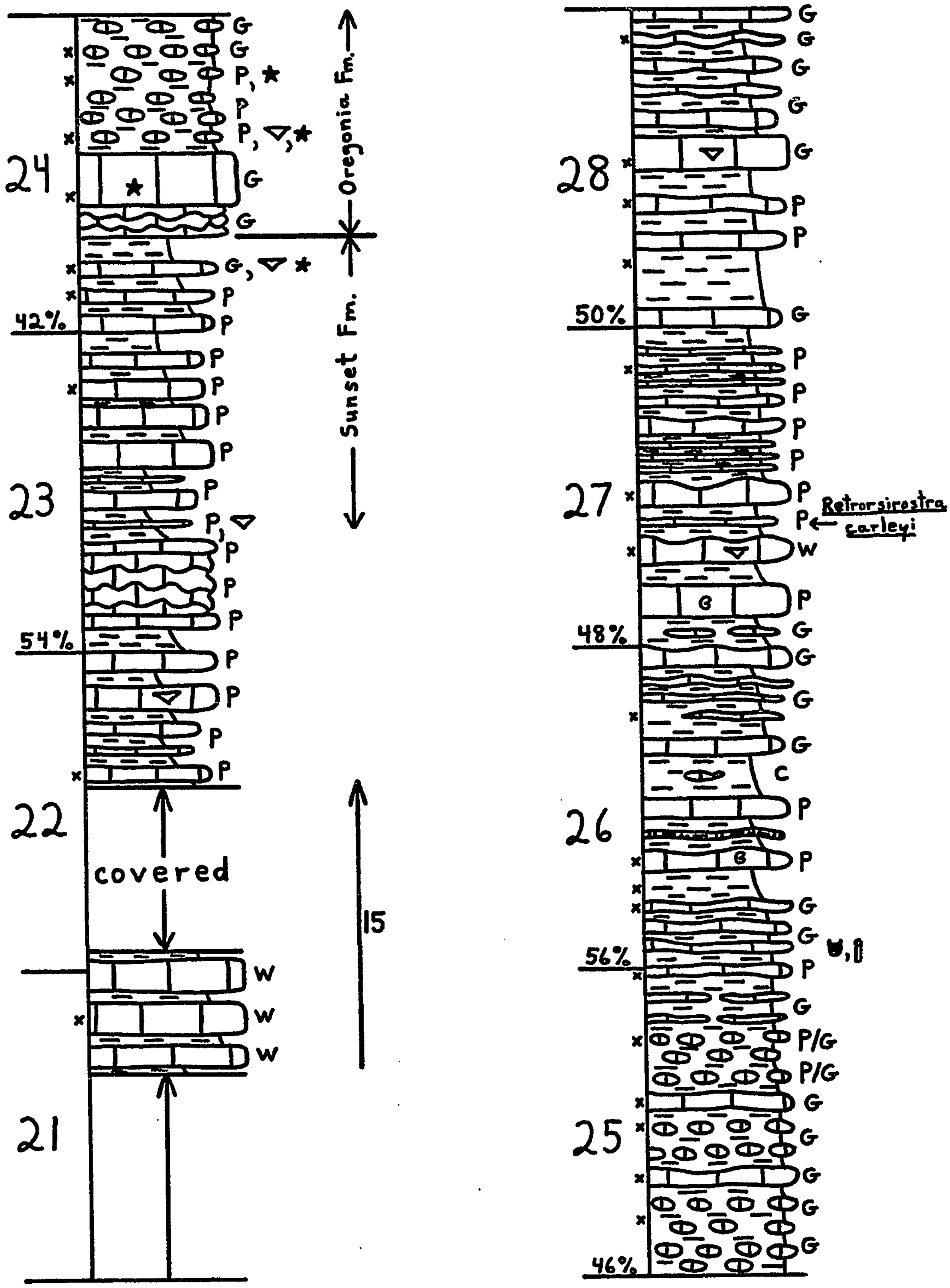

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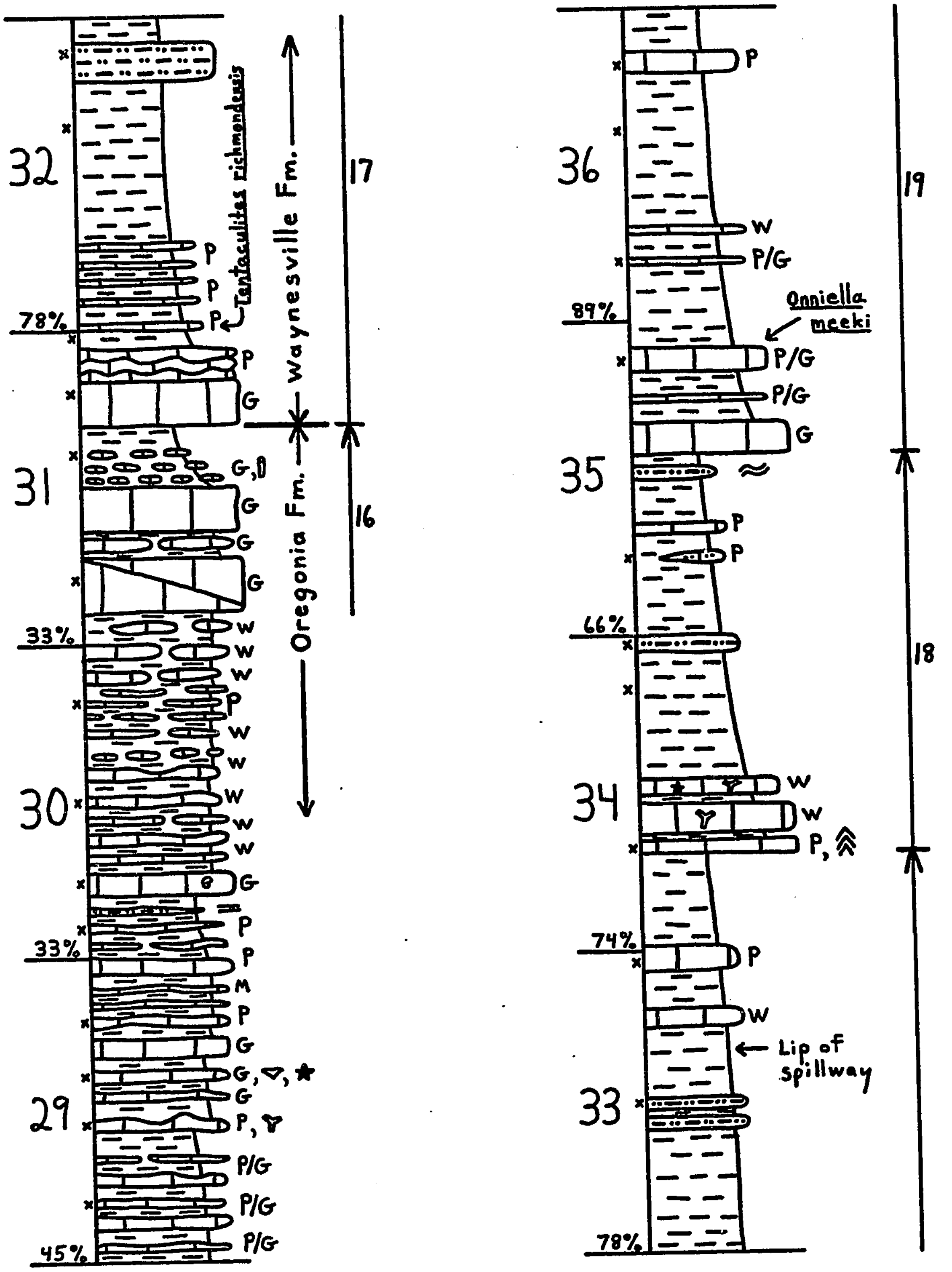

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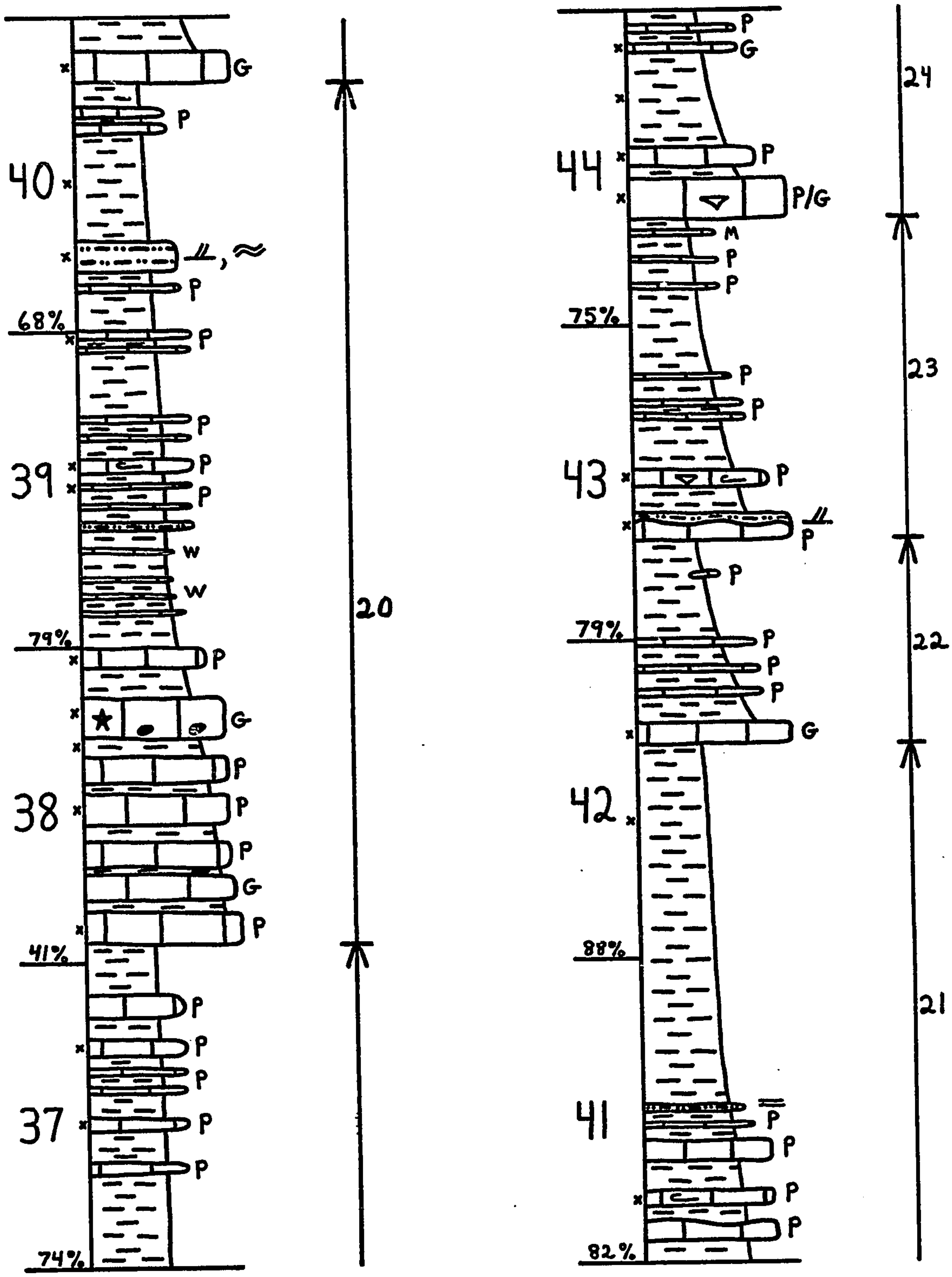

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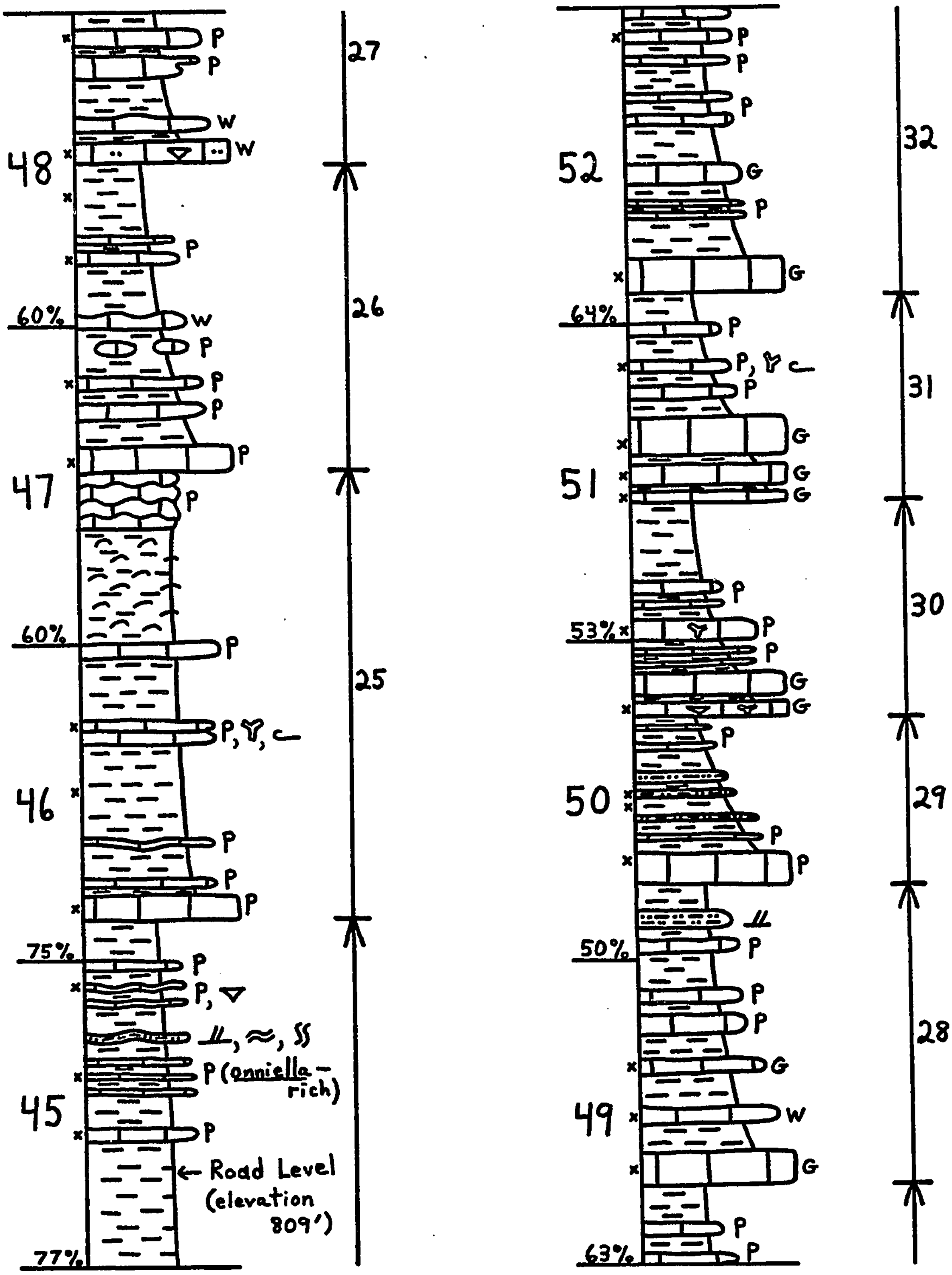

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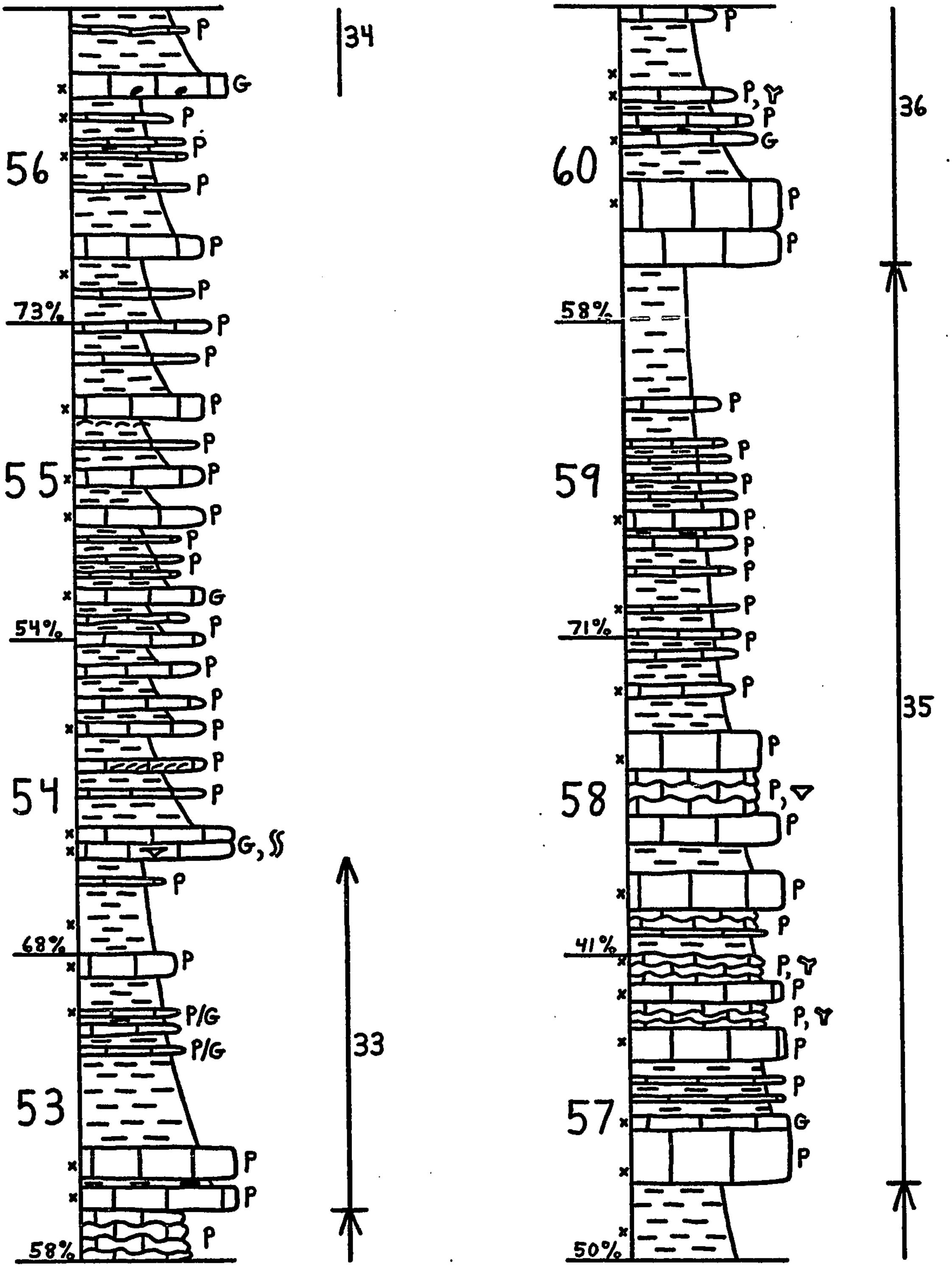

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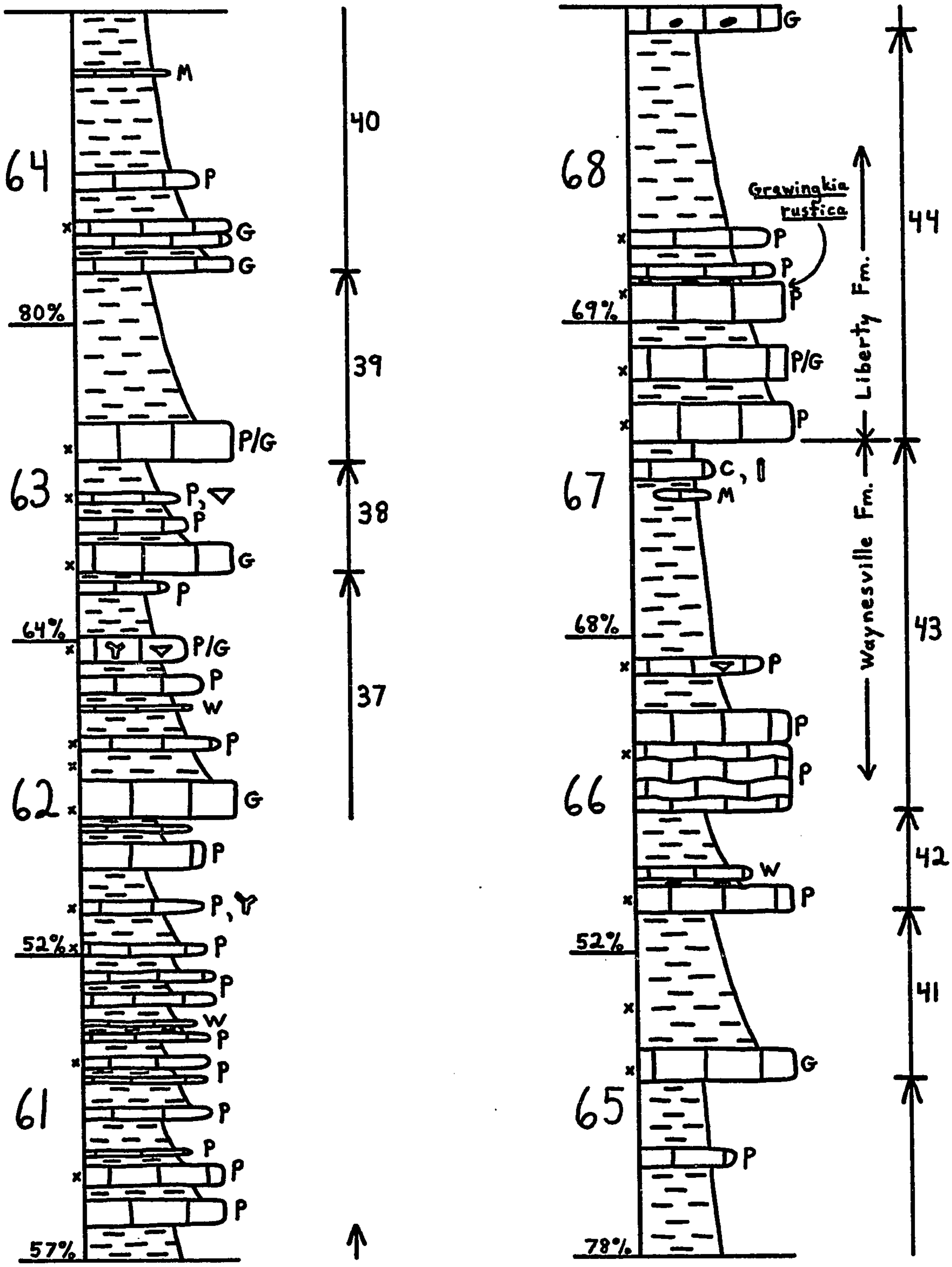

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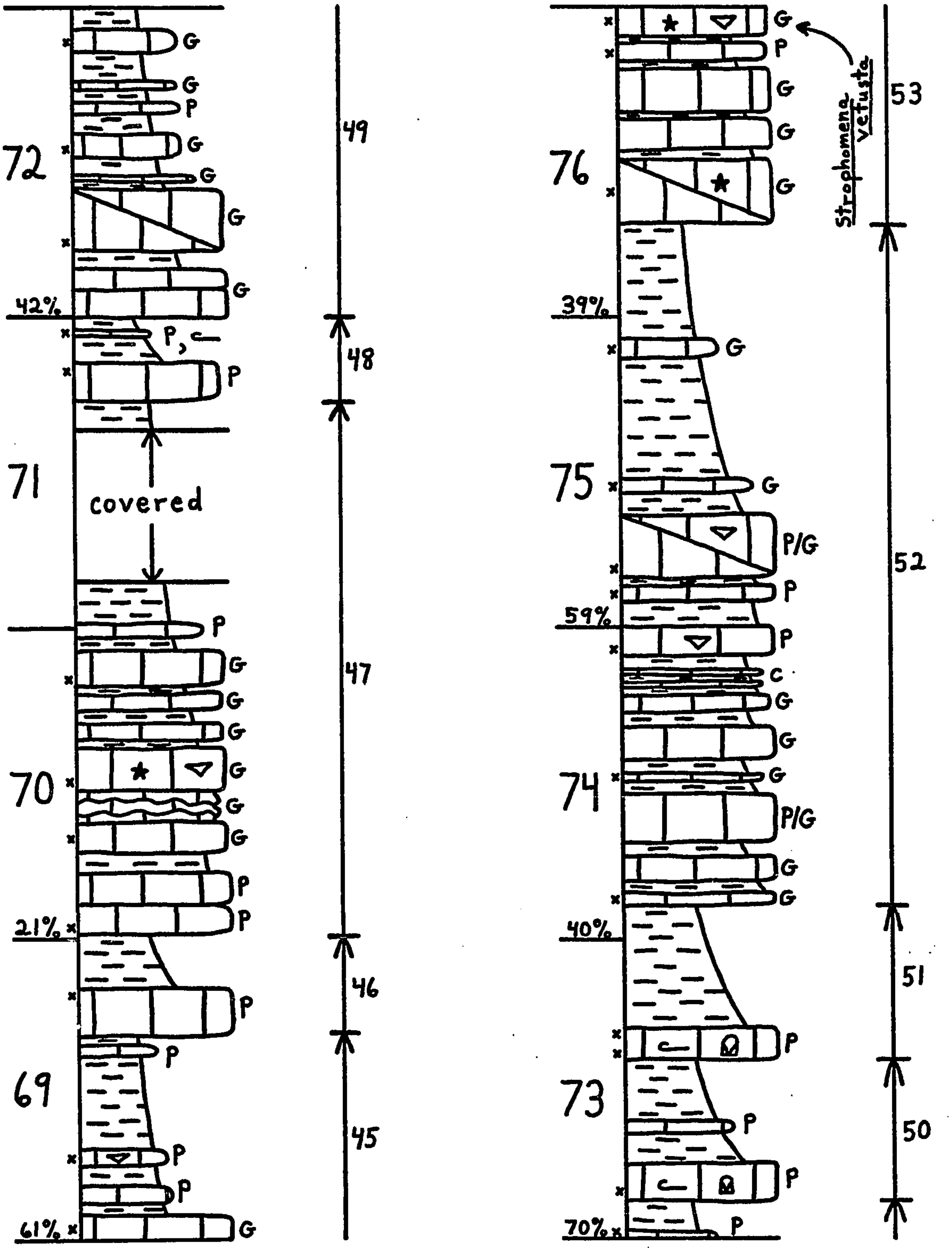

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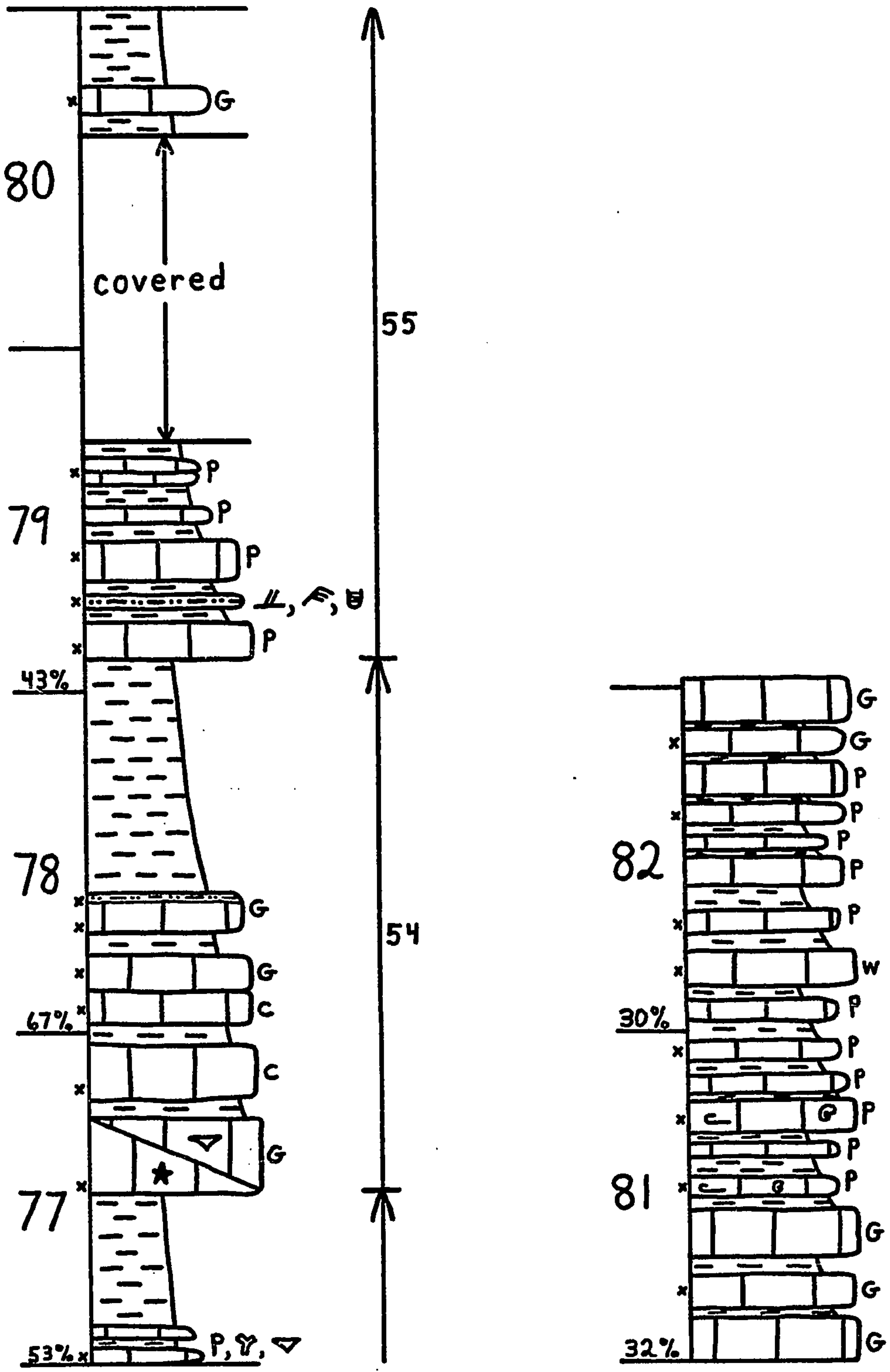
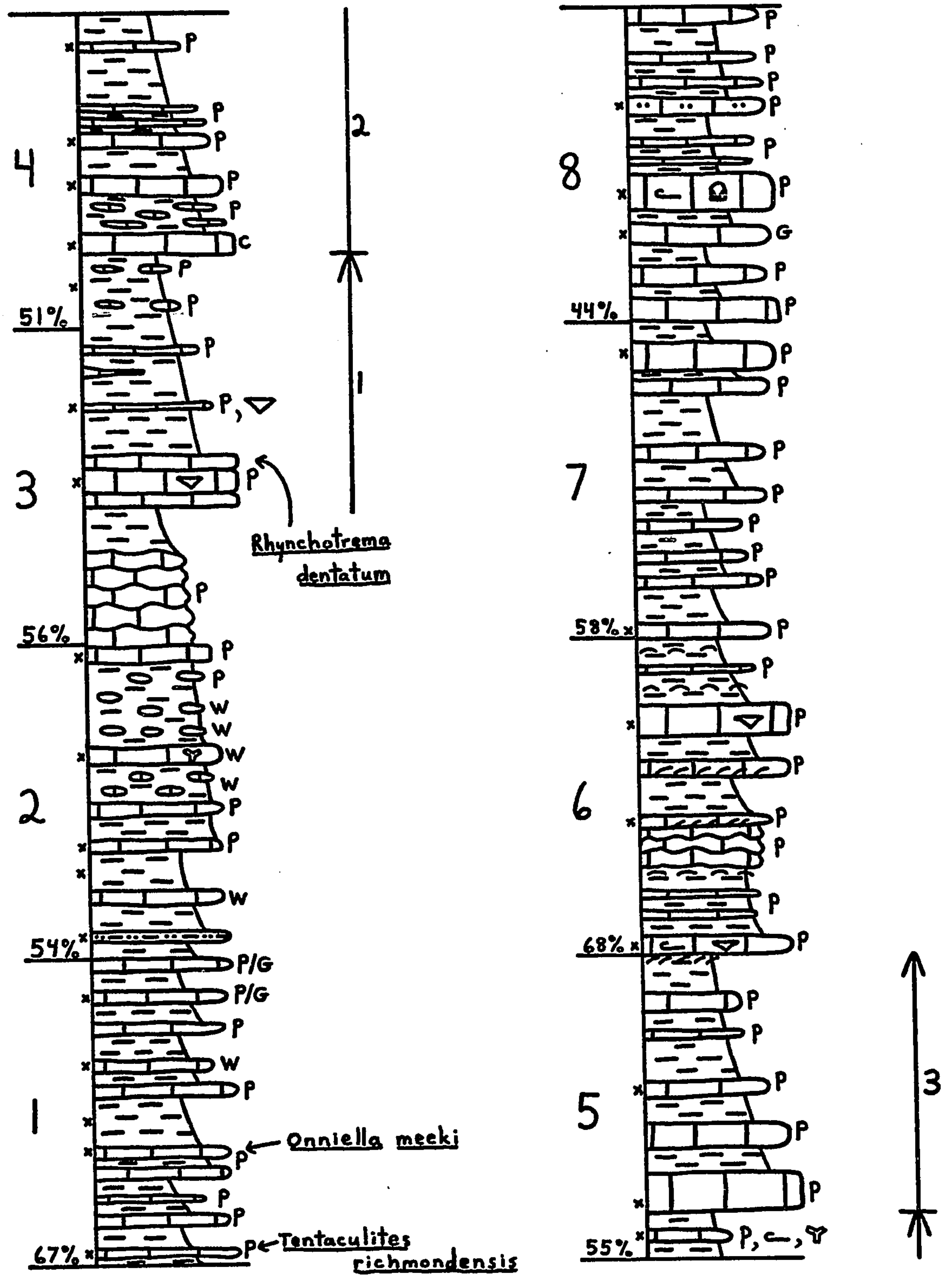


BROOKVILLE NORTH (Waynesville Fm.)



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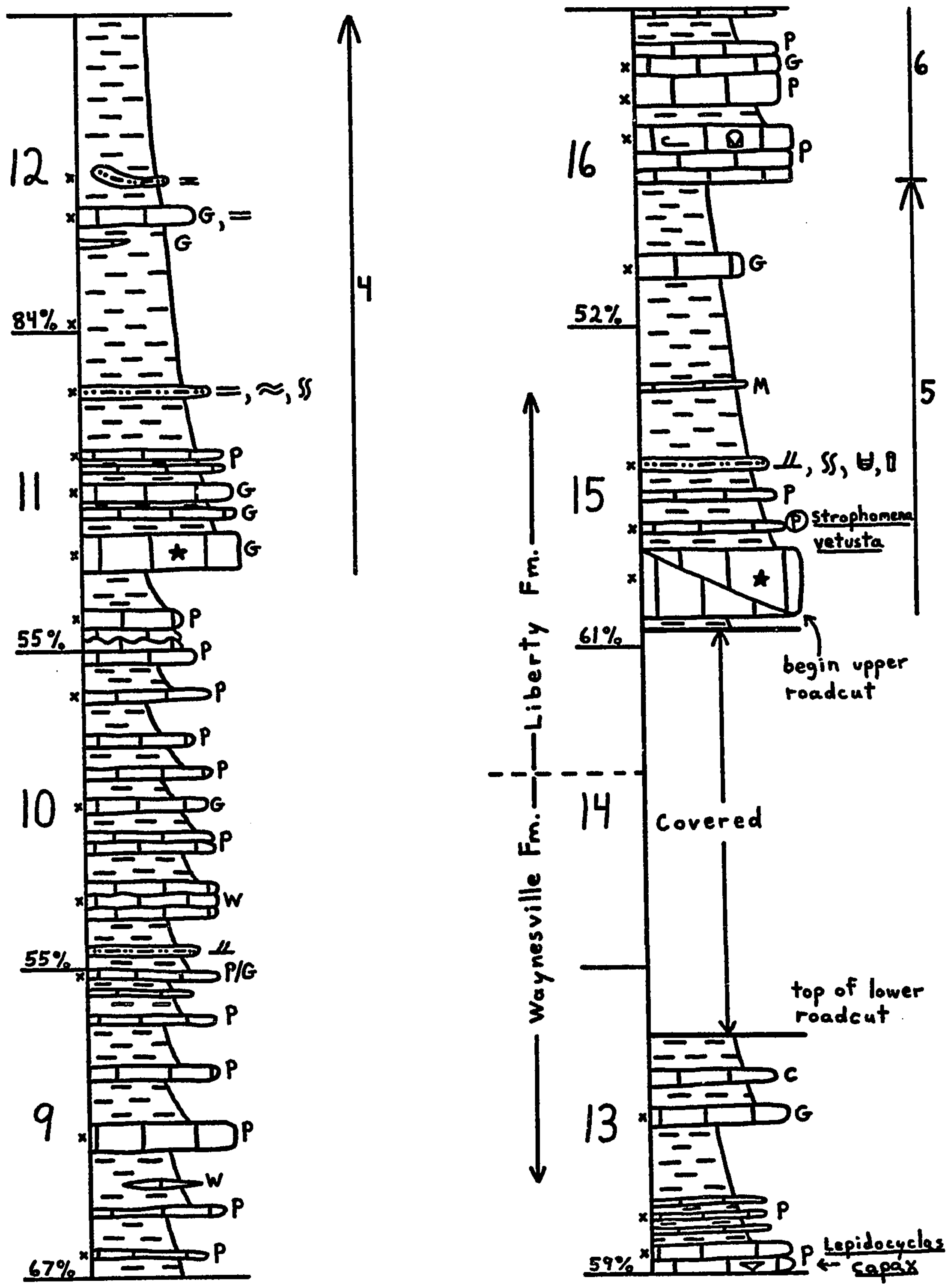
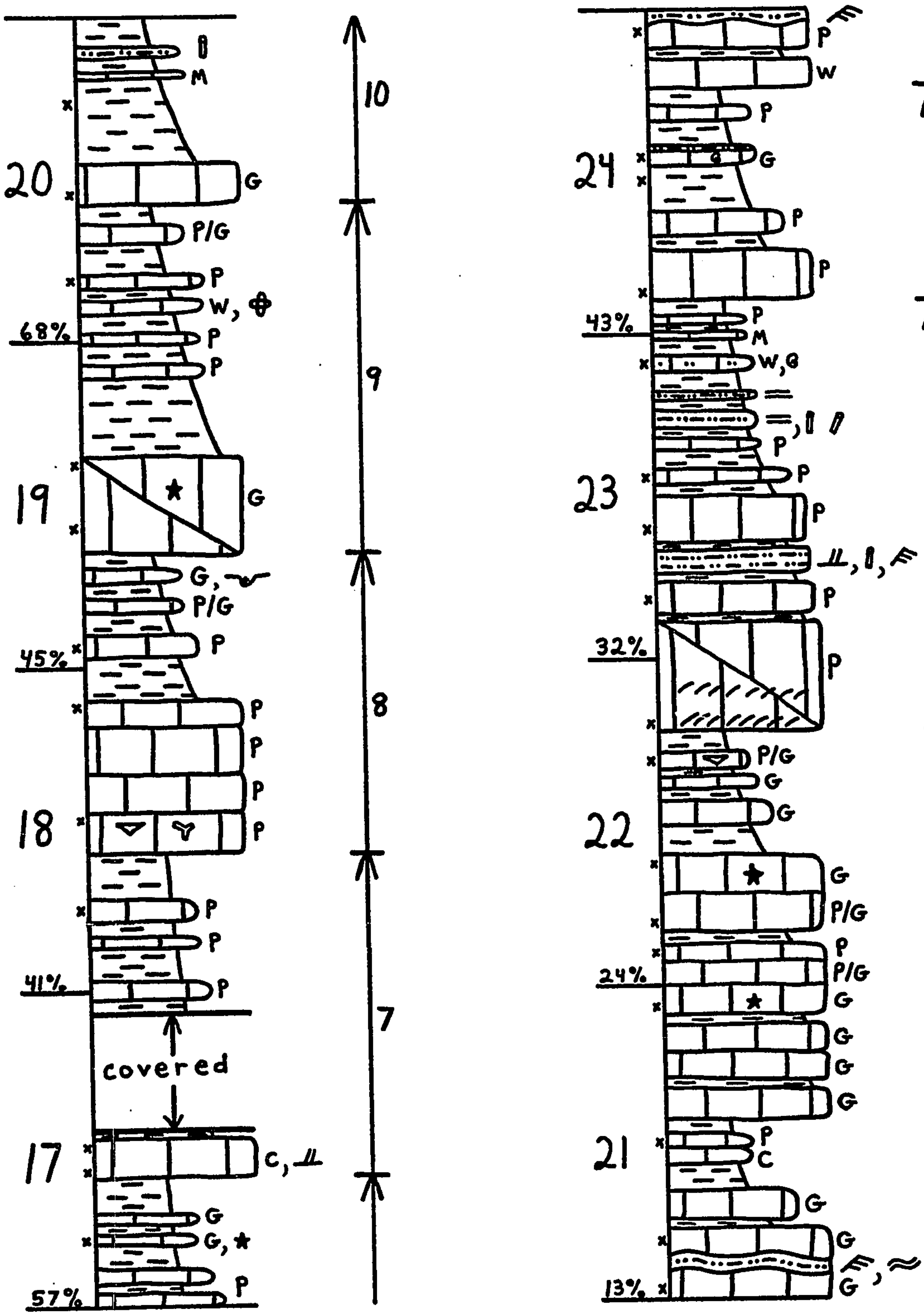


BROOKVILLE NORTH (cont.)



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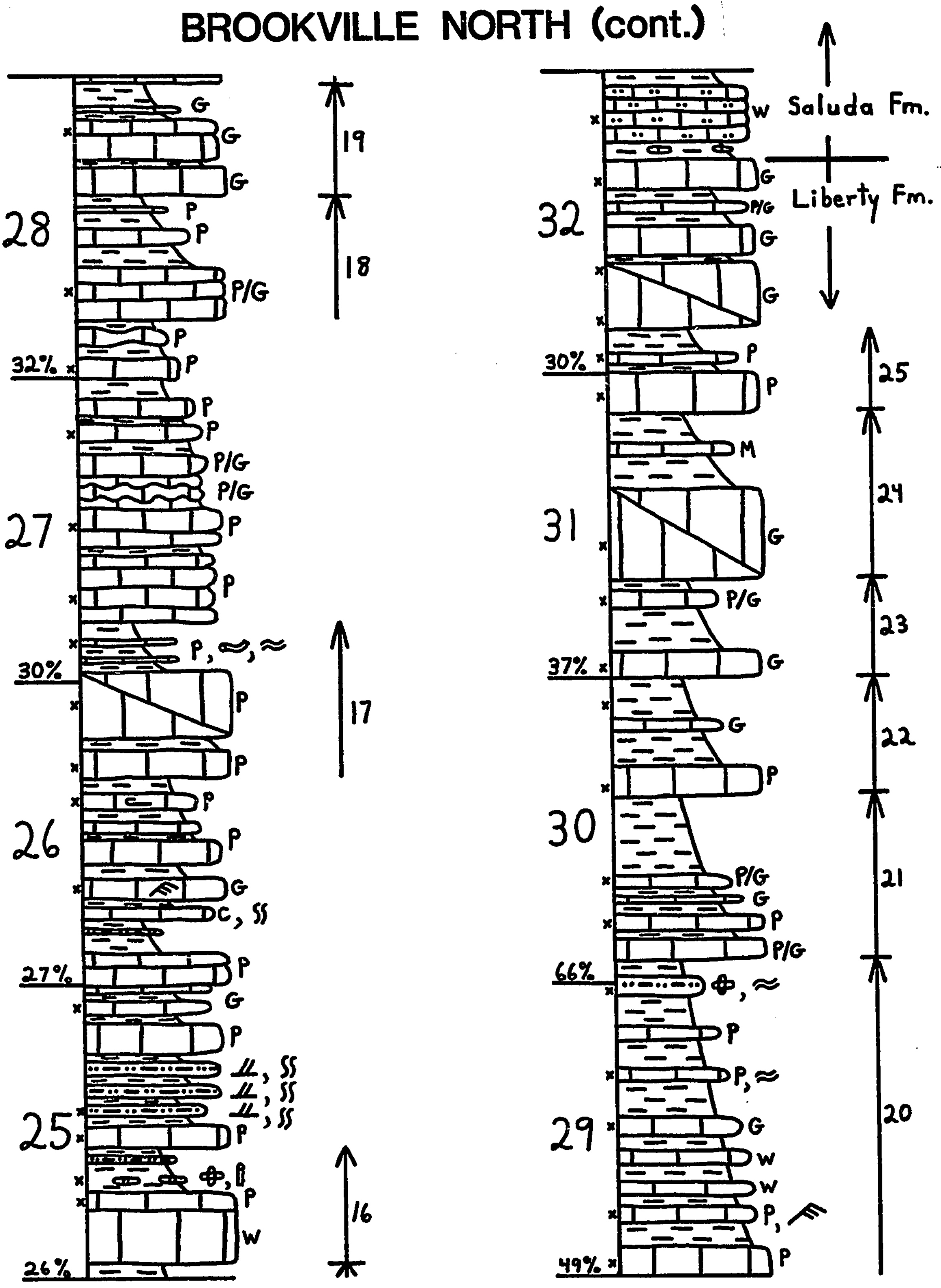

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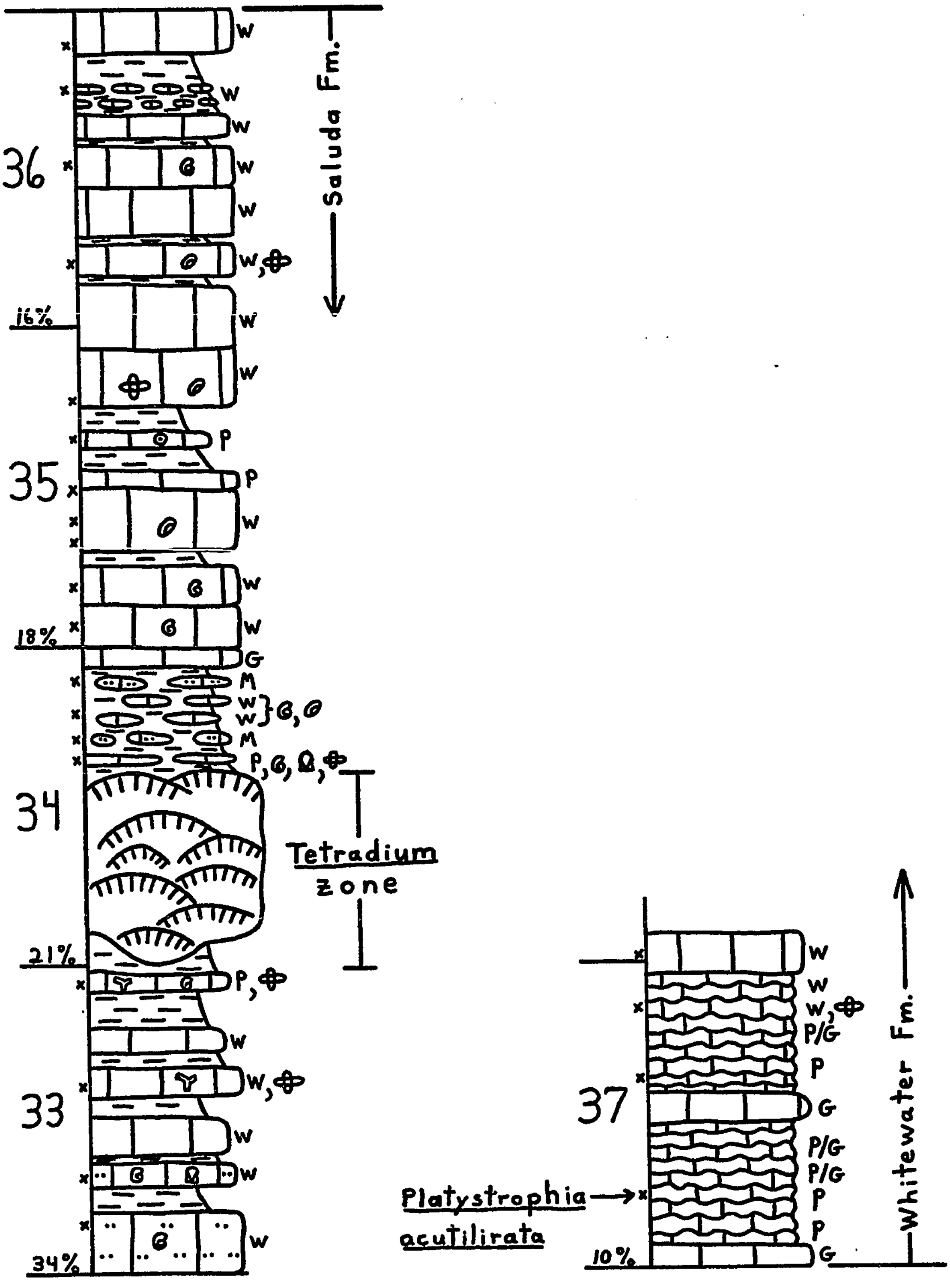
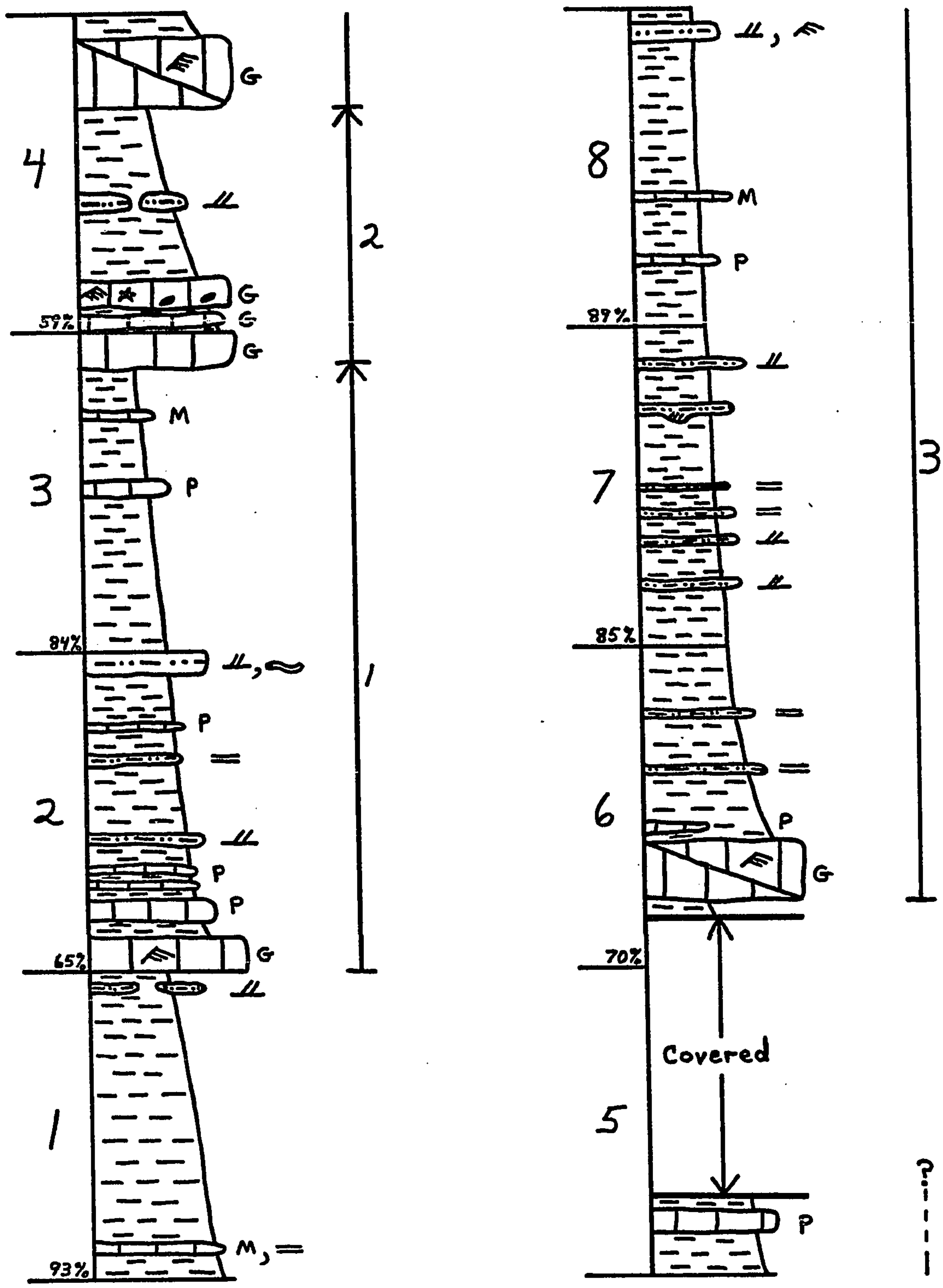


GEORGETOWN, OHIO



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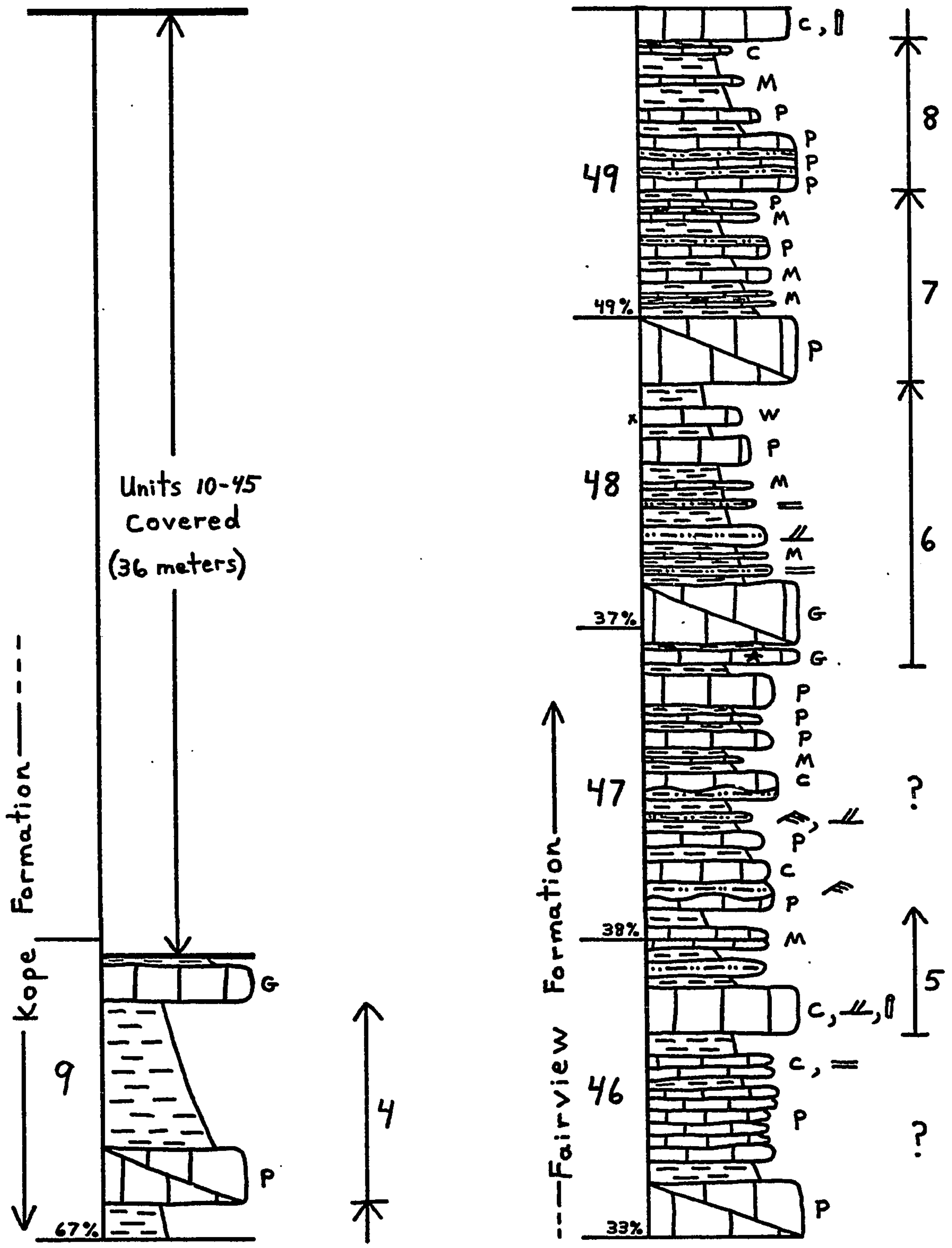

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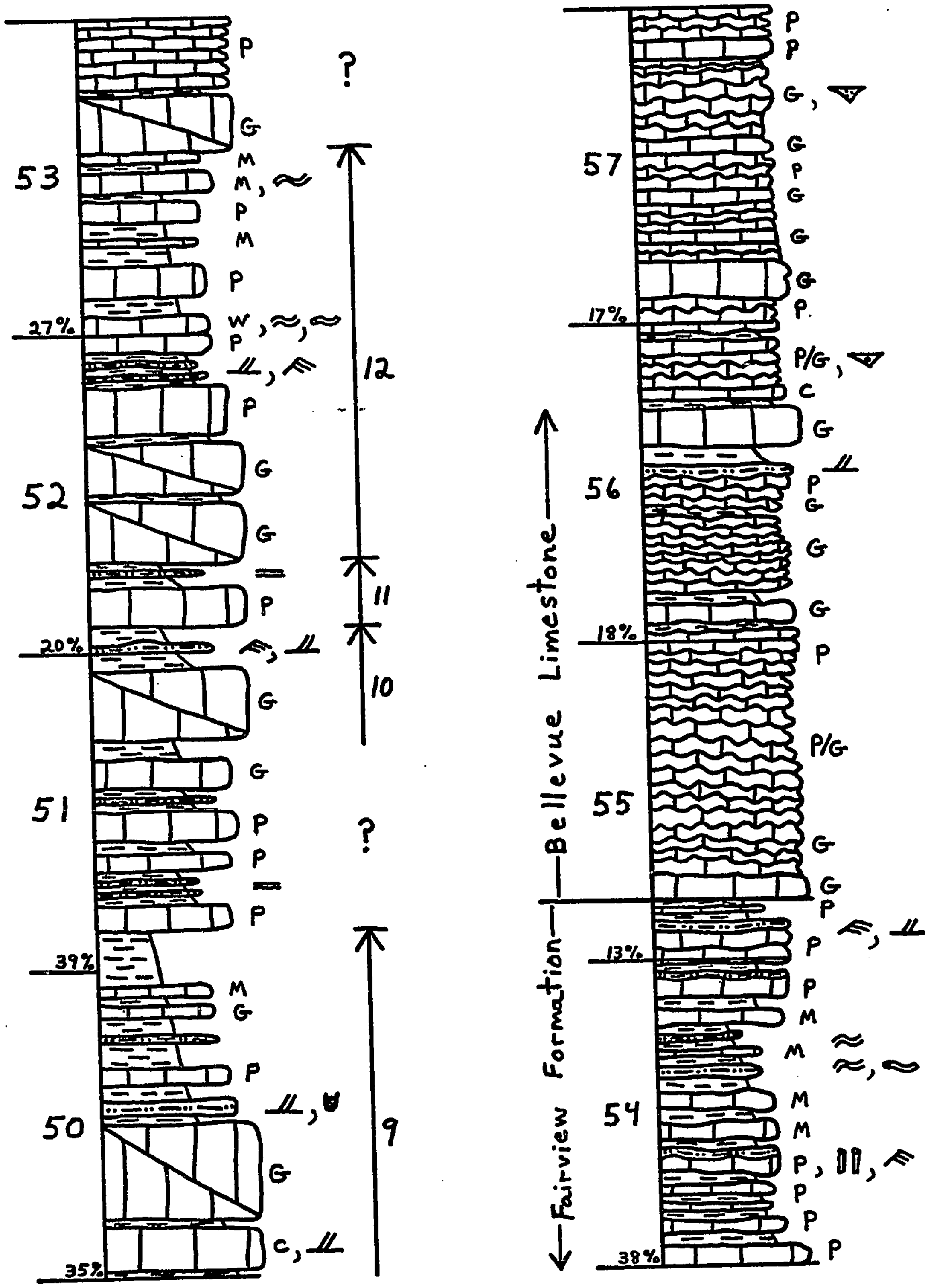

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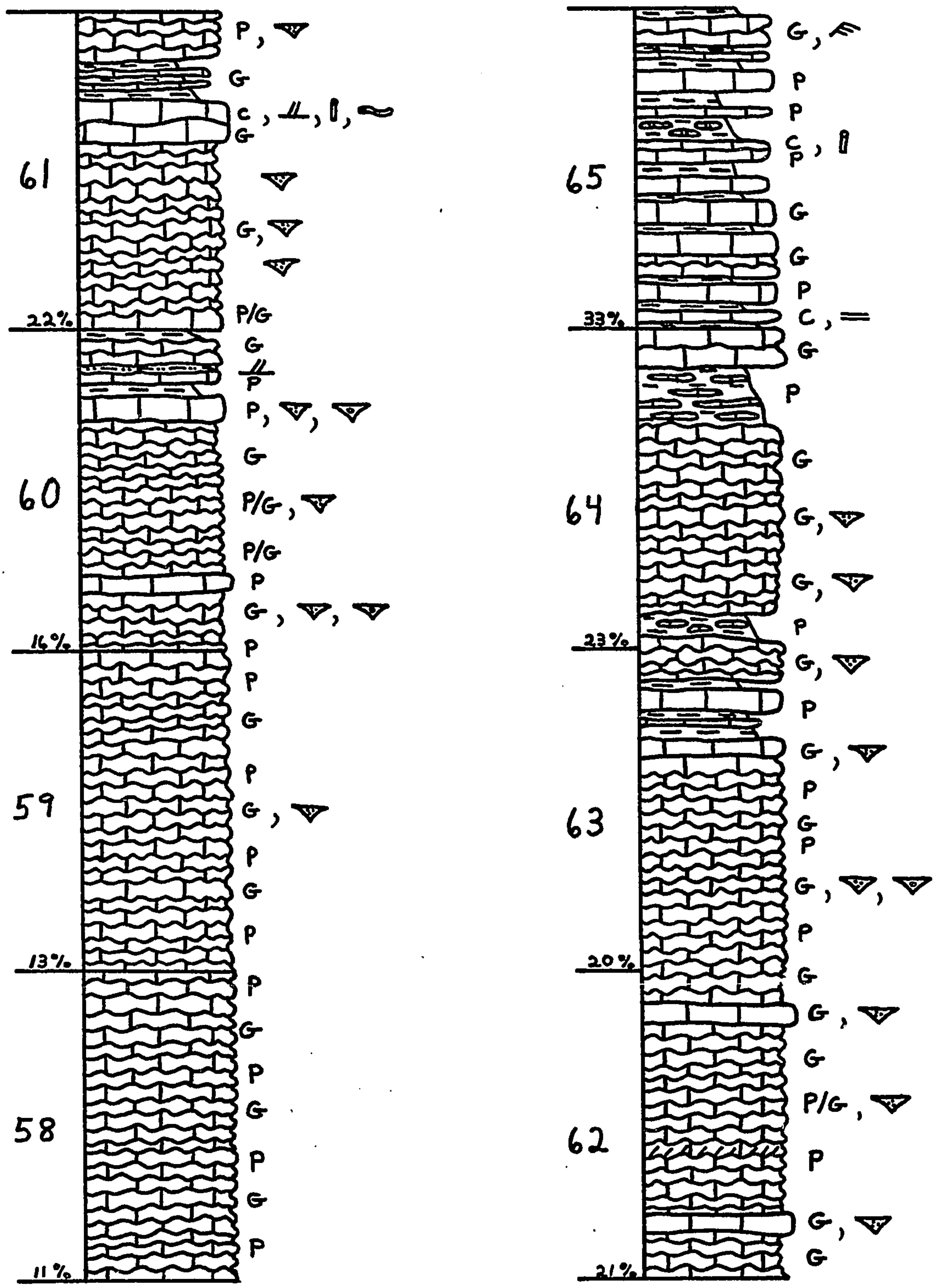

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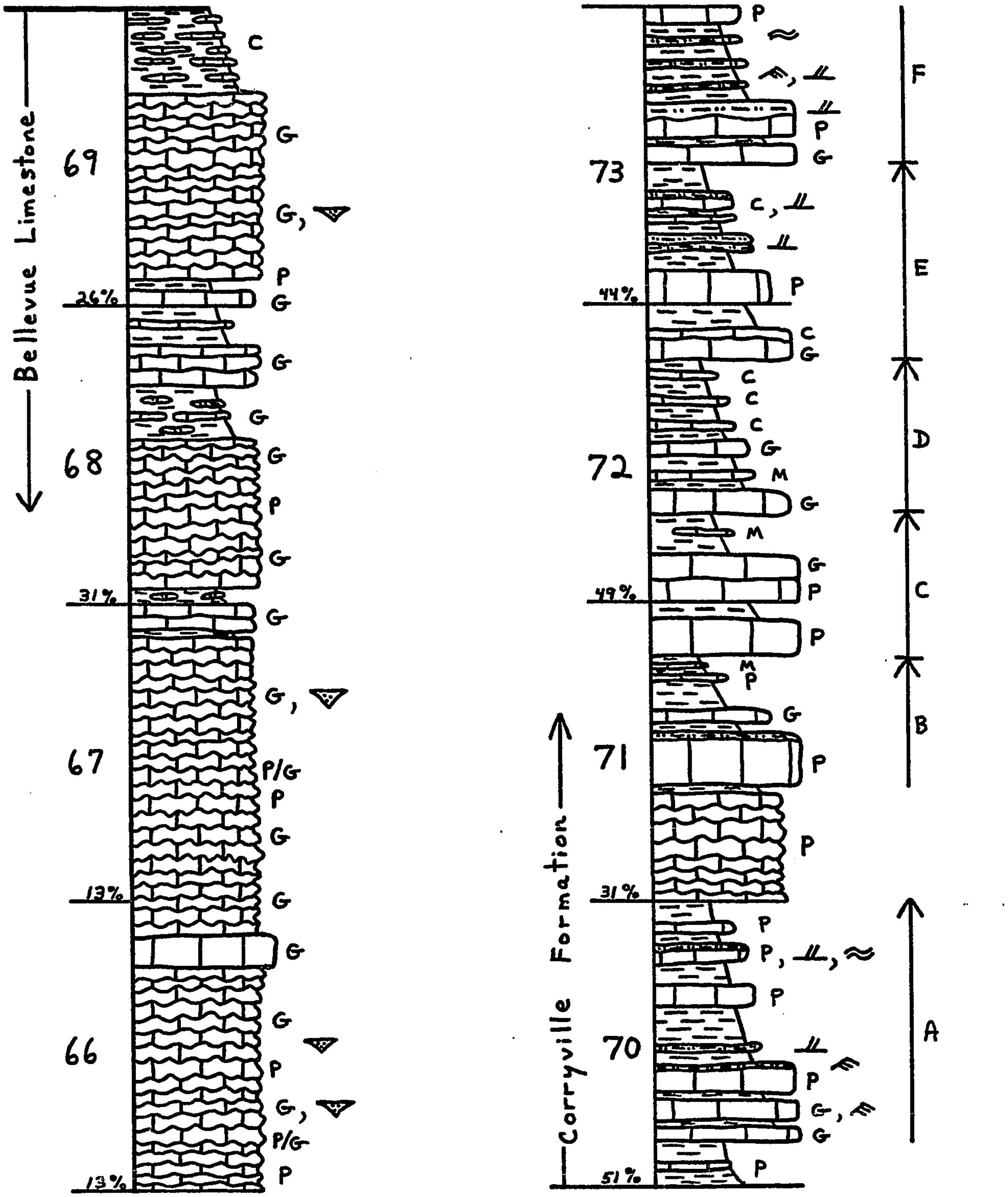

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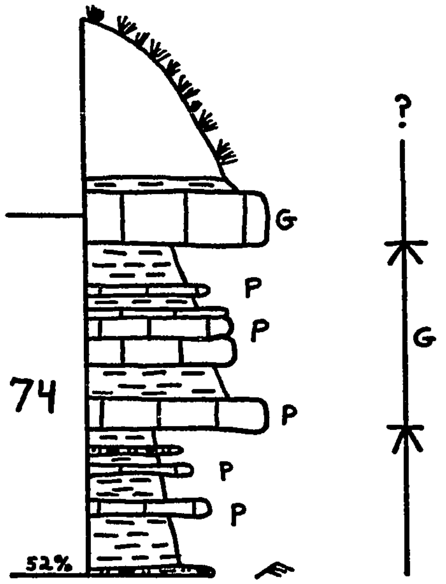
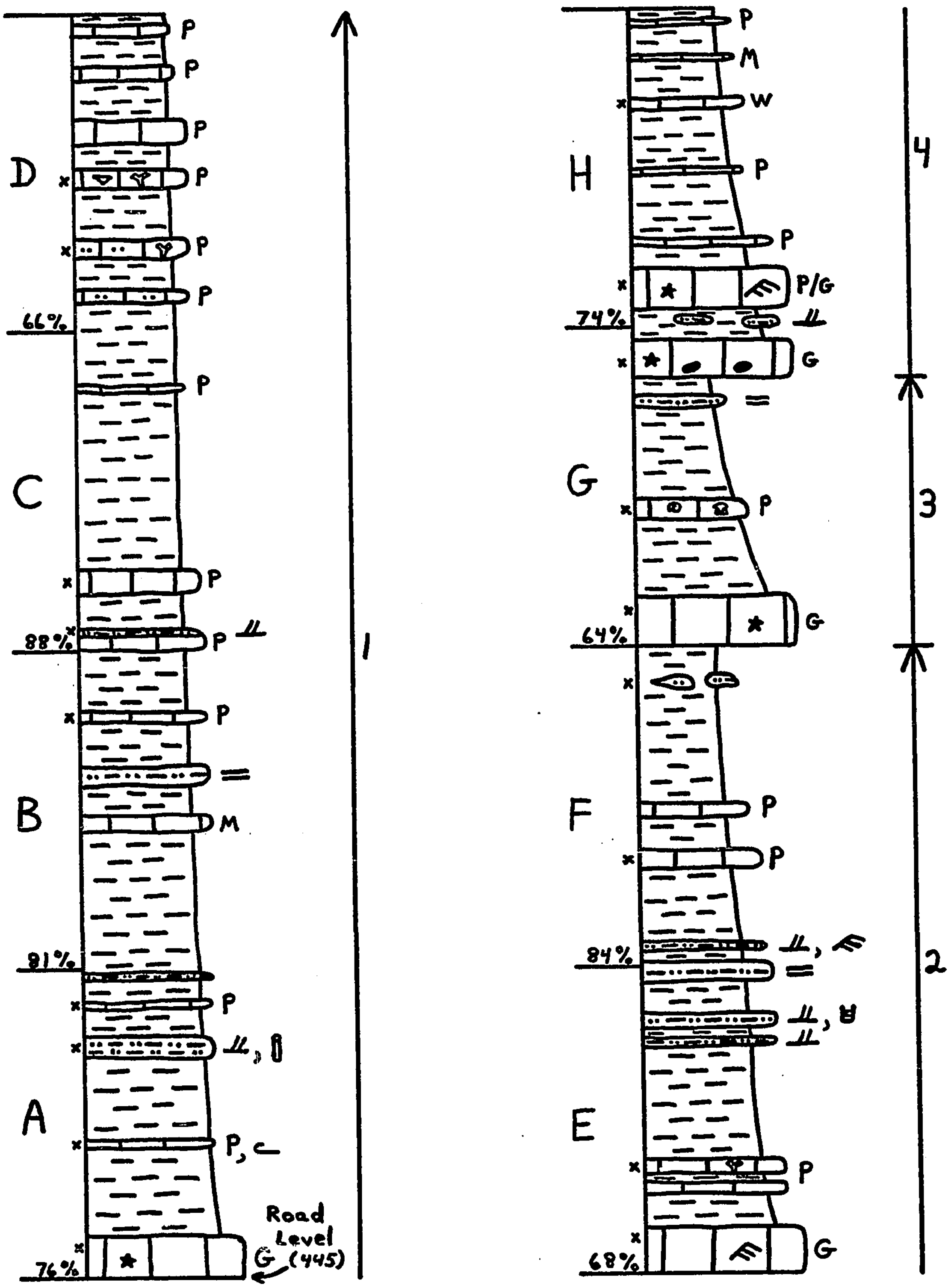


I-275 East / KY. Rt. 445 (Kope Fm.)



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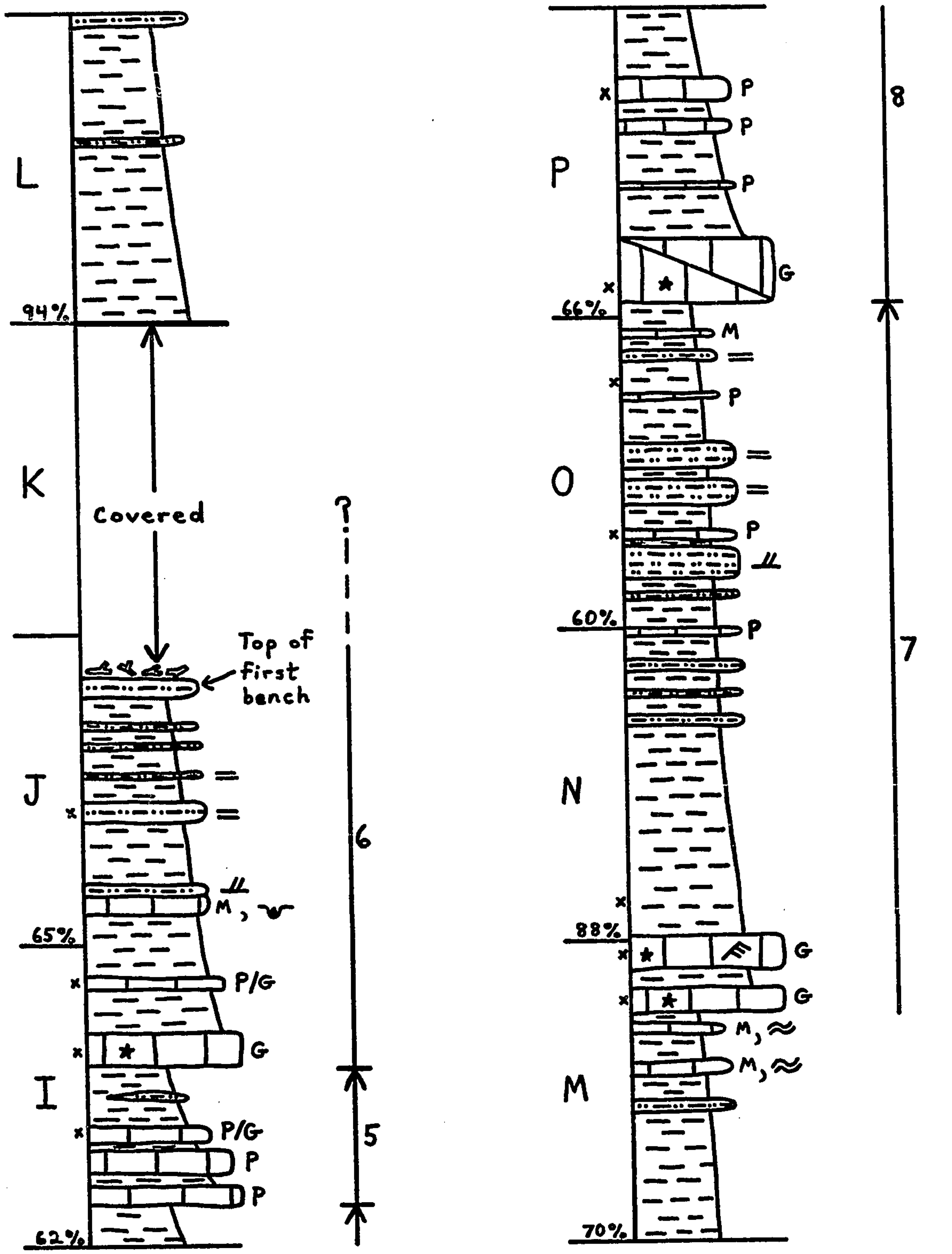

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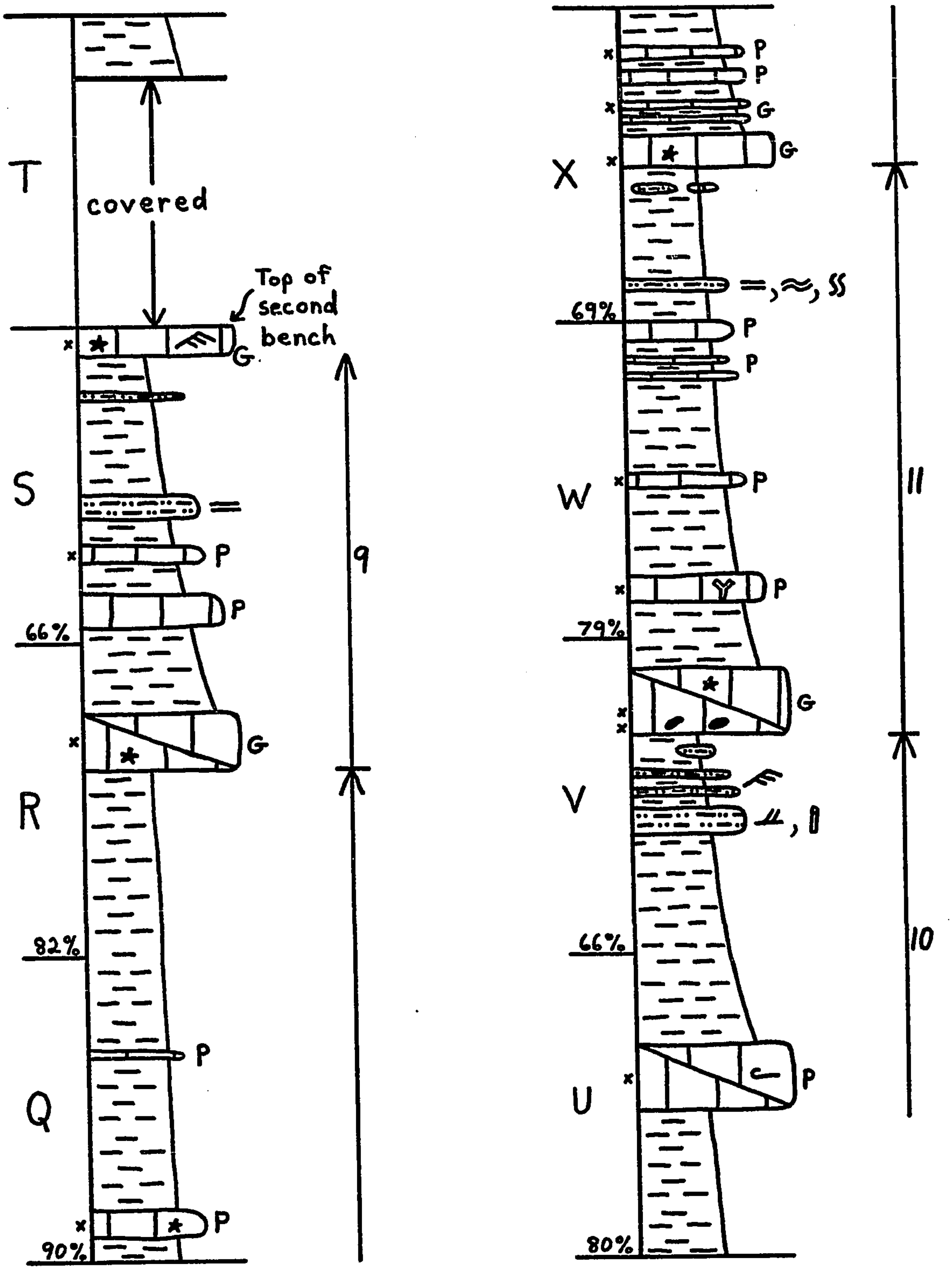

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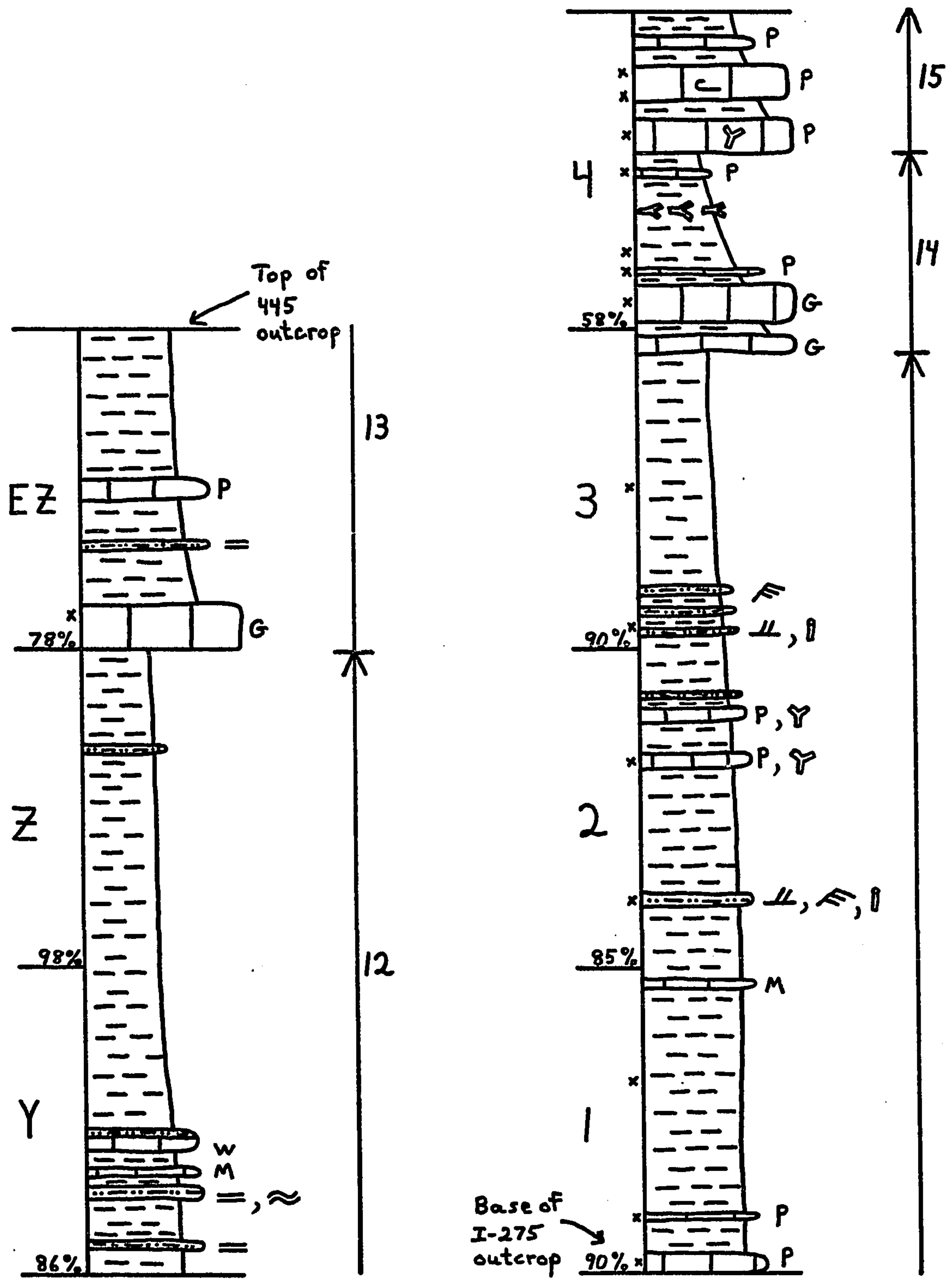

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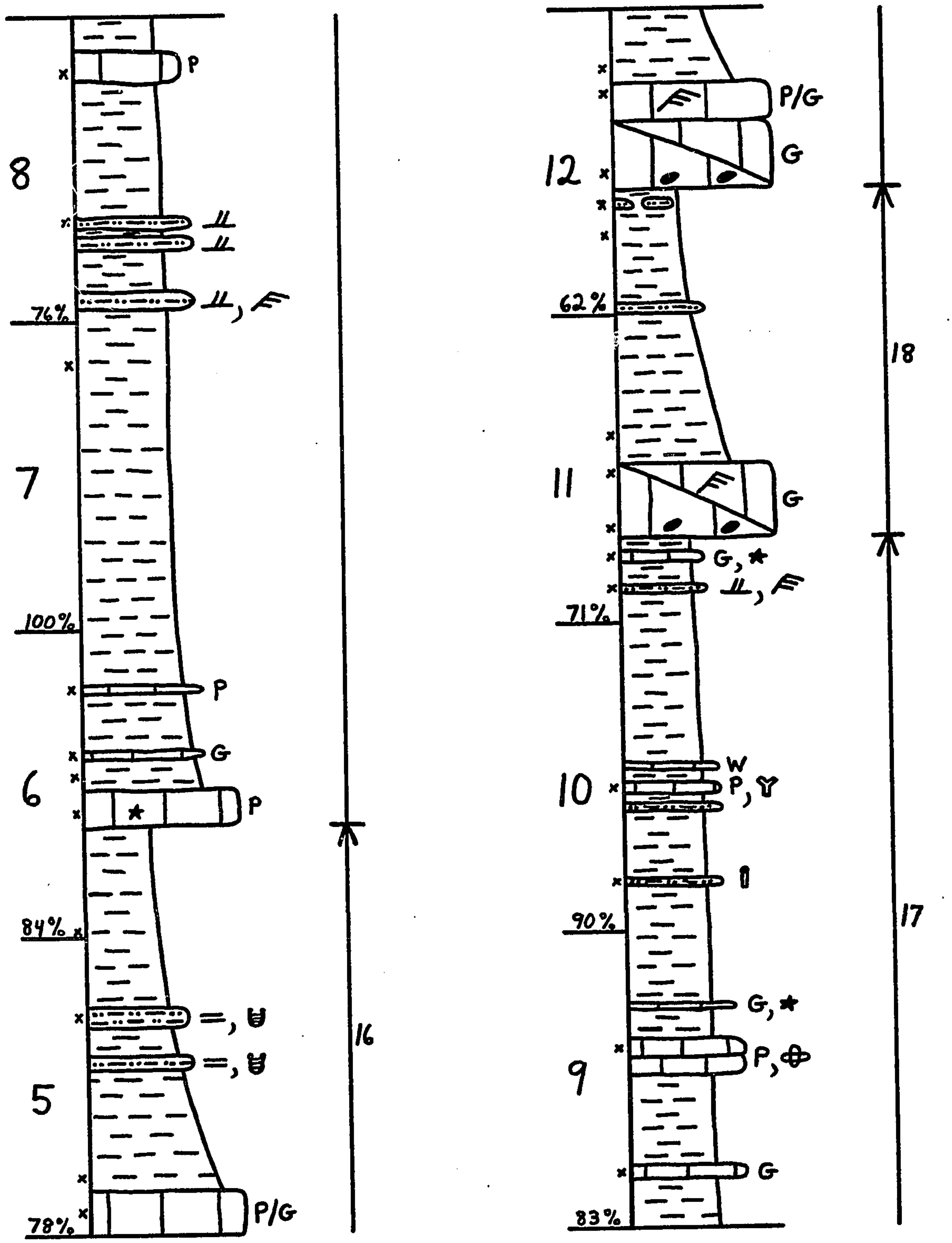

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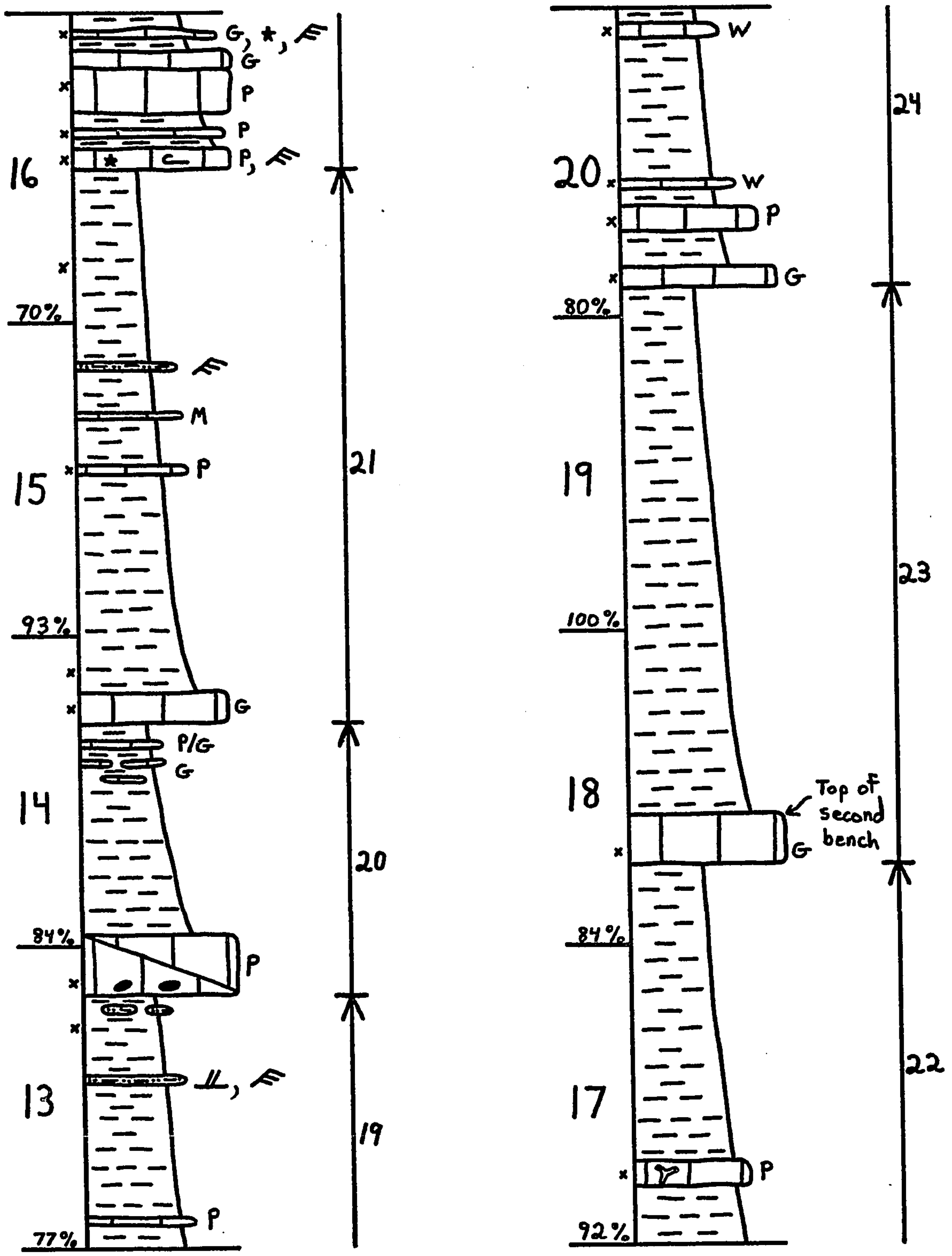

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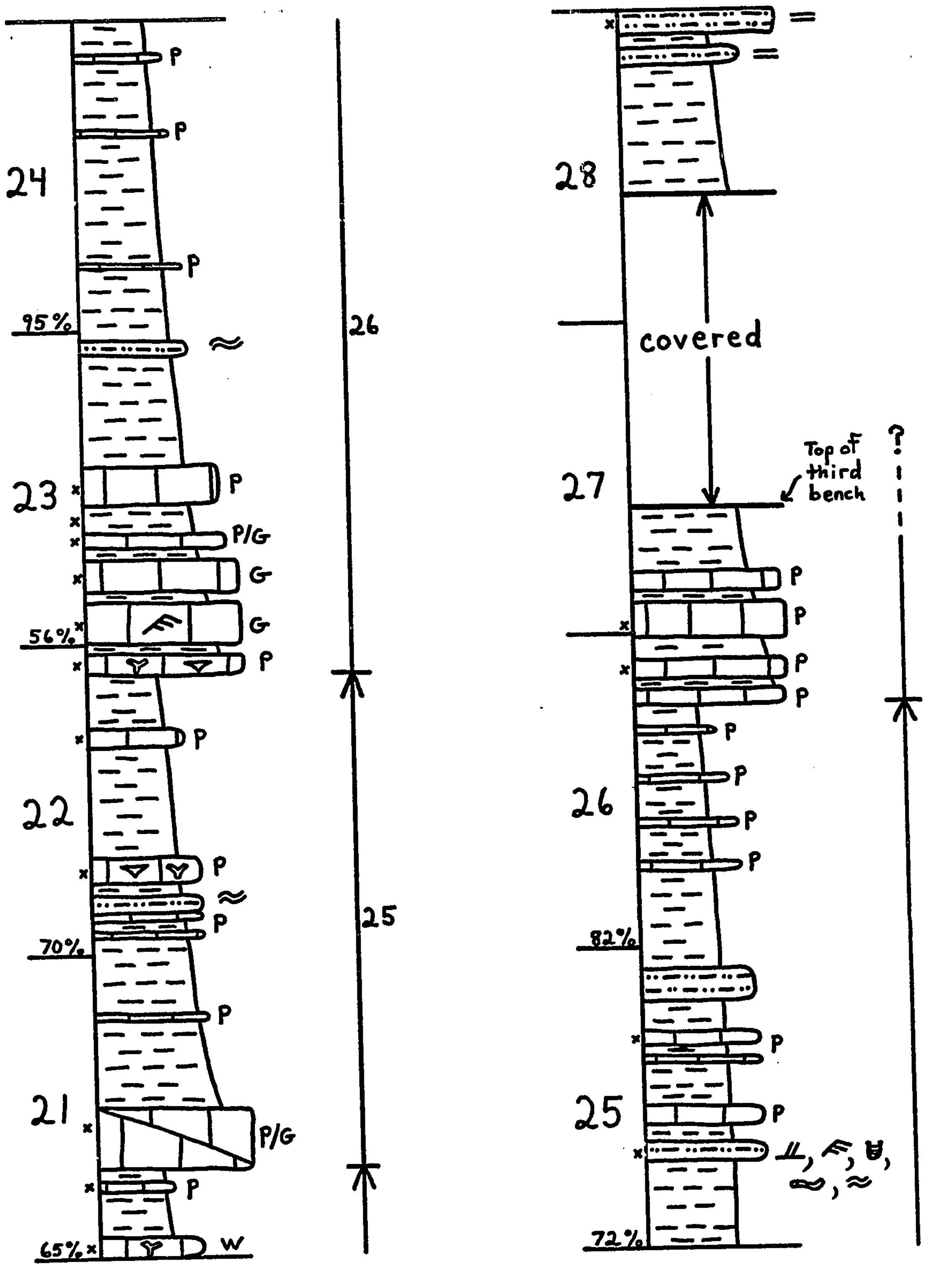

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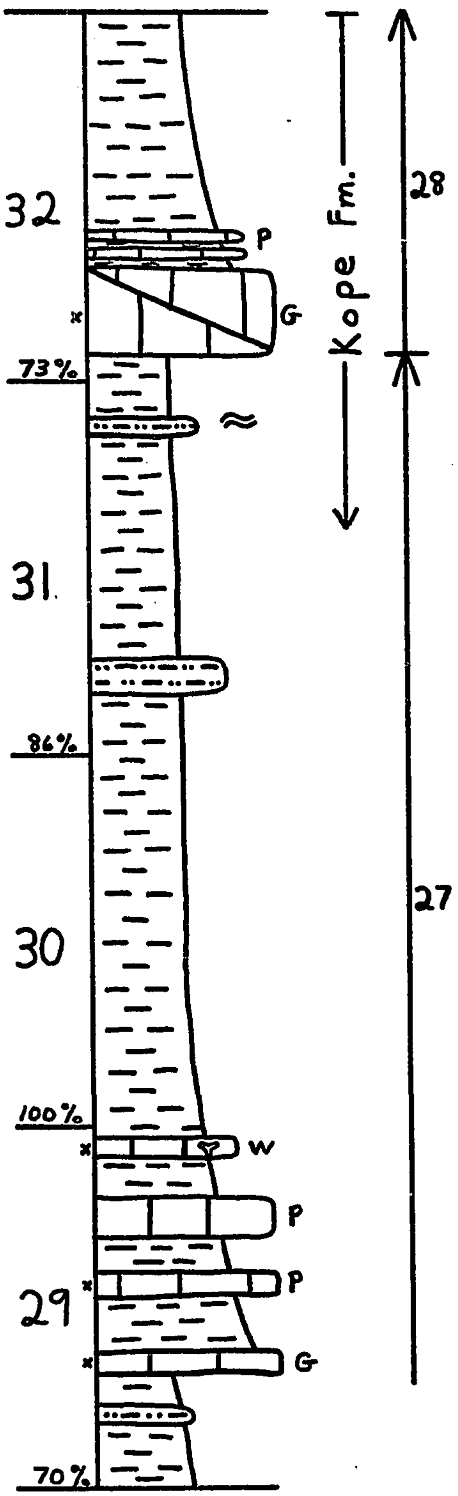
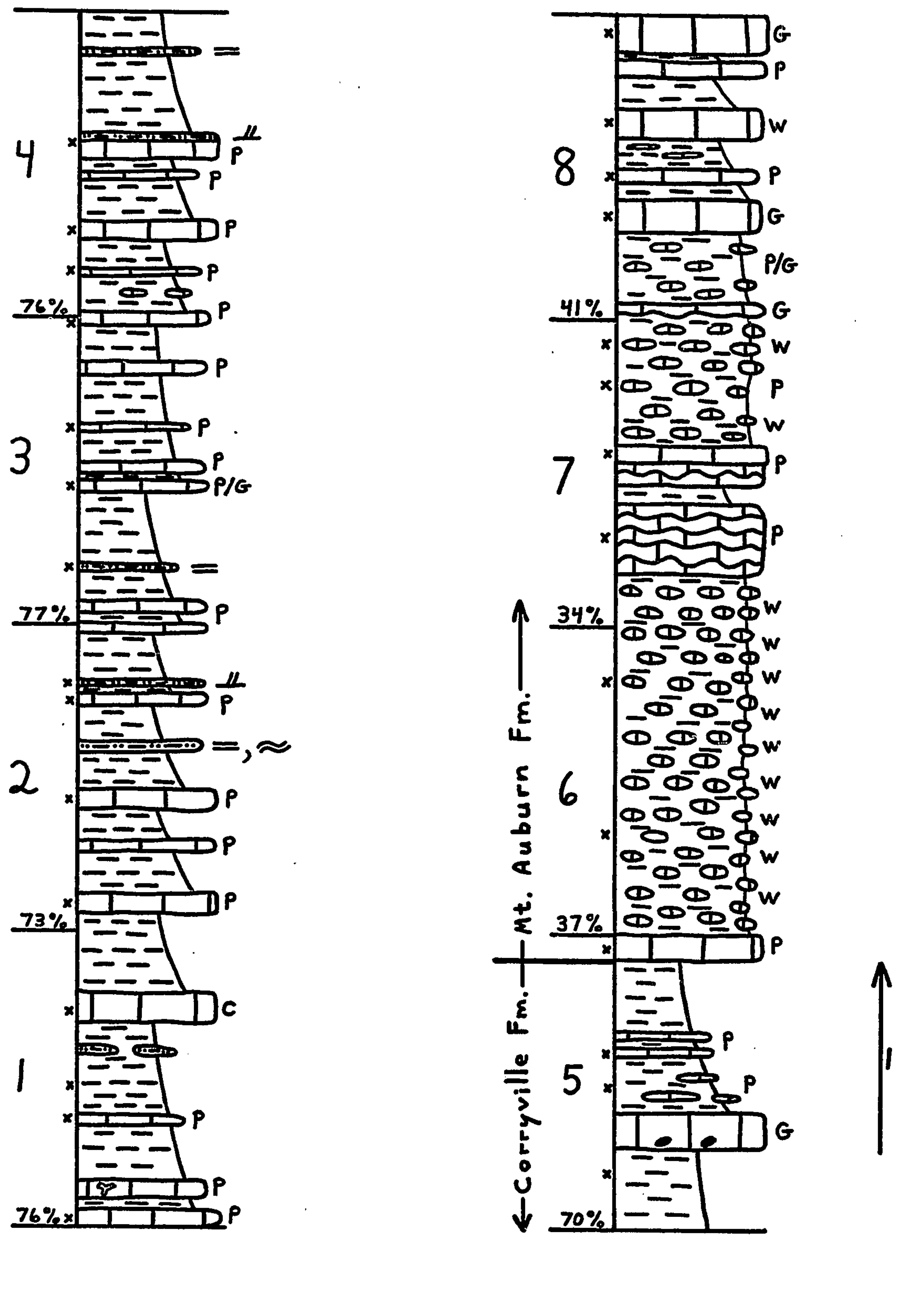


MIDDLETOWN, OHIO



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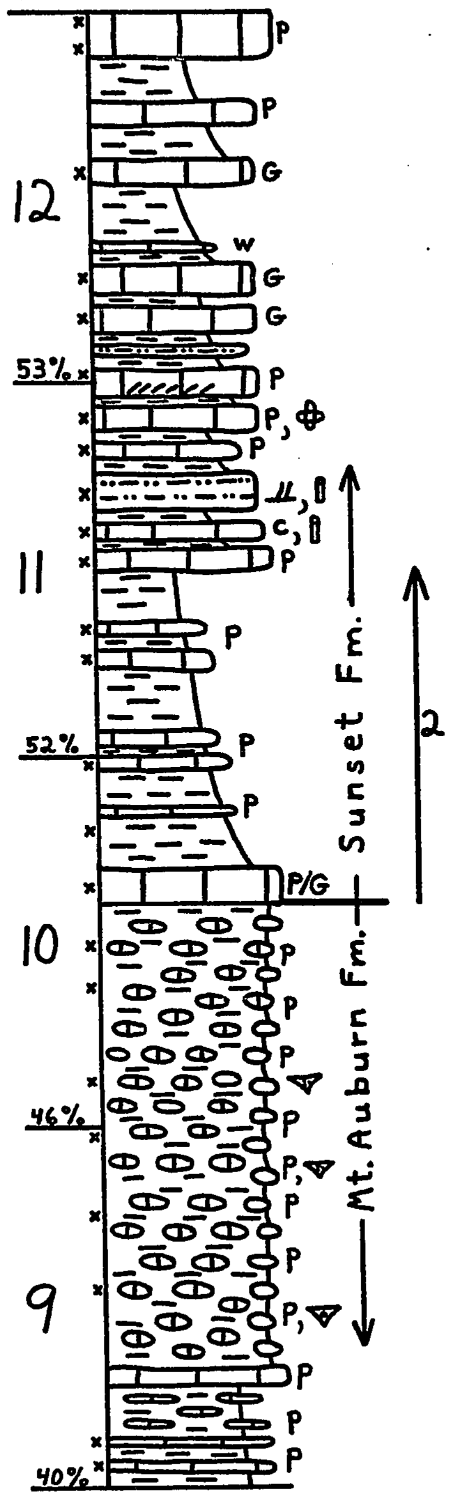
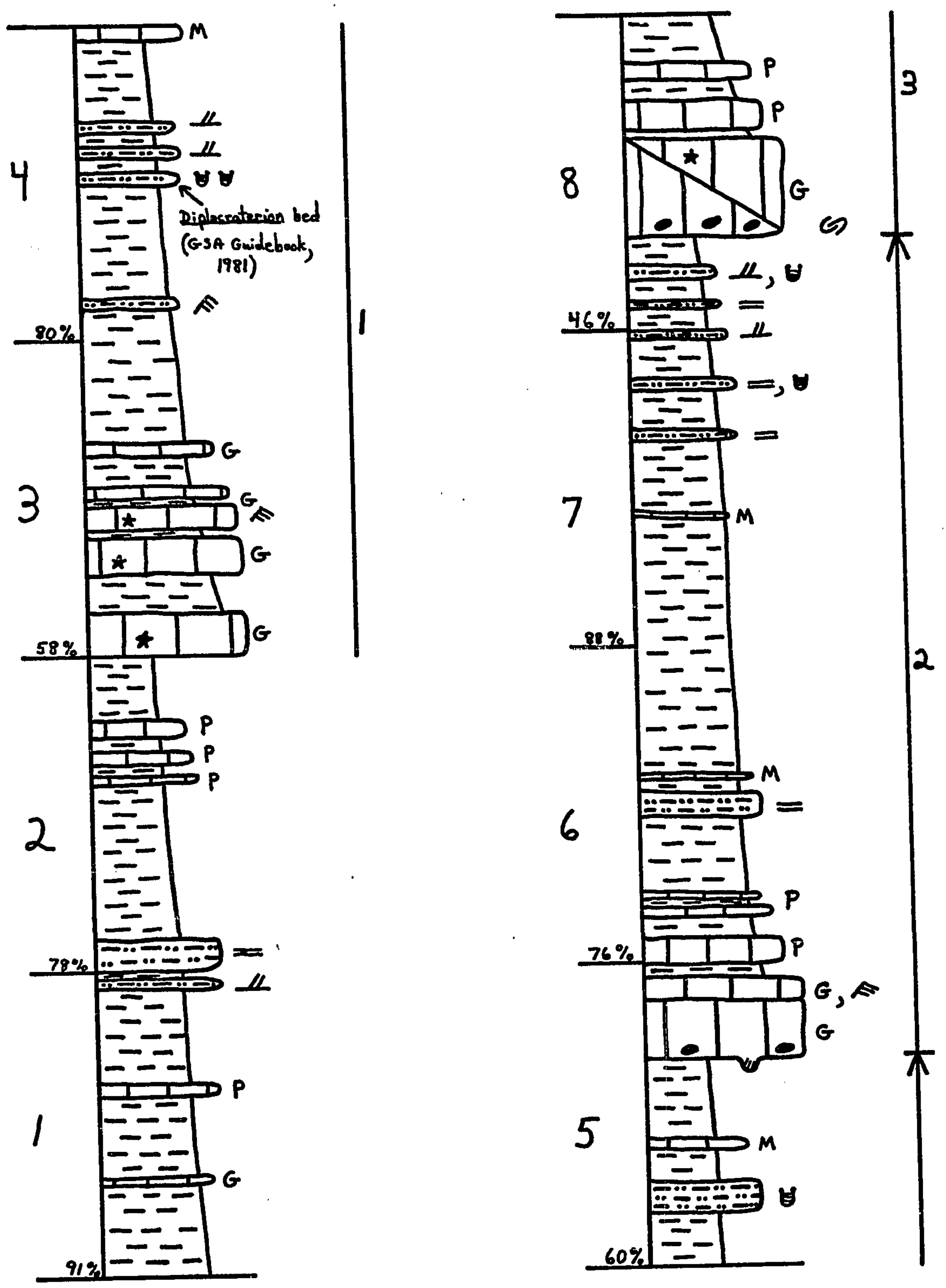


REIDLIN ROAD (Kope Fm.)



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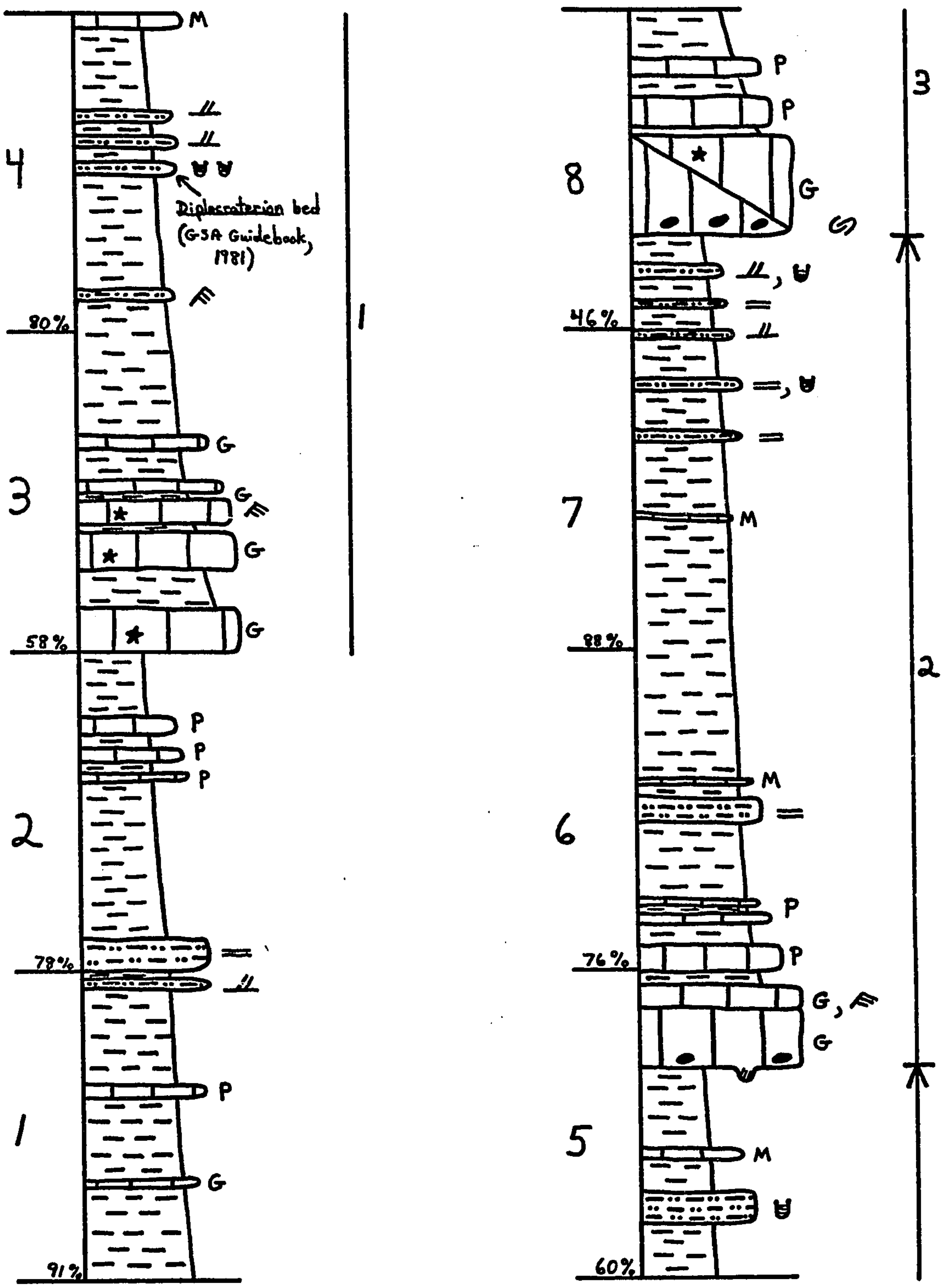

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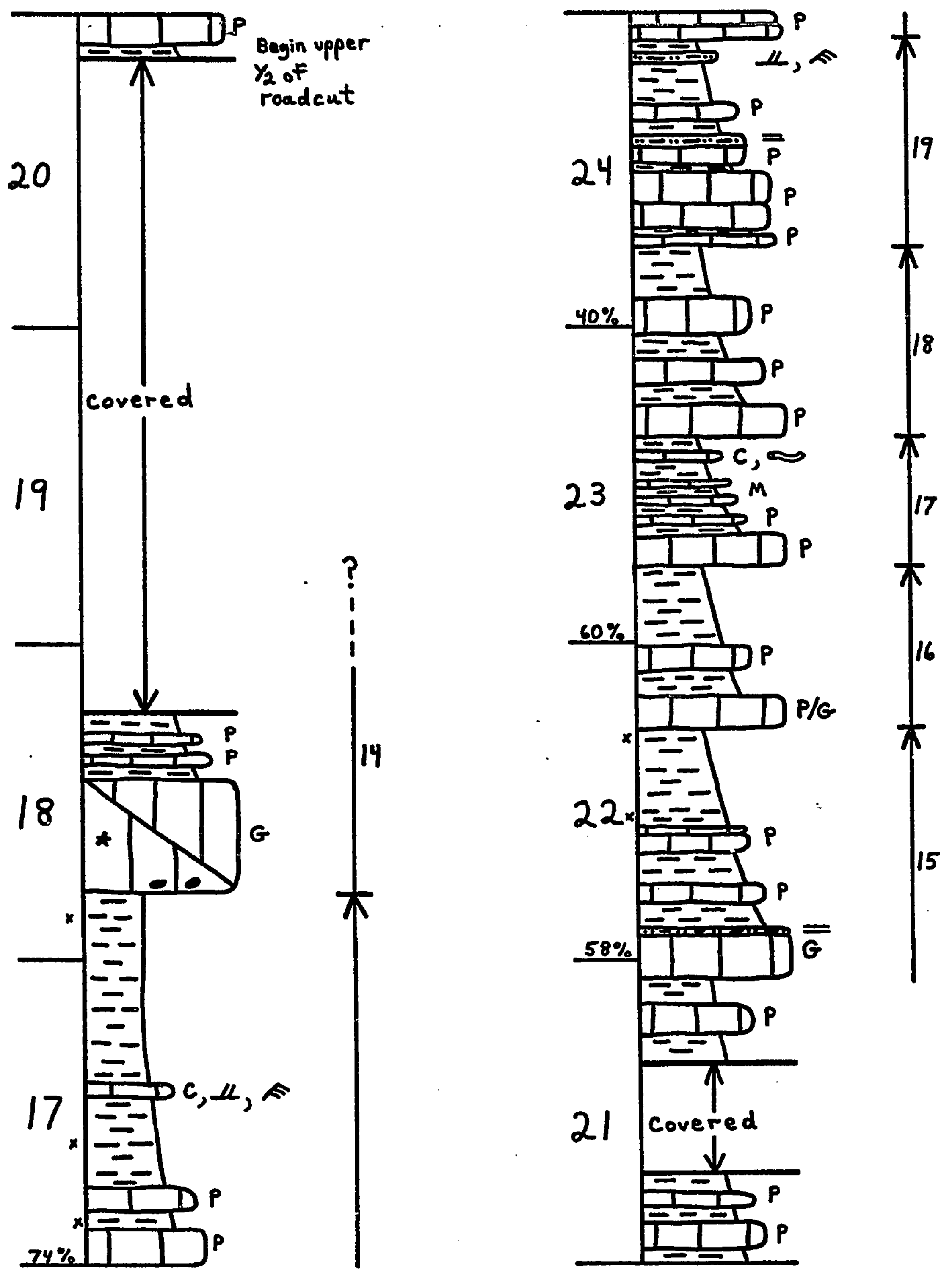

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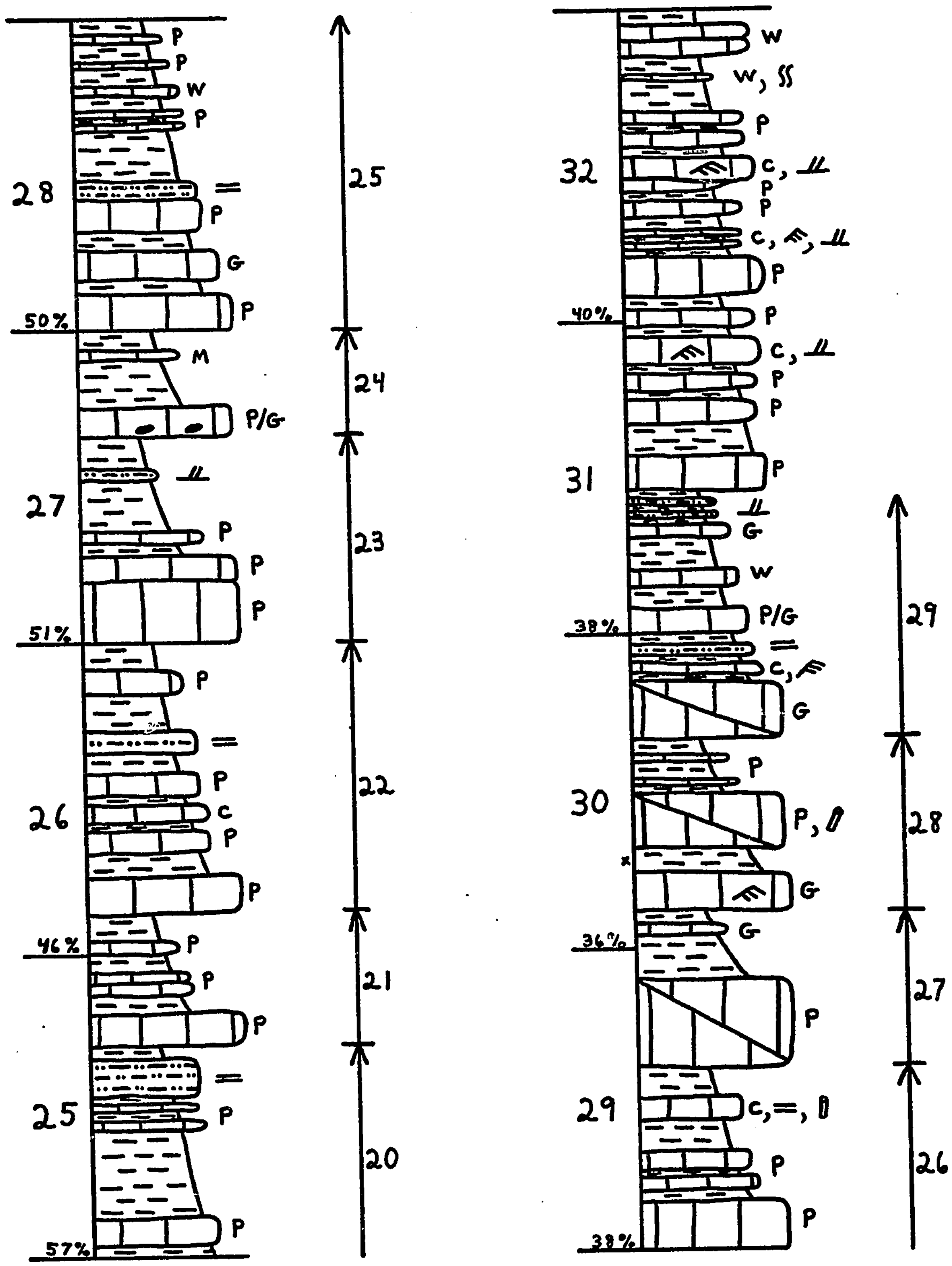

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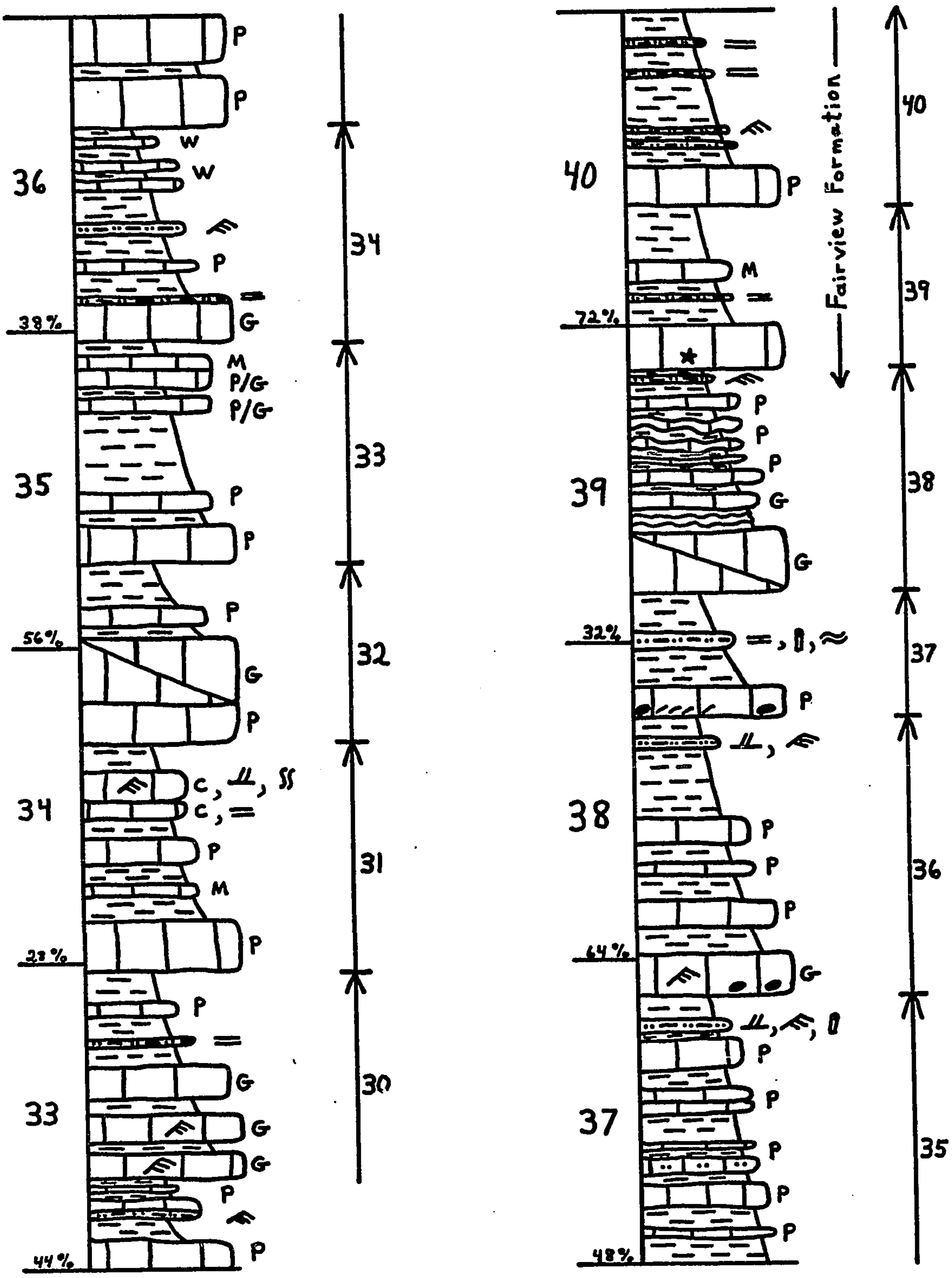

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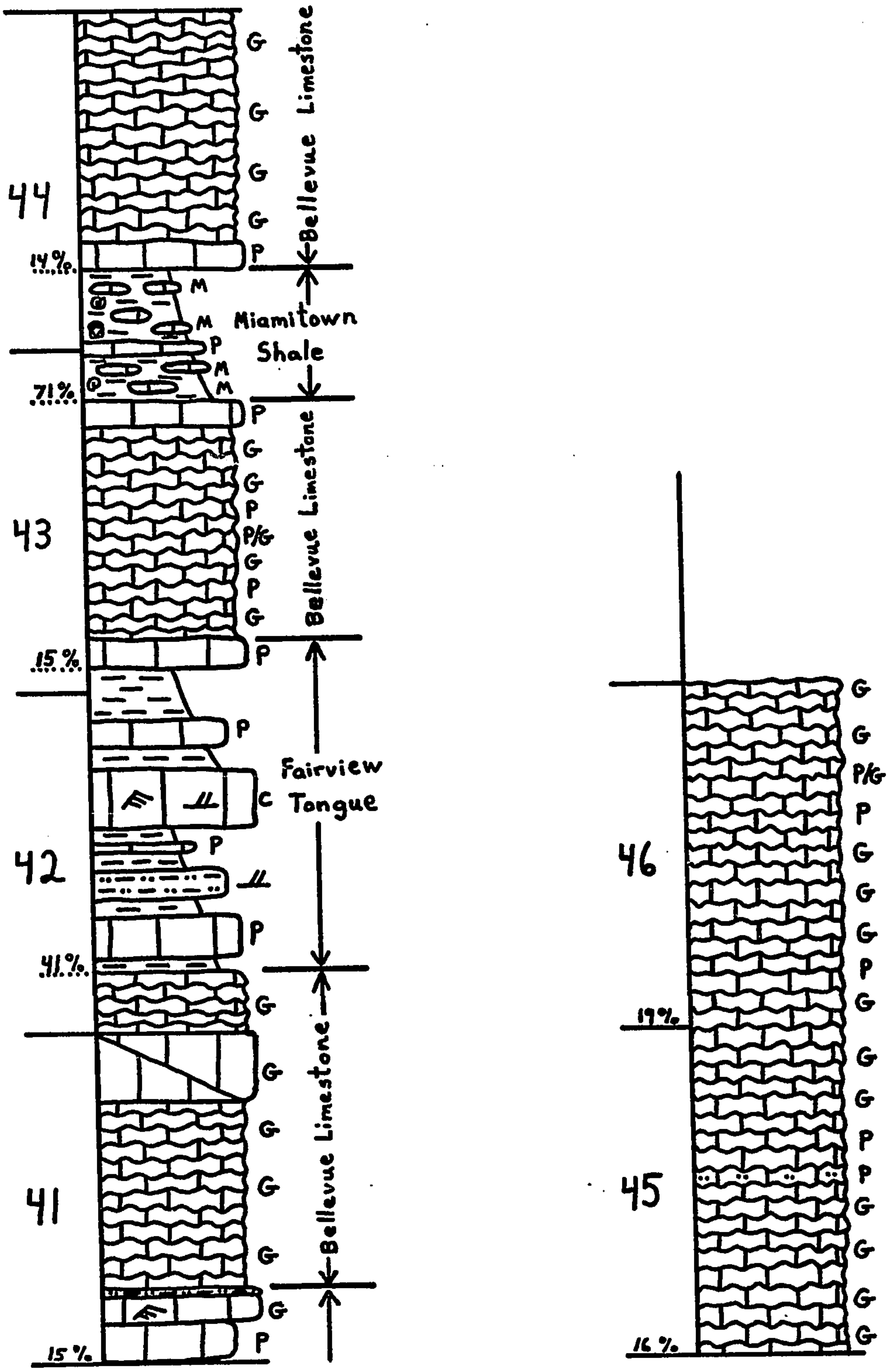
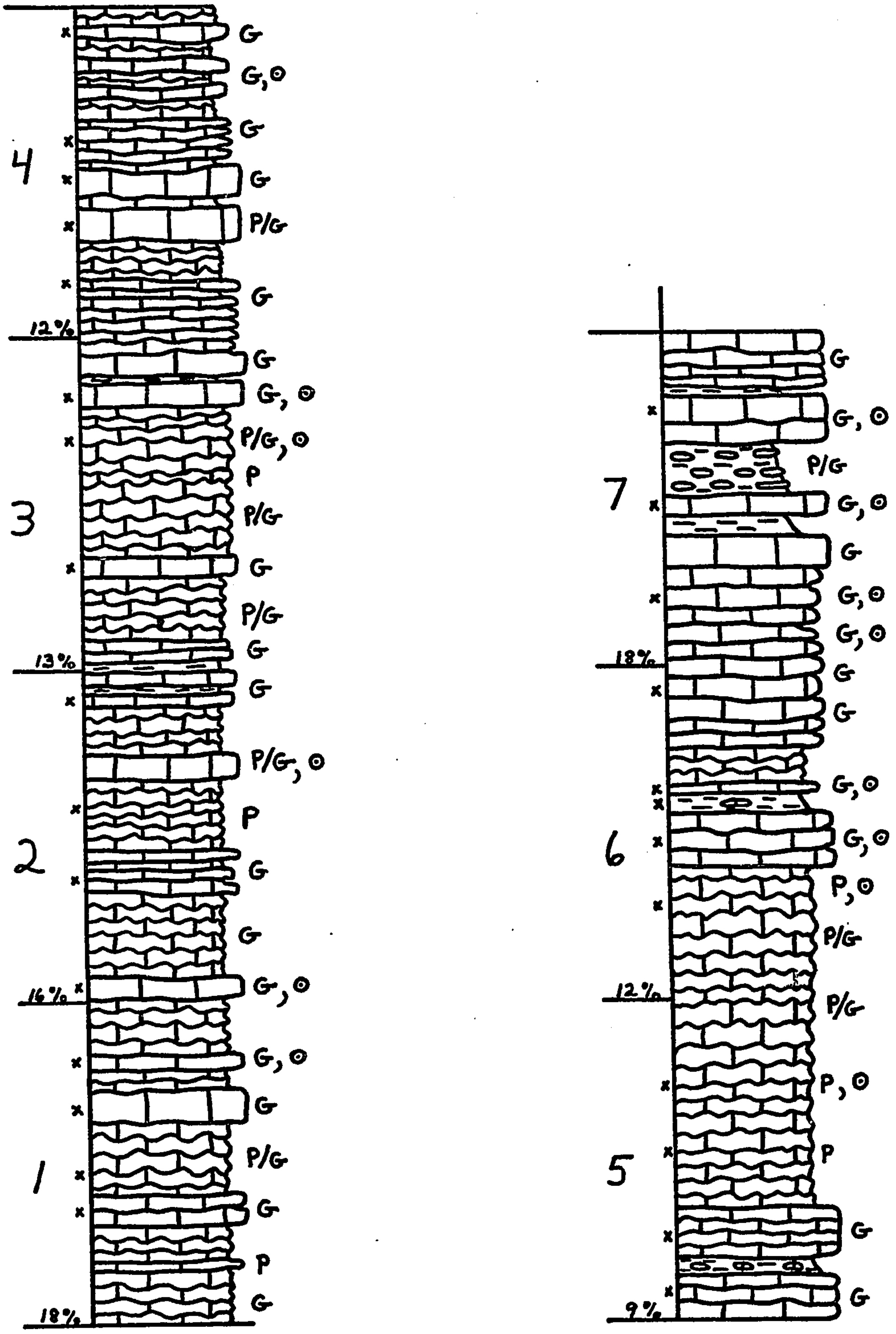
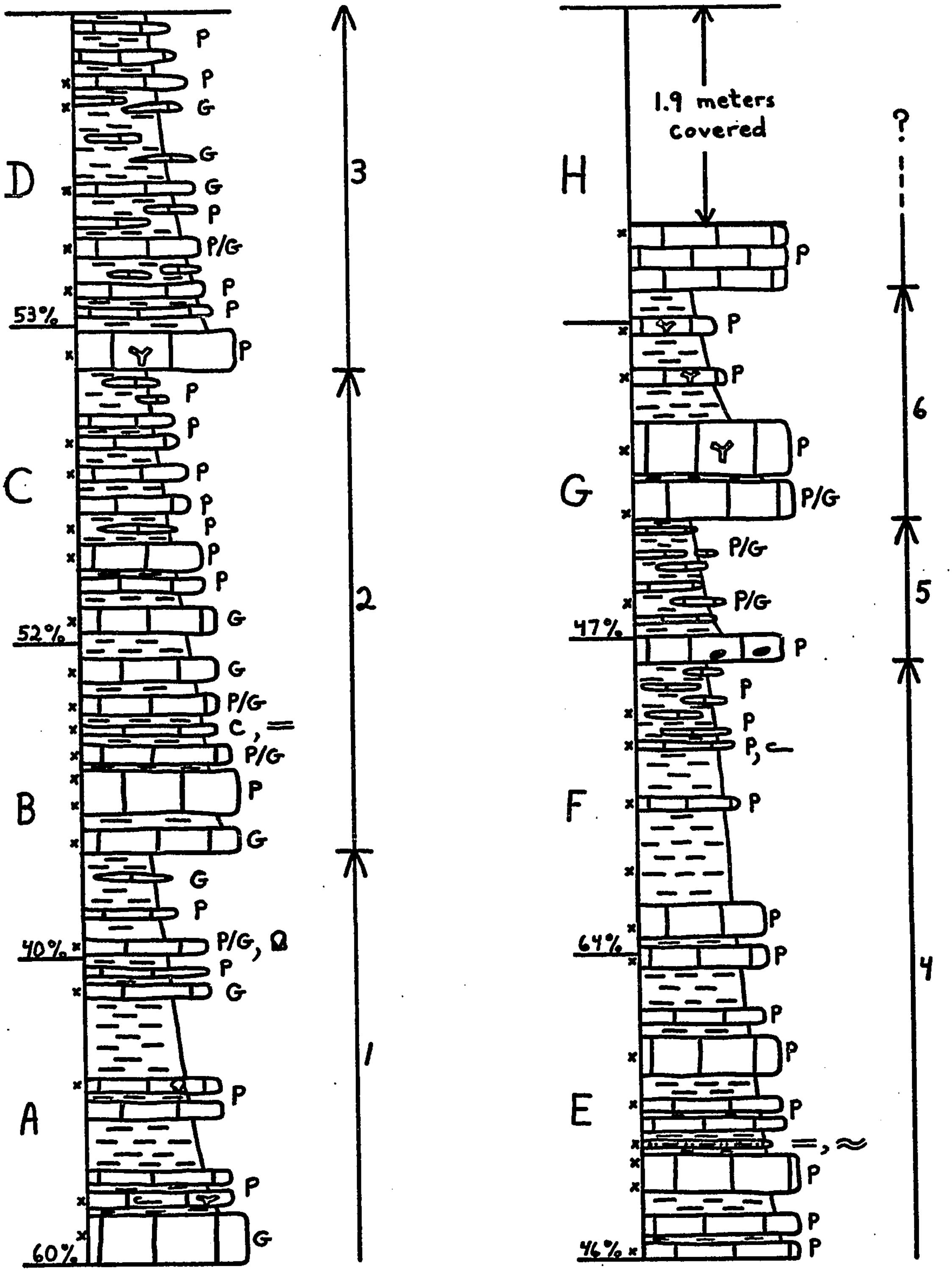


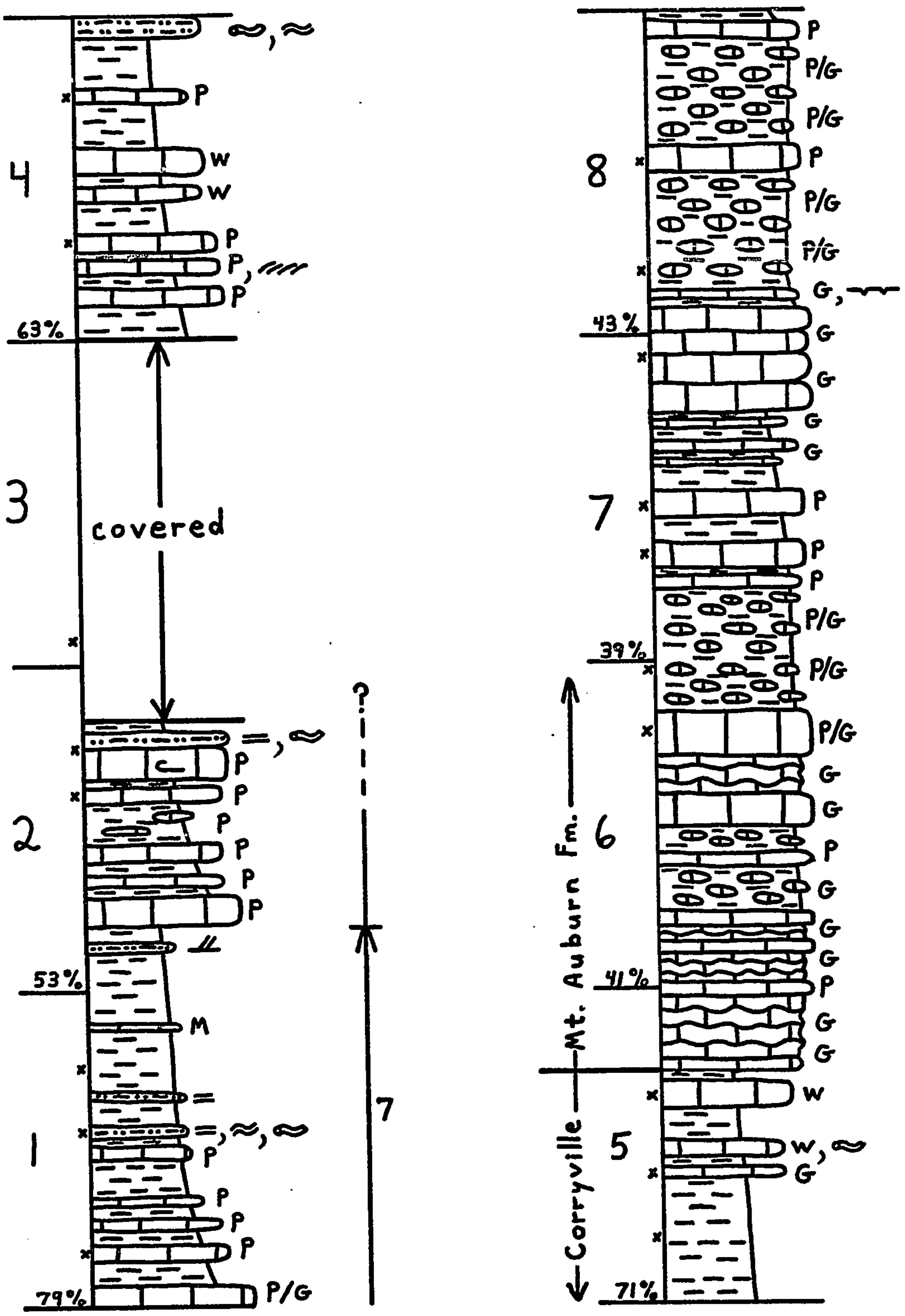
RICHMOND, IND. (Whitewater Fm.)



RUMPKE LANDFILL (Corryville Fm.)



RUMPKE LANDFILL (cont.)



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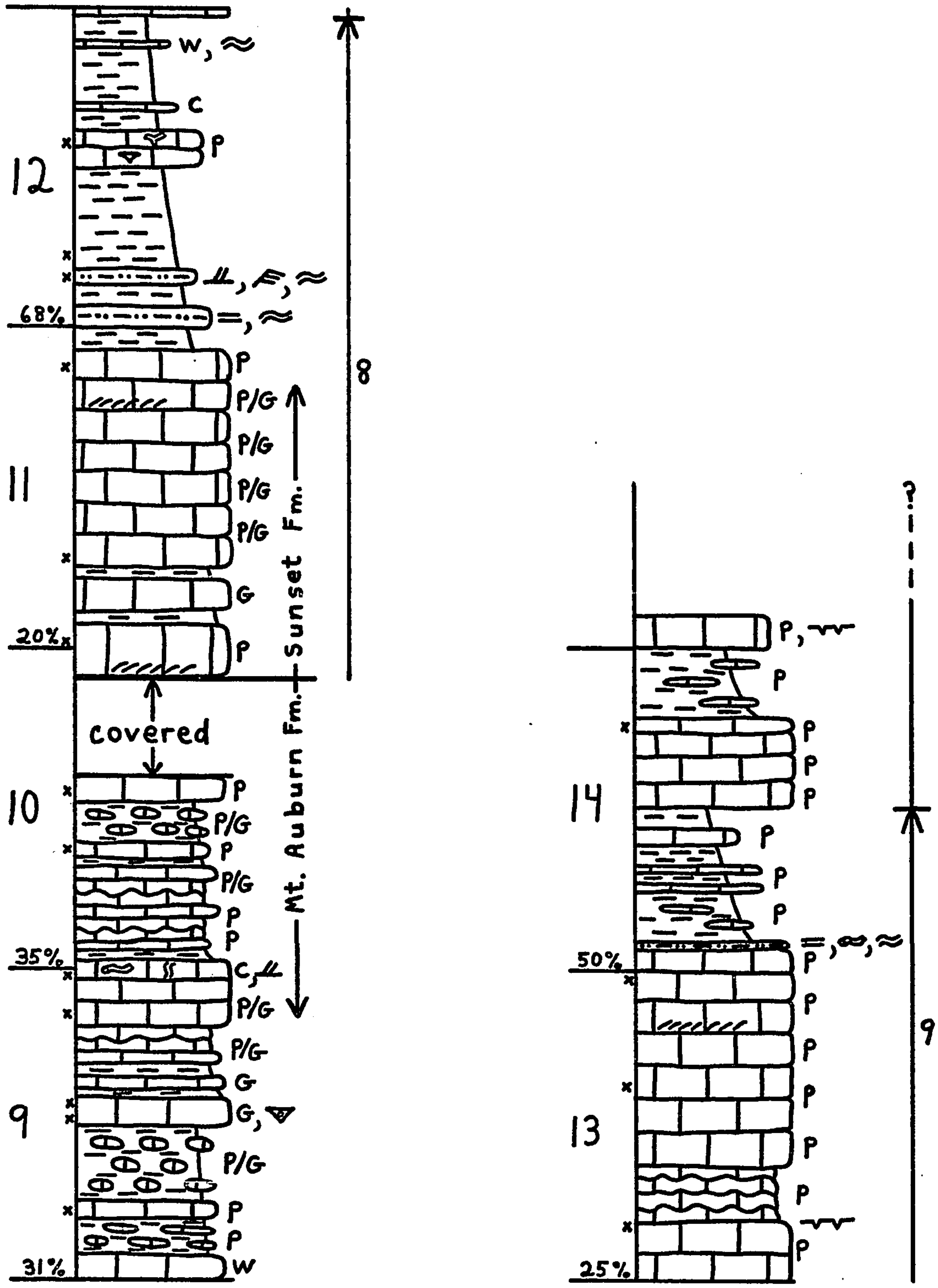


APPENDIX 4

HAND SPECIMEN DESCRIPTIONS OF CARBONATE ROCKS

Key to Appreviations

Br = brachiopods

Bz = bryozoans

Ce = cephalopods

Cl = corals

Co = conodonts

Cr = crinoids

Ga = gastropods

Gr = graptolites

On = algal onkoids

Os = ostracods

Pe = pelecypods

Sc = scolecodonts

Tr = trilobites

(S) = shale hemicycle

(C) = carbonate hemicycle

N/A = not applicable, or none observed

P/G = poorly washed grainstone

subhoriz. = subhorizontal

parall. = parallelism

mod. = moderate

SAMPLE	FOSSILS				TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Aiken H.S. 1.26 (c)	Cr, Br, Bz, Pe	Rafinesquina Zygospira	5	none	inclined (10°)	mod.	mod.	2 mm	Grainstone	Sunset Formation
1.4 (c)	Br	Rafinesquina	1	none	inclined (45°)	mod.-low	mod.	2.5 mm	Packstone	matrix is very silty
1.5 (c)	Br, Bz, Tr, Cr	Rafinesquina	4	none	subhoriz.	mod.-low	mod.-poor	6 mm	Packstone	
1.65 (c)	Br, Bz, Tr, Cr, Ga	Rafinesquina Cyclora	5	none	subhoriz.	mod.-low	mod.	6 mm	Packstone	
1.9 (c)	(Cr), Br, Bz	Rafinesquina Zygospira	4	none	random	very high	very well	1 mm	Grainstone	
2.2 (s)	Cr, Br, Bz, Tr, Ga	Rafinesquina Cyclonema	5	Trichophycus (base of bed)	random	high	well	3.5 mm	Grainstone	
2.4 (s)	Br	Zygospira	1	Diplocraterion	random	very high	very well	0.4 mm	Calcisiltite	laminated
2.52 (s)	Br, Bz, Tr, Cr	Rafinesquina	4	none	subhoriz.	low	poor	10 mm	Packstone	Some bryozoans are encrusting.
2.8 (c)	(Ga), Br, Bz	Rafinesquina Zygospira Cyclora	4	none	random	high	very well	2 mm	Grainstone	
3.15 (c)	Br, Bz, Tr, Cr	Rafinesquina Zygospira	5	none	subhoriz.	mod.	mod.	3 mm	Packstone	Highly-broken fragments on top of bed.

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Aiken H.S. 3.3(s)	Br, Bz, Ga	Rafinesquina Cyclora	3	(Gastropod?) trails on top of bed.	N/A	N/A	N/A	N/A	siltstone	
3.75(s)	Br, Bz, Tr, Cr	Zygospira	4	none	subhoriz.	mod.-high	mod.-well	2.5 mm	Packstone	silty matrix
3.8(c)	Cr, Br, Ga, Tr	Zygospira Cyclonema Cyclora	5	Chondrites (top of bed); inclined tube.	subhoriz.	very high	very well	1 mm	Grainstone	
3.9(c)	Cr, Br, Bz, Tr	Rafinesquina	4	none	inclined (45°)	high	well	2.5 mm	Grainstone	
4.1(c)	Cr, Br, Bz, Tr	Rafinesquina Zygospira	5	vertical tube (escape?)	N/A	very high	very well	0.4 mm	Calcisiltite	cross-laminated
4.2(c)	Cr, Br, Bz, Tr, Ga	Rafinesquina Zygospira Cyclonema	6	none	subhoriz.	mod.-high	mod.	Bimodal: 9 mm/ 0.4 mm	Grainstone	
4.5(c)	Br, Bz, Ga, Cr	Rafinesquina Zygospira Cyclonema Cyclora	6	none	subhoriz.	high	mod.-poor	Bimodal: 10 mm/ 0.5 mm	Packstone	many small, black grains (phosphate?)
4.76(s)	Br, Bz	Zygospira	2	none	N/A	N/A	N/A	N/A	Siltstone	laminated
4.86(s)	Br, Bz, Cr	Rafinesquina Zygospira	4	none	subhoriz.	high	mod.	Bimodal: 20 mm/ 1 mm	Packstone	
5.44(s)	Br, Tr, Ga, Cr	Rafinesquina Cyclora	4	none	subhoriz.	high	mod.-well	1 mm	Packstone	many small, black grains (phosphate?)

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Aiken H.S 5.55(c)	Br, Bz, Cr, Tr	Zygospira	4	none	subhoriz. (good parall.)	mod.-high	mod.-well	5 mm	Packstone	silty matrix
5.6 (c)	Br	Rafinesquina	1	none	N/A	N/A	N/A	N/A	Siltstone	laminated
5.76 (s)	Br, Bz, Tr, Cr	Rafinesquina Zygospira	5	none	subhoriz.	high	mod.	3 mm	Packstone	silty matrix
5.88 (s)	Br	Zygospira	1	Trichophycus + Chondrites (top of bed)	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
6.2 (c)	(Cr) Br, Tr, Bz, Ga	Zygospira Cyclora	5	none	random	high	well	2 mm	Grainstone	
6.5 (s)	Br, Bz, Ga, Pe	Rafinesquina Zygospira Cyclora	5	none	subhoriz.	mod.-high	mod.	3.5 mm	Packstone	Small, black grains (phosphate?)
6.6 (s)	Cr, Br, Bz, Tr	Rafinesquina Zygospira	5	none	subhoriz.	mod.-high	mod.-well	3 mm	P/G	silty matrix
7.2	Cr, Br, Bz, Tr	Rafinesquina Zygospira	5	none	subhoriz.	high	well	2 mm	Grainstone	Oregonia Formation
7.3	Br, Bz, Cr, Tr	Zygospira Flexicalymene	4	none	random	high	well	1.5 mm	Packstone	argillaceous
7.5	Cr, Br, Bz, Tr, Ga	Zygospira Cyclora	5	inclined tube	random	high	well	1 mm	Packstone	argillaceous

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Aiken H.S. 7.6	Br, Cr, Bz, Ga	Rafinesquina, Zygospira, Cyclora	5	none	random	high	well	2 mm	Packstone	argillaceous
7.8	Br, Cr, Bz	Leptaena, Zygospira	4	none	random	high	well	1 mm	Packstone	argillaceous
8.0	Br	Rafinesquina	1	none	N/A	N/A	N/A	0.3 mm	Calcisiltite	
8.2	Br, Bz, Cr, Tr	Zygospira	4	inclined tube	Subhoriz.	very high	well	1 mm	Wackestone / Grainstone	1 cm / 5 cm — gradational contact
8.3	Bz, Br, Pe, Ga, Cr	Platystrophia, Zygospira, Cyclora	6	none	subhoriz.	mod.-high	mod.-well	2.5 mm	Packstone	bored Platystrophia encrusting Bz.
8.45	Br, Tr	Zygospira	2	horizontal tubes on base of bed	N/A	N/A	N/A	0.4 mm	Calcisiltite	
8.8	Br, Cr	Rafinesquina, Zygospira	3	inclined tube	N/A	N/A	N/A	0.4 mm	Calcisiltite	
8.9	Br, Bz, Cr, Tr, Ga	Zygospira, Cyclora	5	none	subhoriz.	high	well	2 mm	P/G	matrix increases upward.

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Batavia 1.3 (c)	(Cr), Br, Bz, Tr, Ga	Onniella, Cyclora	5	none	random	high	well	2 mm	P/G	Kope Formation
1.6 (c)	Bz, Br, Tr	Onniella, Zygospira, Orbiculoidea	5	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
2.28 (s)	Br, Bz, Tr, Cr	Onniella, Flexicalymene	4	Chondrites (10%; horizontal)	subhoriz.	mod.	mod.-well	3 mm	Wackestone	
2.32 (s)	?	N/A	N/A	Chondrites (15%; horizontal)	subhoriz.	very high	very well	0.3 mm	Calcisiltite	
2.7 (c)	(Cr), Br, Bz, Tr, Ga	Cyclora	5	none	random	very high	very well	1.5 mm	Grainstone	mud chips near base
3.0 (c)	Cr, Br, Bz, Tr, Ga	Onniella, Sowerbyella, Cyclora	6	none	random	very high	very well	1 mm	Grainstone	
3.3 (s)	Bz, Br, Tr, Ga, Cr	Onniella	5	none	subhoriz.	mod.	mod.-poor	5 mm	Wackestone	
3.62 (s)	Tr	N/A	1	Chondrites (80%; inclined; pyrite-filled)	N/A	N/A	N/A	N/A	Micstone	
4.2 (c)	Cr, Br, Bz, Tr, Ga	Cyclora	5	none	subhoriz.	mod.-high	well	2 mm	P/G	
4.4 (c)	Cr, Br, Bz, Tr	Onniella, Zygospira	5	none	subhoriz.	mod.-high	mod.-well	2 mm	Grainstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Batavia 4.8 (s)	Br, Bz, Cr, Tr	Onniella, Zygospira	5	none	subhoriz.	mod.-high / very high	mod.-well / very well	2 mm / 0.2 mm	Packstone / calcisiltite	1cm / 1cm — abrupt contact
5.6 (c)	Cr, Bz, Br, Ga	Onniella, cyclora	4	none	subhoriz. (good parall.)	very high / high	very well / very well	1 mm / 2 mm	Packstone / Grainstone	4cm / 2cm — gradational "
5.7 (c)	(Br), (Tr), Bz, Cr, Ga	Onniella, cyclora	5	none	subhoriz. (good parall.)	mod.-high	mod.-well	3.5 mm	Packstone	
6.7 (s)	Br, Bz, Tr, Cr	Onniella, Zygospira, Sowerbyella	6	none	subhoriz.	mod.-low	poor	6.5 mm	Packstone	
7.0 (s)	Br, Bz, Tr	Onniella, Orbiculoidea	4	none	random	low	poor	7 mm	Wackestone	
7.2 (c)	(Cr), (Br), Tr, Ga	Onniella, cyclora	4	none	subhoriz.	high	well	2.5 mm	Grainstone	
7.5 (c)	(Cr), (Br), Bz, Tr, Ga	Onniella, Sowerbyella, cyclora	6	none	random	high	mod.-well	3 mm	Grainstone	
7.6 (c)	(Cr), Br, Tr, Ga	Onniella, cyclora	4	none	random	high	very well	1 mm	Grainstone	
7.8 (c)	(Br), Bz, Tr, Cr	Onniella, Sowerbyella	5	none	inclined (10°)	mod.-low	mod.-poor	8 mm	Packstone	
7.9 (c)	Br, Bz, Tr, Cr, Ga	Onniella, Zygospira, cyclora	6	none	subhoriz.	high	mod.-well	3 mm	Packstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Batavia 8.8 (c)	Br, Bz, Tr, Ga, Cr	Onniella Zygospira Cyclora	6	none	subhoriz.	high	mod.-well	2.5 mm	Packstone	mud chips up to 7cm long
9.0 (s)	Cr, Br, Bz, Ga, Tr, Gr	Onniella Zygospira Cyclora	7	none	subhoriz.	high	well	1 mm	P/G	
9.8 (s)	N/A	N/A	N/A	color mottling	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
10.5 (c)	N/A	N/A	N/A	none	horizontal (good parall.)	very high	very well	0.4mm	Calcisiltite	
10.6 (c)	Cr, Br, Bz, Tr	Onniella Sowerbyella	5	none	subhoriz.	mod.	mod.	3 mm	P/G	
11.9 (s)	Br, Bz, Tr, Cr, Ga	Onniella Zygospira Cyclora	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
13.5 (c)	(Tr), Br, Bz, Cr	N/A	4	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
14.3 (c)	(Bz), Br, Tr	Onniella	3	none	subhoriz.	mod.	mod.	6 mm	P/G	
15.1 (s)	N/A	N/A	N/A	Diplocraterion	N/A	N/A	N/A	N/A	Siltstone	laminated
15.5 (c)	Cr, Br, Bz, Tr, Ga	Onniella Cyclora	5	none	subhoriz.	high	well	2 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Batavia 15.8 (c)	Cr, Br, Bz, Tr, Ga	Cyclora	5	none	horizontal (good parall.)	high	well	1 mm	P/G	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Blue Rock S1	Br, Bz, Cr, Tr, Os	Onniella, Rafinesquina	6	none	random	high	mod.-well	1 mm	Wackestone	argillaceous
S2	Br, Cr, Bz, Tr, Os, Ga	Cyclora, Rafinesquina	6	none	subhoriz.	mod.	poor	Bimodal: 7 mm/ 0.5 mm	Wackestone	argillaceous
S3	Br, Bz, Cr, Tr, Ga	Cyclora, Rafinesquina	5	none	random	high	mod.-well	1 mm	Packstone	many small black (phosphatic?) grains.
S4	Br, Bz, Cr, Tr, Pe, Ga	Cyclora, Rafinesquina, Zygospira	7	none	random	mod.-high	mod.-well	3 mm	Packstone	silty matrix
S5	Br, Cr, Bz, Ga	Cyclora, Rafinesquina, Zygospira	5	none	random	very high	very well	0.6 mm	Packstone	argillaceous
S6	Br, Cr, Ga	Cyclora	3	none	random	very high	very well	0.5 mm	Wackestone	silty matrix
S7	Br, Cr, Bz, Tr, Os	Rafinesquina	5	none	random	mod.-high	mod.-poor	5 mm	Wackestone	silty matrix
S8	Br, Cr, Tr, Bz, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	mod.-high	mod.	4 mm	Packstone	
S9	Br, Cr, Bz, Ga	Cyclora, Rafinesquina, Zygospira	5	none	random	high	mod.-well	1.5 mm	Packstone	argillaceous
S11	Br, Bz, Tr, Ga	Cyclora, Ga (unknown genus), Rafinesquina, Zygospira	6	none	subhoriz.	mod.-high	mod.-poor	3.5 mm	P/G	silty matrix

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Blue Rock S 12	Br, Bz, Ga, Tr, Cr	*Cyclora* *Platystrophia*	5	none	subhoriz.	mod.	mod.-poor	7 mm	Packstone	silty matrix
S 13	Br, Bz, Tr, Ga, Cr	*Cyclora* *Cyclonema* *Zygospira*	6	none	subhoriz.	mod.	mod.	4 mm	Packstone	
S 14	Br, Tr	*Zygospira*	2	color mottling	N/A	very high	very well	0.4 mm	Calcisiltite	
S15 (c)	(Br), (Bz), Tr, Ga	*Cyclora* *Rafinesquina*	4	none	inclined (10°)	high	well	2 mm	Grainstone	Sunset Formation
S16 (c)	Br, Bz, Tr, Ga	*Cyclora* *Rafinesquina* *Zygospira*	5	none	subhoriz.	very high	very well	1 mm	P/G	
S17 (s)	Br, Bz	*Zygospira*	2	Chondrites; color mottling	subhoriz.	very high	very well	1 mm	Wackestone	silty matrix
S18 (s)	Br, Bz	*Rafinesquina* *Zygospira*	3	color mottling	subhoriz.	very high	very well	0.3 mm	Calcisiltite	laminated
S19 (c)	Br	*Rafinesquina* *Zygospira*	3	Chondrites; vertical tubes	subhoriz.	very high	very well	0.4 mm	Calcisiltite	2 sets of truncated cross-laminae.
S20 (c)	Br	*Rafinesquina* *Trematis* *Zygospira*	3	none	subhoriz.	very high	very well	0.4 mm	Calcisiltite	
S21 (c)	Br, Bz, Tr	*Rafinesquina* *Zygospira*	4	color mottling	subhoriz.	very high	very well	0.4 mm	Calcisiltite	laminated

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Blue Rock S22(c)	Br, Bz, Tr	Rafinesquina Zygospira	4	none	subhoriz.	Bimodal: very low/ very high	poor	Bimodal: 2.5 mm/ 0.5 mm	Packstone	
S23(c)	Br, Cr, Bz	Rafinesquina	3	none	random	very high	very well	0.5 mm	Calcisiltite	
S24(s)	Br, Bz, Tr	Rafinesquina Zygospira	4	abundant Chondrites	subhoriz.	mod.	mod.-poor	3.5 mm	Packstone	
S25(s)	(Br), Bz, Tr, Cr	Rafinesquina Zygospira	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam C.2 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Siltstone	cross-laminated; Corryville Fm.
C.4 (c)	Br, Bz, Tr	Rafinesquina Zygospira	4	none	subhoriz.	mod.-low	poor	8 mm	Packstone	
C.6 (c)	Br, Bz, Cr, Ga	Cyclora Onniella Rafinesquina Zygospira	6	none	subhoriz.	mod.	poor	7 mm	Packstone	
C.9 (c)	Br, Bz	Hallopora Rafinesquina Zygospira	3	none	subhoriz.	low	poor	10 mm	Packstone	
D.8 (s)	Br, Bz, Tr, Pe	Onniella Zygospira	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
D.92 (c)	Br, Bz, Tr, Cr, Pe	Zygospira	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
1.2 (c)	Br, Bz	Onniella	2	none	subhoriz.	high	well	1 mm	Grainstone	
1.9 (c)	(Bz), Br, Cr	N/A	3	none	random	mod.-high	mod.	4 mm	Grainstone	
2.18 (s)	Br, Bz, Tr, Pe, Cr	Zygospira	5	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
2.3 (s)	Cr, Br, Bz, Tr	N/A	4	none	random	high	well	1 mm	Grainstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 2.46 (s)	(Bz), Cr, Ga	*Cyclora*	3	none	random	very high	well	2 mm	Grainstone	
2.9 (c)	(Bz), Cr, Br, Tr	*Zygospira*	4	none	random	high	well	2 mm	Grainstone	
3.0 (c)	(Bz), Cr, Tr	N/A	3	none	subhoriz.	mod.-high	mod.-well	3.5 mm	Grainstone	
3.1 (c)	Br, Bz, Pe	N/A	3	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
3.5 (s)	Br, Bz, Cr, Tr	*Rafinesquina*	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
4.5 (s)	Br, Bz, Tr, Ga	N/A	4	none	subhoriz.	mod.-high	mod.	4 mm	Packstone	
4.74 (s)	Br, Bz, Cr, Tr, Ga	*Cyclora*	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
5.3 (s)	Br, Bz, Tr	*Onniella* *Zygospira*	4	none	subhoriz.	mod.-low	mod.-poor	6 mm	Wackestone	silty matrix
5.5 (s)	Br, Bz, Cr, Tr, Pe	*Zygospira*	5	none	subhoriz.	low	poor	7 mm	Packstone	
5.9	Br, Bz, Cr, Tr, Ga, Pe	*Cyclora*	6	*Chondrites* (top of bed)	subhoriz.	high	mod.-well	1.5 mm	Wackestone	silty matrix

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 6.5	Br, Bz, Cr, Tr, Ga, Os	Cyclora Rafinesquina Zygospira	7	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
6.82	(Ga), Bz, Br, Tr, Cr	Cyclora Zygospira	5	none	random	high	well	1 mm	Wackestone	
7.4	(Ga), Cr, Br, Bz	Cyclora	4	none	inclined (15°)	high	well	2 mm	Grainstone	highly abraded grains on top of bed.
7.8	Br, Bz, Cr, Tr, Ga, Pe	Cyclora Rafinesquina	6	none	subhoriz.	mod.	poor	5.5 mm	Packstone	
8.3	(Br), Bz, Cr, Tr, Ga	Cyclora Rafinesquina	5	none	subhoriz.	mod.-low	mod.-poor	9 mm	Packstone	
9.4 (c)	(Br), Bz, Cr, Tr, Ga	Cyclora Onniella Rafinesquina	6	none	subhoriz.	mod.	poor	9 mm	Packstone	
9.6 (c)	(Ga), Br, Bz, Cr	Cyclora Onniella Rafinesquina	5	none	random	mod.-high	mod.-well	2.5 mm	Wackestone	
10.8 (c)	Br, Cr, Bz, Ga	N/A	5	none	subhoriz.	mod.-high	mod.-well	Bimodal: 10 mm / 1 mm	Grainstone	Sunset Formation
11.0 (c)	Br, Cr, Bz, Ga	Cyclora Rafinesquina	4	none	inclined (40°)	very high	very well	0.5 mm	Grainstone	
11.5 (s)	Br, Bz, Tr, Ga	Rafinesquina Zygospira	5	none	subhoriz.	mod.-low	poor	8 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 11.9 (s)	Br, Bz, Tr, Cr	Onniella Zygospira	5	none	inclined (30°)	mod.	mod.	5 mm	Packstone	
12.0 (c)	(Ga), Br, Bz, Cr	Cyclora	4	none	inclined (10°)	mod.-high	mod.-well	2 mm	Packstone	textural inversion
12.2 (c)	(Cr), (Ga), Br, Bz, Tr	Cyclora	5	none	inclined (10°)	high	very well	2 mm	Grainstone	intraclasts
12.4 (c)	Br, Bz, Cr, Tr, Ga	Cyclora Zygospira	5	none	subhoriz.	mod.	mod.	5 mm	Packstone	
12.8 (s)	Br, Bz, Cr, Tr, Ga	Cyclora Onniella Zygospira	6	none	subhoriz.	mod.-high	mod.-well	2.5 mm	Packstone	
12.94 (s)	Cr, Br, Bz, Tr	N/A	4	none	horizontal (good parall)	very high	well	1 mm	Grainstone	
13.5 (s)	(Tr), Br, Bz, Cr	Onniella Rafinesquina Zygospira	6	none	subhoriz.	mod.-low	mod.-poor	4.5 mm	Packstone	
14.0 (s)	Br, Bz, Tr, Ga	unknown Ga genus Rafinesquina Zygospira	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
14.14 (s)	(Tr), Br, Bz, Cr, Ga	Rafinesquina Zygospira	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
14.4 (c)	Br, Bz, Tr, Ga	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	mod.	poor	4.5 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 14.9 (s)	Br, Bz, Cr, Tr, Ga, Pe	unknown Ga genus, Rafinesquina, Zygospira	7	none	subhoriz.	mod.	poor	8 mm	Packstone	
14.98 (s)	Br, Bz	Rafinesquina, Zygospira	3	Rhizocorallium, Chondrites	N/A	N/A	N/A	N/A	Siltstone	
15.2 (c)	(Cr), (Ga), Br, Bz	Cyclora, Rafinesquina	4	none	inclined (10°)	very high	well	1.5 mm	Grainstone	
15.4 (s)	Br, Bz, Tr, Ga	Cyclora, Rafinesquina, Zygospira	5	color mottling	subhoriz.	low	poor	7 mm	Packstone	
15.6 (c)	Br, Bz, Tr, Ga	Cyclonema, Rafinesquina	4	none	subhoriz.	low	poor	9 mm	Packstone	
16.2 (c)	Br, Bz, Cr, Tr, Pe, Ga	Cyclora, unknown Ga genus, Rafinesquina	7	none	subhoriz.	mod.-low	poor	8 mm	Packstone	
16.6 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Siltstone	
16.81 (s)	Tr, Bz, Br, Cr, Ga, Pe, Os	unknown Ga genus, Onniella, Rafinesquina	8	none	subhoriz.	low	poor	9 mm	Packstone	
17.25	Br, Cr, Bz, Tr, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	mod.-high	mod.	4 mm	P/G	
17.8	Br, Cr, Bz, Tr, Ga	Cyclora, Rafinesquina, Zygospira	5	none	random	very high	very well	0.6 mm	Grainstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 18.1 (c)	Br, Bz, Cr, Tr, Ga	Cyclora, Onniella, Rafinesquina, Zygospira	7	none	subhoriz.	mod.	poor	6 mm	Packstone	discontinuous, 1mm thick silt layer in middle of bed.
18.3 (c)	Br, Bz, Cr, Tr, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
18.94 (c)	Br, Bz, Cr, Tr, Ga	Cyclora, Rafinesquina, Strophomena	6	none	subhoriz.	mod.-low	poor	9 mm	Packstone	
19.8 (c)	Br, Bz, Cr, Tr, Ga, Gr	unknown Ga genus, Rafinesquina	6	none	subhoriz.	low	poor	10 mm	Packstone	
21.8 (c)	Br, Bz, Cr, Tr, Cl, Os, Pe	Rafinesquina, Zygospira	8	none	subhoriz.	low	poor	6 mm	Wackestone	
22.6	Br, Bz, Cr, Tr, Pe	Rafinesquina, Zygospira	6	none	subhoriz.	low	poor	10 mm	Packstone	
23.8	Br, Bz, Cr, Tr, Pe	Rafinesquina, Zygospira	6	none	subhoriz.	mod.	mod.	7 mm	Packstone	
24.1	Br, Bz, Cr, Tr, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	high	well	2 mm	Packstone	textural inversion
24.2	(Cr), (Bz), Bz, Tr, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	high	mod.-well	3 mm	Grainstone	encrusting Bz
24.4	(Cr), Bz, Ga	Cyclora, Rafinesquina	3	none	subhoriz.	very high	very well	2 mm	Grainstone	Oregonia Formation

SAMPLE NUMBER	FOSSILS TYPES	FOSSILS GENERA	GENERIC DIVERSITY	BIOTURBATION	TEXTURE ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 24.6	(Br), (Cr), Bz, Tr, Ga	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	high	mod.-well	3 mm	Packstone	encrusting Bz
24.8	(Cr), Br, Bz, Ga	Cyclora, Onniella, Rafinesquina, Zygospira	6	none	subhoriz.	high	mod.-well	2 mm	Packstone	encrusting Bz
24.9	Br, Bz, Cr, Tr, Ga, Os	Cyclora, Zygospira	6	vertical tubes + conical burrow on base	Subhoriz.	high	well	1 mm	Grainstone / Wackestone	2 cm / 2 cm
Float 25	Br, Cr, Bz, Os	Rafinesquina, Zygospira	5	none	random	very high	very well	0.6 mm	Grainstone	articulated Cr stem (5 cm long).
25.2	Br, Bz, Cr, Ga, Sc	Cyclora, Zygospira, Inarticulate Br	6	none	inclined (20°)	very high	very well	0.7 mm	Grainstone	
25.3	Br, Bz, Cr, Tr, Ga, Os	Cyclora, Zygospira, Inarticulate Br	7	none	subhoriz.	very high	well	1 mm	Grainstone	
25.5	Cr, Br, Pe, Ga, Os	Cyclora, Zygospira	5	none	subhoriz.	very high	well	1 mm	Grainstone	
25.6	Br, Bz, Cr, Ga	Cyclora, Zygospira	4	none	subhoriz.	very high	well	1 mm	Grainstone	
25.8	Br, Bz, Cr, Ga	Cyclora, Zygospira	4	none	subhoriz.	very high	well	1 mm	P/G	
25.99	Br, Bz, Cr, Ga, Os	Cyclora, Rafinesquina, Zygospira	6	none	subhoriz.	mod.-high	mod.-poor	4 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 26.2	Br, Cr, Bz, Os	N/A	4	none	subhoriz.	very high	well	1 mm	Grainstone	graded (1.5mm → 0.5mm)
26.3	Br, Bz, Cr, Tr, Ga, Pe, Os	Rafinesquina Zygospira	8	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
26.8	Br, Bz, Cr, Ga	Cyclora Rafinesquina Zygospira	5	none	random inclined (10°)	mod. mod.-high	poor mod.-well	15 mm 4.5 mm	Grainstone Grainstone	(silty)
27.3	(Br), Bz, Ga	Cyclora Rafinesquina Zygospira	4	none	random	mod.	poor	10 mm	Wackestone	
27.5	Br, Bz, Cr, Tr, Ga	Cyclora Rafinesquina Zygospira	6	none	subhoriz.	mod.	poor	5 mm	Packstone	
27.8	Br, Bz, Tr, Ga, Os	Cyclora Rafinesquina Zygospira	6	none	subhoriz.	mod.	mod.	7 mm	Packstone	
28.4	Br, Bz, Cr, Tr, Os	Cyclora Rafinesquina Zygospira	6	none	subhoriz.	mod.-high	mod.-well	3.5 mm	Packstone	
28.5	(Br), Ga	Cyclora Rafinesquina Zygospira	3	none	subhoriz.	high	well	3.5 mm	Grainstone	
28.9	Br, Ga, Bz	Cyclora Rafinesquina Zygospira	4	none	random	high	mod.-well	3.5 mm	Grainstone	
29.2	Br, Cr, Bz, Ga	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	mod.-high	mod.	4 mm	P/G	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 29.5	(Bz), Br, Tr, Cr, Ga, Os, Sc	Cyclora Isotellus Zygospira	7	none	subhoriz.	mod.-low	poor	5 mm	Packstone	
29.6	(Cr), (Br), Bz, Tr, Ga	Cyclora Rafinesquina Zygospira	6	none	inclined (poor parall.)	mod.-high	poor	Bimodal: 30 mm/ 1.5 mm	Grainstone	
29.8	Br, Bz, Cr, Tr, Sc, Ga	Cyclora Rafinesquina Zygospira	7	none	subhoriz.	mod.	mod.-poor	3.5 mm	Packstone	
30.1	Br, Bz, Cr, Tr, Ga	Cyclora Rafinesquina Zygospira	6	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
30.2	(Ga), Br, Bz, Cr, Os	Cyclora Rafinesquina Zygospira	7	none	random	high	well	1 mm	Grainstone	inarticulate Br
30.5	Br, Bz, Cr, Ga	Cyclora Zygospira	4	none	random	high	mod.-well	1 mm	Wackestone	
30.8	Br, Bz, Cr, Tr, Ga, Sc	Cyclora Rafinesquina Zygospira	7	none	subhoriz.	very high	well	2 mm	Packstone	
31.2 (c)	Br, Cr, Bz, Ga, Os	Cyclora Zygospira	5	none	subhoriz.	very high	very well	0.7 mm	Grainstone	
31.6 (s)	Br, Bz, Ga, Os	Cyclora	4	none	subhoriz.	very high	very well	0.7 mm	Grainstone	
31.8 (c)	Br, Bz, Cr, Ga, Os	Cyclora Onniella Rafinesquina	6	none	subhoriz.	mod.-high	mod.	5 mm	Grainstone	Waynesville Formation

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 32.0(s)	Br, Bz, Cr, Tr, Os, Sc, Ga	Tentaculites Onniella Zygospira	8	none	subhoriz.	mod.	mod.-poor	5.5 mm	Packstone	
32.9(s)	(Os), Tr, Br, Bz	N/A	4	none	N/A	N/A	N/A	N/A	Siltstone	
33.5(s)	Os, Tr	N/A	2	none	N/A	N/A	N/A	N/A	Siltstone	
33.95(s)	Br, Bz, Cr, Tr, Ga, Os	Tentaculites Onniella	6	none	subhoriz.	mod.	poor	7 mm	Packstone	
34.3(c)	(Bz), Br, Cr, Tr, Os	N/A	5	none	subhoriz.	mod.	poor	6 mm	Packstone	Cone-in-cone on top of bed.
34.99(s)	Br, Bz, Cr, Tr	Flexicalymene Onniella	4	none	N/A	N/A	N/A	N/A	Siltstone	Unrolled Flexicalymene oriented nose down (10°) near base of bed.
35.25(s)	Cr, Br, Bz, Sc	Onniella	4	none	horizontal (good parall.)	mod.-high	mod.-poor	4.5 mm	Packstone	silty matrix. Base of bed is a siltstone.
35.92(c)	Br, Bz, Cr, Tr, Os	Flexicalymene Onniella	5	none	subhoriz.	low	poor	8 mm	P/G	
36.2(s)	Br, Bz, Cr, Tr, Os, Ga	Cyclora Onniella	6	none	subhoriz.	mod.	poor	4.5 mm	P/G	
36.8(s)	Br, Bz, Cr, Tr, Os, Ga	Cyclora Onniella	6	none	subhoriz.	mod.	poor	4.5 mm	Packstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brockville Dam 37.5 (s)	Br, Bz, Cr, Tr, Os	Onniella	5	none	subhoriz.	mod.	poor	5 mm	Packstone	
37.7 (s)	Br, Bz, Cr, Tr, Ga, Os	Cyclora Onniella	6	none	subhoriz.	mod.-high	mod.-poor	2.5 mm	Packstone	
38.1 (c)	Br, Bz, Cr, Tr, Ga, Os	Cyclora Onniella	6	none	subhoriz.	mod.	poor	6 mm	Packstone	pyrite crystals up to 5 mm.
38.5 (c)	Br, Bz, Tr, Ga, Os	Cyclora Onniella	5	none	subhoriz.	mod.	poor	6 mm	Packstone	
38.8 (c)	(Cr), Br, Bz, Os, Ga	Cyclora Onniella	5	none	random	high	well	3 mm	Grainstone	
38.98 (c)	Br, Bz, Cr, Tr	Rafinesquina	4	none	subhoriz.	mod.	poor	5 mm	Packstone	
39.5 (s)	Br, Bz, Cr, Tr, Ga, Os	Cyclora Onniella	6	none	subhoriz.	mod.	poor	4 mm	Packstone	
39.6 (s)	(Tr), Br, Bz, Cr, Os	Onniella Rafinesquina	6	none	subhoriz.	mod.-high	mod.	4 mm	Packstone	
40.0 (s)	Br, Bz, Cr, Tr, Os	Onniella Rafinesquina	6	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
40.25 (s)	Cr	N/A	1	none	N/A	N/A	N/A	N/A	Siltstone	Cr column 6cm long near base.

SAMPLE	FOSSILS				TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 40.8 (c)	Br, Cr, Bz, Ga, Os	Cyclora Onniella Rafinesquina	6	none	subhoriz.	high	mod.-well	3.5 mm	Grainstone	
41.2 (c)	(Tr), Br, Bz, Cr, Ga, Os	Cyclora Onniella Rafinesquina	7	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
42.7 (c)	Br, Bz, Tr, Cr, Ga, Os	Tentaculites Rafinesquina	6	none	subhoriz.	mod.-high	mod.	4 mm	Grainstone	
43.4 (c)	Br, Bz, Cr, Tr, Pe, Ga	Cyclora Onniella	6	none	subhoriz.	mod.	poor	6 mm	Packstone	thin siltstone layer on top — scoured contact.
43.5 (c)	(Br), (Tr), Bz, Cr, Os	Onniella Rafinesquina	6	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
44.4 (c)	(Br), Bz, Ga	Onniella	3	none	inclined (10°)	mod.-high	mod.-well	6 mm	P/G	
44.5 (c)	Br, Bz, Cr, Tr, Ga, Os, Sc	Cyclora Onniella	7	none	subhoriz.	mod.	poor	6 mm	Packstone	
44.86 (s)	Br, Bz, Tr, Os	Onniella	4	none	subhoriz.	very high	very well	0.6 mm	Grainstone	
45.42 (s)	Br, Bz, Cr, Tr, Os	Onniella	5	none	subhoriz.	low	poor	9 mm	Packstone	
45.6 (s)	(Br), Bz, Tr	Onniella	3	none	random	low	mod.	15 mm	Packstone	Onniella -rich (90% of fauna)

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 45.9 (s)	(Br), Bz, Tr, Os	Onniella Rafinesquina	5	none	subhoriz.	low	poor	7 mm	Packstone	
46.15 (c)	Br, Bz, Cr, Tr, Os	Onniella	5	none	subhoriz.	mod.	poor	6 mm	Packstone	
46.7 (s)	(Bz), (Tr), Br, Ga, Os	Cyclora Onniella Rafinesquina inarticulate Br	7	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
47.6 (c)	Br, Bz, Cr, Tr, Ga	Cyclora Onniella	5	none	subhoriz.	mod.-high	mod.-well	3 mm	Packstone	
47.8 (c)	(Br), Bz, Tr, Cr, Ga	Cyclora unknown Ga genus Onniella	6	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
48.2 (s)	Br, Bz, Tr, Ga, Os	Cyclora Tentaculites Onniella Rafinesquina	7	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
48.55 (c)	(Br), Bz, Cr, Ga	Onniella Rafinesquina	5	none	subhoriz.	low	poor	15 mm	Wackestone	silty matrix
48.9 (s)	Br, Bz, Cr, Tr, Ga	Cyclora Tentaculites unknown Ga genus	7	none	subhoriz.	high	mod.-well	2.5 mm	Packstone	
49.3 (c)	Br, Bz, Ga	Cyclora Tentaculites Rafinesquina Zygospira	6	none	subhoriz.	mod.	poor	Bimodal: 10 mm/ 1 mm	Grainstone	inarticulate Br
49.5 (c)	Br, Bz, Tr	Onniella Rafinesquina Zygospira	5	none	subhoriz.	mod.	poor	5 mm	Wackestone	

SAMPLE	FOSSILS				TEXTURE				ROCK	
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	NAME	COMMENTS
Brookville Dam 49.64 (s)	Cr, Br, Bz, Ga, Os	Tentaculites Onniella Leptaena Rafinesquina	7	none	inclined (10°)	mod.-high	poor	Bimodal: 10 mm/ 1 mm	Grainstone	encrusting Bz
50.3 (c)	Br, Bz, Cr, Ga, Os	Cyclora Tentaculites unknown Ga genus Onniella	9	none	subhoriz.	mod.	poor	6 mm	Packstone	other genera: Rafinesquina Zygospira
50.5 (s)	Br, Bz, Ga, Os	Tentaculites Onniella Rafinesquina inarticulate Br	6	vertical tubes	subhoriz.	high	well	0.5 mm	Calcisiltite	Graded: 1 mm → 0.2 mm
50.8 (c)	(Br), (Bz), Ga, Tr	Onniella Rafinesquina	5	none	subhoriz.	mod.-high	mod.	5.5 mm	Grainstone	
51.0 (c)	(Bz), Br, Tr, Ga, Sc	Onniella Rafinesquina	6	none	subhoriz.	mod.-high	poor	Bimodal: 12 mm/ 0.5 mm	Packstone	micrite envelopes
51.45 (c)	Br, Bz	Onniella Rafinesquina	3	vertical tubes (indistinct walls)	subhoriz.	very high	very well	0.3 mm	Calcisiltite	sole marks
51.5 (c)	Br, Bz, Cr, Tr, Ga, Sc	Cyclora Tentaculites Onniella	9	none	subhoriz.	mod.-high	mod.	4.5 mm	Grainstone	other genera: Leptaena Rafinesquina
51.6 (c)	Br, Bz, Tr, Ga	Tentaculites unknown Ga genus Onniella	7	none	subhoriz.	mod.-high	mod.	5.5 mm	Grainstone	other genera: Rafinesquina Rhynchotrema
51.85 (s)	(Bz), (Tr), Br, Ga, Sc	Cyclora Tentaculites Onniella	8	none	subhoriz.	mod.	poor	7 mm	Packstone	other genera: Platystrophia Rafinesquina
52.1 (c)	Br, Bz, Ga, Sc	Cyclora Tentaculites	5	none	subhoriz.	very high	very well	0.7 mm	Grainstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 52.9 (s)	Br, Bz, Cr, Tr, Ga, Pe, Os, Sc	Cyclora Tentaculites Caritodens	10	none	subhoriz.	mod.-low	poor	6 mm	Packstone	other genera: Onniella Rafinesquina
53.2 (c)	Br, Bz, Cr, Tr, Ga, Os	Cyclora Tentaculites Onniella Rafinesquina	8	none	subhoriz.	mod.	poor	5 mm	Packstone	
53.3 (c)	Br, Bz, Ga, Os	Tentaculites unknown Ga genus Onniella Rafinesquina	6	none	subhoriz.	low	poor	8 mm	Packstone	
53.8 (s)	Br, Bz, Tr, Ga	Cyclora Platystrophia Rafinesquina	5	none	subhoriz.	mod.	poor	6 mm	P/G	
53.95 (s)	Br, Bz, Cr, Tr, Ga, Sc	Cyclora Cyclonema Tentaculites Onniella	8	none	subhoriz.	mod.-high	mod.	3.5 mm	Packstone	
54.3 (c)	(Br), (Bz), Tr, Ga, Sc	Cyclora Onniella Platystrophia	6	none	subhoriz. (good parall.)	very high	well	1 mm	Grainstone	
54.4 (c)	Br, Bz, Tr, Sc	Onniella	4	none	subhoriz. (good parall.)	very high	very well	0.6 mm	Grainstone	
54.7	Br, Bz, Tr, Ga, Pe	Cyclora unknown Ga genus Onniella	6	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
55.14	Br, Bz, Cr, Tr, Ga, Pe	Cyclora Onniella Rafinesquina	7	none	subhoriz.	mod.-high	mod.-well	4.5 mm	Grainstone	
55.4	Br, Bz, Cr, Tr, Ga	Cyclora Tentaculites Onniella Platystrophia	7	none	subhoriz.	mod.-high	poor	3 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 55.5	Br, Bz, Cr, Tr	Onniella, Leptaena, Strophomena	6	none	subhoriz.	mod.-high	poor	3.5 mm	Packstone	
55.7	Br, Bz, Tr	Leptaena, Platystrophia, Strophomena	5	none	inclined (poor parall.)	mod.	poor	10 mm	Packstone	
56.53	Br, Bz, Cr, Tr, Ga	Cyclonema, Tentaculites, Onniella, Rafinesquina	7	none	subhoriz.	mod.-high	mod.-poor	4 mm	Packstone	
56.65	Br, Bz, Cr, Tr, Ga	Cyclora, Onniella, Rafinesquina	6	none	subhoriz.	mod.-high	mod.	3 mm	Packstone	
56.75 (c)	Br, Bz, Cr, Tr, Ga, Sc	N/A	6	none	subhoriz.	mod.	poor	Bimodal: 20 mm / 2 mm	Grainstone	intraclasts; occasional micrite envelopes.
57.3 (c)	Bz, Tr, Cr, Ga, Pe	N/A	5	none	inclined (10°)	low / mod.-high	mod.-poor / mod.-well	6 mm / 4 mm	Packstone	---abrupt contact
57.45 (c)	Br, Bz, Tr, Ga, Pe	Rafinesquina	5	none	subhoriz.	mod.-high	mod.	3.5 mm	Grainstone	
57.7 (c)	Br, Bz, Tr, Ga, Sc	Cyclora, Onniella, Rafinesquina	6	none	subhoriz.	mod.	very poor	6 mm	Packstone	large, fan-shaped Bz.
57.9 (c)	Br, Bz, Tr, Ga	Tentaculites, unknown Ga genus, Platystrophia, Rafinesquina	6	none	subhoriz.	mod.	poor	5.5 mm	Packstone	
57.99 (c)	Br, Bz, Cr, Tr, Ga	Onniella, Rafinesquina	6	none	subhoriz.	mod.-low	poor	6 mm	Packstone	Some Br are bored.

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 58.2 (c)	Br, Bz, Tr	Onniella Rafinesquina	4	none	subhoriz.	mod.	poor	6 mm	Packstone	
58.6 (c)	Br, Bz, Cr, Tr, Pe	Rafinesquina	5	none	subhoriz.	mod.	poor	6 mm	Packstone	
58.8 (s)	Br, Bz, Cr, Tr	Onniella Rafinesquina	5	none	subhoriz.	mod.	poor	5 mm	Packstone	
59.1 (s)	Br, Bz, Tr, Ga, Sc	Onniella Rafinesquina	6	none	subhoriz.	mod.-high	mod.-well	3 mm	Packstone	
59.4 (s)	Br, Bz, Tr, Cr, Ga, Pe, Os	Cyclora Onniella Rafinesquina	8	none	subhoriz.	mod.	poor	5.5 mm	Packstone	
60.4 (c)	Br, Bz, Tr, Ga, Pe	Rafinesquina	5	none	subhoriz.	mod.-high / high / mod.	mod. / well / mod.-poor	3 mm / 2 mm / 5.5 mm	Packstone / Grainstone / Packstone	1cm / 1cm / 1cm } abrupt contacts
60.6 (c)	Br, Bz, Cr, Ga	Cyclora Rafinesquina	4	none	subhoriz.	mod.	poor	6 mm	Grainstone	occasional micrite envelopes
60.7 (c)	(Bz), Br, Cr, Tr, Sc	Onniella Rafinesquina	6	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
61.3	Br, Bz, Cr, Tr, Ga	Cyclora Onniella Platystrophia Rafinesquina	7	none	random	mod.-high	poor	4 mm	Packstone	
61.64	Br, Bz, Cr, Tr, Ga	Cyclora Platystrophia Rafinesquina	8	none	subhoriz.	mod.	poor	4.5 mm	Packstone	other genera: Strophomena Zygospira

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 62.0	Br, Bz, Cr, Tr, Ga	Cyclora, unknown Ga genus, Onniella, Rafinesquina	7	none	random	mod.-low	poor	7 mm	Packstone	
62.14	(Bz), Br, Cr, Tr, Sc	Rafinesquina, Zygospira, inarticulate Br	7	none	subhoriz.	mod.	poor	7 mm	Packstone	
62.42 (c)	Br, Bz, Cr, Tr, Ga	Cyclora	5	none	inclined (10°)	high	mod.-well	2.5 mm	Grainstone	rare micrite envelopes.
62.66 (s)	Br, Bz, Cr, Tr, Pe, Ga	Cyclora, Onniella, Platystrophia, Zygospira	8	none	subhoriz.	mod.-high	poor	5 mm	Packstone	
62.94 (s)	Br, Bz, Cr	Hebertella, Onniella, Rafinesquina, Zygospira	6	none	subhoriz.	mod.-high	poor	3 mm	P/G	
63.2 (c)	Br, Bz, Cr, Tr, Sc	Rafinesquina	5	none	subhoriz.	high	mod.	3 mm	Grainstone	rare micrite envelopes.
63.44 (s)	(Br), Bz, Cr, Os	Leptaena, Onniella, Rafinesquina, Zygospira	7	none	random	mod.-low	poor	10 mm	Packstone	
63.6 (c)	Br, Bz, Tr, Sc	Hebertella, Leptaena, Rafinesquina, Zygospira	7	none	random	mod.-low	poor	8 mm	P/G	
64.3 (c)	Br, Bz, Cr, Tr, Ga, Pe, Os	Cyclora, Rafinesquina	7	none	subhoriz. (good parall.)	high	well	2 mm	Grainstone	
65.6 (c)	Br, Bz, Cr, Tr, Ga	Cyclora, Onniella, Rhynchotrema, Strophomena	7	none	subhoriz.	mod.	well	5.5 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 66.14 (c)	Br, Bz, Cr, Tr, Os	Onniella Platystrophia Rafinesquina	7	none	subhoriz.	low	poor	8 mm	Packstone	
66.6 (c)	Br, Bz, Cr, Tr, Os	Hebertella Leptaena Platystrophia	7	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
66.9 (c)	(Br), Bz, Cr, Tr, Ga	Cyclora Lepidocyclas Strophomena Zygospira	7	none	subhoriz.	low	poor	8 mm	Packstone	
67.62 (c)	Br, Bz, Cr, Tr, Os, Co	Leptaena Strophomena	7	none	subhoriz.	low	poor	8 mm	Packstone	Liberty Formation (pyrite-rich)
67.82 (c)	Br, Bz, Cr, Tr	Leptaena Onniella Strophomena	6	none	subhoriz.	high	mod.-well	5 mm	P/G	
68.1 (c)	Br, Bz, Cr, Tr, Ga	Cyclora Lepidocyclas Onniella	8	none	subhoriz.	mod.-high	mod.	3 mm	Packstone	other genera: Rafinesquina Strophomena
68.3 (c)	Br, Bz, Cr, Tr, Ga, Co, Cl	Cyclora Grewinkia Lepidocyclas Strophomena	8	none	subhoriz.	mod.	poor	6 mm	Packstone	
69.0 (c)	Br, Bz, Cr, Tr	Rafinesquina	4	none	horizontal (good parall.)	high	well	1.5 mm	Grainstone	
69.3 (c)	(Br), Bz, Cr, Tr, Ga	Lepidocyclas Onniella Strophomena	7	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
69.8 (c)	Br, Bz, Cr, Tr	Glyptorthis Rafinesquina Strophomena	6	none	subhoriz.	mod.-low	poor	7 mm	Packstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 70.0 (c)	Br, Bz, Cr, Tr	Lepidocyclas, Strophomena, Zygospira	6	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
70.3 (c)	Br, Bz, Cr, Tr	Platystrophia, Strophomena, Thaerodonta	6	none	subhoriz.	mod.-high	mod.	5.5 mm	Grainstone	
70.5 (c)	(Cr), (Br), Bz, Tr	Onniella, Strophomena	5	none	inclined (15°)	high	well	1.5 mm	Grainstone	
70.8 (c)	Br, Bz, Cr, Tr	Onniella, Strophomena	5	none	subhoriz.	very high	very well	1 mm	Grainstone	coarse layer in middle of bed.
71.8 (c)	Br, Bz, Cr, Tr, Os, Ga, Pe	Strophomena, Thaerodonta	8	none	subhoriz.	low	poor	8 mm	Packstone	silty matrix
71.9 (s)	(Tr), Br, Bz, Cr, Ga, Pe	N/A	6	none	subhoriz.	mod.-high	mod.	4 mm	Packstone	
72.2 (c)	Br, Bz, Cr, Tr	Lepidocyclas, Onniella, Strophomena, Thaerodonta	7	none	subhoriz.	high	well	3 mm	Grainstone	rare micrite envelopes.
72.5 (c)	Br, Bz, Cr, Tr	Glyptorthis, Lepidocyclas, Strophomena	6	none	subhoriz.	mod.-high	mod.-poor	5 mm	Grainstone	
72.9 (s)	Br, Bz, Cr, Tr	Strophomena, Zygospira	5	none	subhoriz.	high	well	2.5 mm	Grainstone	
73.0 (s)	Br, Bz, Tr	Glyptorthis, Rafinesquina	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	

SAMPLE	FOSSILS				TEXTURE					
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	ROCK NAME	COMMENTS
Brookville Dam 73.2 (c)	(Tr), (Pe), Br, Bz, Ga	N/A	5	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
73.6 (c)	(Tr), (Pe), Br, Bz, Cr, Os	Strophomena Thaerodonta Zygospira	8	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
73.7 (c)	Br, Bz, Cr, Tr	Glyptorthis Lepidocyclas Strophomena	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
74.1 (c)	Br, Bz, Cr, Tr, Pe	N/A	5	none	subhoriz.	high	well	1.5 mm	Grainstone	
74.5 (c)	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	high	poor	3 mm	Grainstone	
74.9 (c)	(Br), Cr, Bz, Tr	Glyptorthis Rafinesquina Strophomena	8	none	subhoriz.	low	poor	10 mm	Packstone	other genera: Thaerodonta Zygospira
75.1 (c)	Br, Bz, Tr	Strophomena Thaerodonta Zygospira	5	none	subhoriz.	mod.-high	mod.	3.5 mm	Packstone	
75.2 (c)	(Br), Bz, Tr	N/A	3	none	subhoriz.	mod.	mod.	5.5 mm	P/G	
75.45 (c)	Br, Bz, Cr, Tr	Rafinesquina	4	none	subhoriz.	mod.-high	poor	5 mm	Grainstone	
75.9 (s)	Br, Bz, Cr, Tr	Strophomena Zygospira	5	none	subhoriz.	high	well	2 mm	Grainstone	Fines upward to 0.5 mm

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 76.4 (c)	Cr, Br, Bz, Tr	N/A	4	none	inclined (40°)	very high	very well	1 mm	Grainstone	
76.85 (c)	Br, Bz, Cr, Tr, Ga, Pe	Lepidocyclas Strophomena Zygospira	8	none	subhoriz.	mod.	mod.-poor	7 mm	Packstone	
76.95 (c)	Br, Cr, Bz, Tr	Glyptorthis Rafinesquina Strophomena	6	none	subhoriz.	mod.	mod.-poor	4 mm	Grainstone	
77.0 (s)	Br, Bz, Cr, Tr	Strophomena Zygospira	5	none	subhoriz.	mod.-low	mod.-poor	6 mm	Packstone	
77.5 (c)	Cr, Br, Bz, Tr	Rhynchotrema Strophomena Zygospira	6	none	subhoriz.	high	well	2 mm	Grainstone	
77.8 (c)	Br, Bz	N/A	2	none	N/A	very high	very well	0.2 mm	Calcisiltite	
78.0 (c)	Br, Cr, Bz	Rafinesquina	3	none	N/A	very high	very well	0.2 mm	Calcisiltite	
78.12 (c)	Br, Bz, Cr, Tr	Lepidocyclas Rafinesquina	5	none	inclined (25°)	high	well	3 mm	Grainstone	
78.3 (c)	Br, Bz, Cr	Lepidocyclas Strophomena Thaerodonta	5	none	subhoriz.	high	mod.-poor	1 mm	Grainstone	
78.38 (c)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Siltstone	laminated

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville Dam 79.1 (c)	Br, Bz, Cr, Tr	Glyptorthis Strophomena	5	none	subhoriz.	high	mod.	5 mm	Packstone	
79.24 (c)	N/A	N/A	N/A	vertical tubes	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
79.4 (c)	Br, Bz, Cr, Ga	Strophomena Zygospira	5	none	imbricated brachiopods	low	poor	8 mm	Packstone	
79.6 (c)	Br, Bz, Cr, Tr, Ga, Pe	Rafinesquina Zygospira	7	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
80.7 (s)	Br, Ga, Pe	N/A	3	Chondrites (top of bed)	subhoriz.	very high	well	2 mm	Grainstone	thin calcisiltite layers on top and bottom of bed
81.2	Br, Bz, Cr, Tr, Os, Ga, Pe	N/A	7	none	horizontal (good parall.)	very high	very well	0.4 mm / 2 mm	Calcisiltite / Grainstone	-- abrupt
81.5	(Bz), (Ga), Br, Tr, Pe	Zygospira	5	none	subhoriz.	low	poor	8 mm	Packstone	
81.7	(Tr), (Ga), Br, Bz, Cr	Cyclora unknown Ga genus	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
81.9	Br, Bz, Tr, Ga, Pe, Cl	Grewingkia Holtedahlina Strophomena Zygospira	8	none	subhoriz.	mod.-low	very poor	7 mm	Packstone	
82.1	Br, Bz	N/A	2	none	subhoriz.	low	poor	9 mm	Wackestone	

SAMPLE	FOSSILS				TEXTURE				ROCK	
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	NAME	COMMENTS
Brookville Dam 82.3	Br, Bz, Tr, Ga, Pe	Strophomena Zygospira	6	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
82.6	Br, Bz, Tr, Os, Ga, Cl	Lepidocyclas Strophomena Zygospira	8	none	subhoriz.	mod.	poor	5 mm	Packstone	
82.8	Br, Bz, Cr, Tr, Ga, Pe	N/A	6	none	inclined (15°)	mod.	poor	6 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 1.06	Br, Bz, Cr, Tr, Ga, Pe	Tentaculites Onniella Rafinesquina	7	none	subhoriz.	mod.	poor	3.5 mm	Packstone	Waynesville Formation
1.5	Br, Bz, Tr, Ga	Cyclora Tentaculites Onniella Rafinesquina	6	none	subhoriz.	mod.	poor	4 mm	Packstone	abraded fragments on top of bed.
1.66	Br, Bz, Cr, Tr	Onniella Rafinesquina	5	none	random	mod.	poor	5 mm	Wackestone	matrix is all shale.
1.9	Br, Bz, Cr, Tr, Ga, Os	Cyclonema Tentaculites Onniella Rafinesquina	8	none	subhoriz.	high	mod.	3.5 mm	P/G	
2.06	Br, Bz	Onniella Rafinesquina	3	none	N/A	N/A	N/A	N/A	Siltstone	Fossils all line the bottom of bed.
2.36	Br, Bz, Tr, Cr, Ga, Pe, Os	Cyclora Rafinesquina	7	none	subhoriz.	mod.-high	mod.-poor	3 mm	Packstone	abraded fragments on top of bed.
2.65	(Bz), Br, Tr, Cr, Ga, Sc	Cyclora Onniella Zygospira	7	none	random	low	poor	10 mm	Wackestone	large Bz fragments
2.95	Br, Bz, Cr, Tr, Ga	Cyclora Tentaculites Onniella	6	none	random	mod.-high	mod.-well	3 mm	Packstone	textural inversion
3.5 (c)	(Br), Bz, Cr, Tr	Leptaena Platystrophia Rafinesquina Rhynchotrema	7	none	subhoriz.	mod.-low	poor	9 mm	Packstone	
3.76 (s)	(Br), Bz, Cr, Tr, Ga	Cyclora Cyclonema Leptaena Onniella	10	none	subhoriz.	mod.	poor	7 mm	Packstone	other genera: Platystrophia Rafinesquina Zygospira

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 4.3 (c)	Br, Bz, Cr, Tr, Ga	Cyclora	5	none	subhoriz. (good parall.)	very high	very well	0.4 mm	Calcisiltite	
4.45 (c)	Br, Bz, Cr, Tr, Ga, Co	Cyclora Onniella Rafinesquina	7	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
4.6 (s)	Br, Bz, Cr, Ga, Sc	Cyclora Onniella Rafinesquina	6	none	subhoriz.	mod.	poor	5 mm	Packstone	
4.9 (s)	Br, Bz, Cr, Tr, Ga	Tentaculites Leptaena Onniella Rafinesquina	7	none	subhoriz.	mod.	poor	3.5 mm	Packstone	
5.1 (s)	(Bz), (Tr), Br, Cr, Ga, Sc	Onniella Platystrophia	7	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
5.2 (c)	Br, Bz, Tr, Ga	Platystrophia Rafinesquina	5	none	subhoriz.	mod.-low	poor	5.5 mm	Packstone	
5.6 (s)	Br, Bz, Tr, Ga	Cyclora Rafinesquina	4	none	subhoriz.	mod.	mod.	4 mm	Packstone	
6.0	(Br), (Tr), Cr, Bz, Ga	Cyclora Platystrophia Rafinesquina	6	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	encrusting Bz
6.4	(Br), Bz, Cr, Tr	Platystrophia Rafinesquina	5	none	horizontal / imbricate Br	mod. / mod.-low	mod.-poor / poor	5 mm / 10 mm	Packstone	2 cm / 2 cm – gradational contact
6.7	(Br), Bz, Cr, Tr	Onniella Platystrophia Rafinesquina	6	none	subhoriz.	mod.	poor	5.5 mm	Packstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville North 7.0	Br, Bz, Cr, Sc	Rafinesquina, Zygospira	5	none	inclined (10°)	mod.-high	mod.-poor	4 mm	Packstone	silty matrix
7.9	Br, Bz, Cr, Tr, Ga, Pe	Cyclora, Onniella, Rafinesquina	7	none	subhoriz.	mod.	poor	5 mm	Packstone	bored, abraded Br on top of bed.
8.3	Br, Bz, Cr, Tr, Ga	Cyclora, Platystrophia, Rafinesquina	6	none	subhoriz.	high	well	2 mm	Grainstone	abraded fragments
8.4	(Tr), (Pe), Br, Bz, Cr, Ga	Cyclora, unknown Ga genus, Onniella	7	none	subhoriz.	mod.	very poor	6 mm	Packstone	
8.7	Br, Bz, Tr, Ga, Sc	Cyclora, unknown Ga genus, Rafinesquina	6	none	subhoriz.	very low	poor	11 mm	Packstone	silty matrix
9.1	Br, Bz, Cr, Tr, Ga, Sc	Cyclora, Leptaena, Onniella, Rafinesquina	8	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
9.5	Br, Bz, Cr, Tr, Ga, Sc	Cyclora, Platystrophia, Rafinesquina, inarticulate Br	8	none	subhoriz.	mod.-high	poor	4 mm	Packstone	
9.99	Br, Bz, Tr, Cr, Ga, Pe, Os, Sc	Cyclora, Leptaena, Rafinesquina, Zygospira	10	none	subhoriz.	mod.-high	mod.-well	3 mm	P/G	abraded fragments on top of bed.
10.2	(Br), Bz, Cr, Tr	Onniella, Rafinesquina, Strophomena	6	none	inclined (10°)	mod.-low	mod.-poor	9 mm	Wackestone	
10.5	Br, Bz, Cr, Tr, Ga	Cyclora	5	none	subhoriz. (good parall.)	high	mod.-well	3 mm	Grainstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Brookville North 10.86	Br, Bz, Cr, Tr, Ga	Cyclora, Tentaculites, Onniella, Strophomena	7	none	subhoriz.	mod.	poor	5.5 mm	Packstone	
11.1	Br, Bz, Cr, Tr	Onniella, Platystrophia, Strophomena	6	none	subhoriz.	mod.	poor	3.5 mm	Packstone	encrusting Bz
11.3 (c)	(Cr), Br, Bz, Tr, Ga	Cyclora	5	none	random	high	well	1.5 mm	Grainstone	
11.5 (c)	Br, Cr, Bz, Ga, Os, Co	Cyclora, Leptaena, Onniella, Strophomena	8	none	subhoriz.	high	well	1.5 mm	Grainstone	Some large Br and Bz "floating" in bed.
11.6 (c)	Br, Bz, Cr, Tr, Ga, Os	Cyclora, Leptaena, Onniella, Strophomena	8	none	random	mod.-high	poor	5 mm	Packstone	
11.8 (s)	Br, Bz, Cr, Os, Sc	Leptaena, Rafinesquina	6	Chondrites (vertical)	N/A	N/A	N/A	N/A	Siltstone	laminated; all fossils line the base of bed.
12.4 (s)	Br, Bz, Cr, Tr, Os	N/A	5	none	subhoriz.	high	well	each sequence grades from 2 mm to 0.2 mm	Grainstone	5 fining-upward sequences from 0.6 cm to 1.5 cm thick.
12.5 (s)	Br, Bz, Cr, Os	Leptaena, Strophomena	5	Chondrites (vertical and inclined)	N/A	N/A	N/A	N/A	Siltstone	cross-laminated; all fossils line the base of bed.
13.1	(Br), Bz, Cr, Tr, Pe	Glyptorthis, Leptaena, Platystrophia, Strophomena	8	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
13.2	Br, Bz, Cr, Tr, Ga, Sc	Cyclora, unknown Ga genus, Glyptorthis, Lepidocyclas	11	none	horizontal	mod.-low	poor	6 mm	Packstone	other genera: Onniella, Rafinesquina, Strophomena

SAMPLE	FOSSILS				TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 13.5	Br, Bz, Cr, Tr	Rafinesquina, Zygospira	5	none	subhoriz.	high	very well	1 mm	Grainstone	Fines upward to 0.5 mm
15.2 (c)	(Cr), Br, Bz, Tr, Cl	Strophomena	5	none	subhoriz.	high	very well	1.5 mm	Grainstone	Liberty Formation
15.4 (c)	(Br), (Bz), Cr, Tr	Strophomena, Thaerodonta	5	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
15.6 (s)	(Bz), (Os), Cr, Tr, Br	N/A	5	Chondrites (vertical) + vertical tubes	good azimuth orientation on base of bed	N/A	N/A	N/A	Siltstone	cross-laminated; rippled; all fossils on base.
16.2 (s)	Br, Bz, Cr, Tr, Os, Sc	N/A	6	inclined tube (8 cm long x 4 mm wide)	horizontal (good parall.)	high	well	1.5 mm / 0.2 mm	Grainstone / Calcisiltite	sharp contact
16.6 (c)	(Tr), (Pe), Br, Bz, Cr, Os	Onniella, Strophomena, Thaerodonta	8	none	inclined (40°)	mod.-low	mod.-poor	5.5 mm	Packstone	some pellets
16.7 (c)	Br, Bz, Cr, Tr, Cl, Os	Lepidocyclus, Rhynchotrema, Strophomena	8	none	subhoriz.	mod.	poor	6 mm	Packstone	
16.8 (c)	Br, Bz, Cr, Tr, Cl	Lepidocyclus, Strophomena	6	none	subhoriz.	high	mod.-well	2 mm	Grainstone	
17.2 (s)	(Cr), Br, Bz, Tr, Ga	N/A	5	none	subhoriz.	high	mod.-well	2 mm	Grainstone	
17.4 (c)	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	very high	very well	0.3 mm	Calcisiltite	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 17.5 (c)	Br, Cr	N/A	2	none	random	very high	very well	0.2 mm	Calcisiltite	cross-laminated
18.2 (s)	Br, Bz, Tr, Ga	Lepidocyclas Strophomena Zygospira	6	none	subhoriz.	mod.-low	very poor	8 mm	Packstone	
18.5 (c)	Br, Bz, Tr	Strophomena	3	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
18.87 (c)	Br, Bz, Cr, Tr	Holtedahlina Lepidocyclas Strophomena	6	none	subhoriz.	mod.	poor	6 mm	Packstone	
19.0 (s)	Br, Bz, Cr, Tr	Strophomena Thaerodonta	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
19.4 (c)	(Cr), Br, Bz, Tr, Ga	Strophomena Zygospira	6	none	inclined (45°)	very high	very well	0.6 mm	Grainstone	Some large fossils "floating" in bed.
19.6 (c)	(Cr), Br, Tr	Strophomena	3	none	random	high	very well	1.5 mm	Grainstone	
20.16 (s)	Br, Bz, Cr, Tr, Pe, Ga, Os	Rafinesquina Strophomena	8	none	subhoriz.	mod.	poor	5 mm	Packstone	Cr base on top of Rafinesquina shell.
20.4 (c)	Br, Bz, Cr, Tr	Lepidocyclas Strophomena Zygospira	6	none	subhoriz.	high	mod.-well	2.5 mm	Grainstone	
21.0 (c)	Br, Bz, Cr, Tr, Ga	N/A	5	Trichophycus (on base of bed)	subhoriz.	mod.	poor	6 mm	Grainstone	siltstone layer on base of bed (0.5 mm thick).

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	NAME	
Brookville North 21.2 (c)	Br, Bz, Cr, Tr	*Zygospira*	4	none	subhoriz.	mod.	mod.-poor	4 mm	Grainstone	
21.52 (s)	Br, Bz, Cr, Tr	*Strophomena*	4	none	subhoriz.	mod.	poor	3.5 mm	Packstone	
21.9 (c)	(Cr), Br, Bz, Ga	*Cyclora*	4	none	subhoriz.	high	well	2.5 mm	Grainstone	
22.1 (c)	Br, Tr, Bz, Pe	N/A	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
22.2 (c)	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	mod.-high	mod.-poor	5 mm	P/G	
22.4 (c)	(Cr), Br, Bz, Tr, Sc	*Strophomena*	5	none	subhoriz.	high	mod.	2.5 mm	Grainstone	
22.7 (s)	(Br), Bz, Cr, Tr, Sc	*Lepidocyclas* / *Rafinesquina*	6	none	random	low	very poor	8 mm	P/G	
22.8 (c)	Br, Bz, Cr, Tr	*Rafinesquina*	4	none	subhoriz.	mod.	poor	5.5 mm	Packstone	silty, laminated matrix
23.2 (c)	Br, Bz, Cr, Tr	*Lepidocyclas* *Rafinesquina*	5	none	subhoriz.	low	mod.-poor	8 mm	Packstone	silty matrix
23.4 (c)	Br, Bz, Cr, Tr	*Rafinesquina*	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 23.56 (s)	Br, Bz, Tr, Ga, Pe	Strophomena	5	none	subhoriz.	mod.	mod.	5 mm	Packstone	
23.9 (s)	Br, Bz, Tr, Ga, Sc	Zygospira	5	none	subhoriz.	mod.	mod.-poor	4 mm	Wackestone	silty matrix
24.1 (c)	Br, Bz, Cr, Tr, Ga, Pe, Cl	Rafinesquina Zygospira	8	none	subhoriz.	mod.	poor	6 mm	Packstone	
24.54 (s)	Br, Bz, Cr, Tr, Ga	Rafinesquina	5	none	subhoriz.	mod.	mod.-poor	5.5 mm	Grainstone	intraclasts; Silica replacement of fossils.
24.9 (c)	Br, Bz, Cr, Tr, Os, Sc	Zygospira	6	none	subhoriz.	mod.-low	poor	5 mm	Packstone	
25.3 (c)	Br, Bz, Cr, Tr, Ga, Pe, Os, Sc	Zygospira	8	none	subhoriz.	mod.	mod.	5 mm	Packstone	
25.34 (s)	Br	Zygospira	1	color mottling + horizontal tubes	N/A	N/A	N/A	N/A	Siltstone	
25.5	Br, Bz, Tr, Ga, Pe	Strophomena Zygospira	6	none	subhoriz.	low	poor	6.5 mm	Packstone	silica replacement of fossils.
25.6	N/A	N/A	N/A	vertical and inclined tubes	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
25.9	Br, Bz, Tr, Sc, Co	N/A	5	none	horizontal	high	well	1 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 26.3	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	high	mod.-well	2 mm	Grainstone	silica replacement of Fossils.
26.6	(Tr), Br, Bz, Cr Ga, Cl	Rafinesquina Zygospira	7	none	random	mod.	poor	6 mm	Packstone	silica replacement of Fossils.
26.7 (c)	Br, Bz, Cr, Tr, Cl, Ga	Cyclora Strophomena Zygospira	7	none	subhoriz.	mod.-high	poor	3 mm	Packstone	silica replacement; Coral is 8.5 cm long, and is bored.
26.9 (c)	Br, Bz, Tr, Cl, Ga, Pe	N/A	6	none	inclined (45°)	mod.-low	poor	7 mm	Packstone	
27.14 (s)	Br, Bz, Cr, Tr, Pe	Strophomena	5	Chondrites (horizontal, top and bottom) Trichophycus (top)	horizontal	high	mod.-well	1.5 mm	Siltstone / Packstone / Siltstone	cross-laminated →Gradational →Abrupt laminated
27.2	Br, Bz, Cr, Tr, Ga, Os	N/A	6	none	subhoriz.	mod.-high	mod.-poor	4 mm	Packstone	
27.3	Br, Bz, Cr, Tr, Ga, Pe	Cyclora Lepidocyclas Strophomena	7	none	subhoriz.	high	mod.	2.5 mm	Packstone	
27.5	Br, Bz, Cr, Tr, Os	Zygospira	5	none	subhoriz.	high	well	1 mm	Packstone	
27.8	Br, Bz, Cr, Tr, Ga	Lophospira Rafinesquina Zygospira	6	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
28.0	Br, Bz, Tr, Ga	Lophospira Lepidocyclas Strophomena	5	none	subhoriz.	mod.	poor	5 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 28.4 (s)	Br, Bz, Cr, Tr, Ga	N/A	5	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
28.8 (c)	Br, Bz, Ga, Os	Lophospira	4	none	subhoriz.	high	poor	Bimodal: 2mm/ 0.3mm	Grainstone	
29.0 (c)	Br, Bz, Tr	Lepidocyclus Strophomena Zygospira	5	none	subhoriz.	mod.	poor	5 mm	Packstone	
29.2 (c)	Br, Bz, Tr, Cr, Ga, Pe, Os	N/A	7	none	subhoriz.	mod.	mod.	4.5 mm	Packstone	
29.5 (s)	Br, Bz, Tr, Ga, Os	N/A	5	none	subhoriz.	mod.-low	mod.	6 mm	Packstone	
29.7 (s)	Br, Bz, Tr, Os	Zygospira	4	Chondrites (top of bed)	horizontal (good parall.)	high	mod.-well	2 mm	Packstone	
29.96 (s)	N/A	N/A	N/A	Chondrites; abundant color mottling.	N/A	N/A	N/A	N/A	Siltstone	
30.2 (c)	Br, Bz, Cr, Tr, Ga, Os	Lophospira Rafinesquina Zygospira	7	none	subhoriz.	mod.	poor	7 mm	Packstone	
30.3 (c)	(Bz), Br, Tr, Ga, Pe	N/A	5	none	subhoriz.	mod.	poor	5 mm	P/G	
30.6 (c)	Br, Bz, Tr, Ga	N/A	4	none	random	mod.	mod.	6 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 31.0 (c)	Br, Bz, Cr, Tr, Ga	Lophospira	5	none	subhoriz.	mod.-high	poor	Bimodal: 10 mm/ 0.5 mm	Grainstone	intraclasts
31.25(s)	Br, Bz, Cr, Tr, Os	Lepidocyclas	5	none	subhoriz.	high	mod.	3 mm	P/G	
31.4 (c)	Br, Bz, Cr, Tr	N/A	4	none	random	high	well	2 mm	Grainstone	
31.9 (c)	(Tr), Br, Bz, Ga	N/A	4	none	subhoriz.	mod.-high	mod.-well	2 mm	Packstone	
32.05(s)	Br, Bz, Tr, Ga	N/A	4	none	subhoriz.	high	very poor	3 mm	Packstone	
32.2	Br, Bz, Tr, Ga	Cyclora Lophospira	5	none	subhoriz.	high	well	1.5 mm	Grainstone	
32.34	Br, Bz, Cr, Tr, Ga, Sc, Os	Zygospira	7	none	subhoriz.	high	poor	Bimodal: 10 mm/ 1 mm	P/G	
32.6	Br, Bz, Cr, Tr, Pe, Ga	Zygospira	6	none	subhoriz.	mod.-high	poor	4 mm	Grainstone	intraclasts
32.8	Br, Bz, Cr, Tr, Ga, Pe, Cl, Sc	Lepidocyclas	8	none	random; mixed lumps of carbonate and silt.	med.	poor	7 mm	Wackestone	very silty matrix; Saluda Fm.
33.2	(Ga), Br, Bz, Pe	N/A	4	none	random	low	poor	8 mm	Wackestone	large intraclast; silty matrix

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 33.3	(Ga), (Pe), Br, Tr, Bz, Os	N/A	6	none	horizontal	mod.	poor	3 mm	Wackestone	
33.6	(Bz), Sc	N/A	2	color mottling	subhoriz.	low	mod.	8 mm	Wackestone	
33.94	(Ga), (Bz), Tr, Pe	N/A	4	color mottling	subhoriz.	low	mod.-poor	9 mm	Packstone	
34.65	(Ga), (Pe), Os, Bz, Cl	N/A	5	color mottling	subhoriz.	mod.	mod.	5.5 mm	Packstone	
34.7	Ga, Os	N/A	2	color mottling	subhoriz.	mod.-high	mod.	2 mm	Micstone	silty matrix
34.8	(Ga), (Os), Bz, Cl	N/A	4	color mottling	subhoriz.	mod.	mod.-poor	1.5 mm	Wackestone	
34.9	Os, Ga, Bz	N/A	3	color mottling	N/A	N/A	N/A	N/A	Micstone	silty matrix
35.04	Os, Ga	N/A	2	none	subhoriz.	high	well	0.8 mm	Grainstone	
35.2	(Ga), Bz	N/A	2	none	subhoriz.	mod.	well	1 mm	Wackestone	
35.3	(Os), Ga	N/A	2	color mottling	subhoriz.	mod.	well	1 mm	Wackestone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 35.4	(Os), Ga, Br, Bz	Zygospira	4	color mottling	subhoriz.	low	mod.	2 mm	Wackestone	
35.5	Os, Bz	N/A	2	none	subhoriz.	mod.	well	2 mm	Wackestone	
35.65	Os, Ga, Pe, On, Bz	N/A	5	none	subhoriz.	mod.-high	mod.-poor	2 mm	Packstone	
35.8	(Os), Br, Bz, Ce	Plaesiomys	4	color mottling	subhoriz.	low	mod.	1 mm	Wackestone	
36.2	(Os), Ga	N/A	2	color mottling	subhoriz.	mod.	mod.	1 mm	Wackestone	
36.5	(Ga), Os	N/A	2	none	subhoriz.	mod.	mod.-poor	2 mm	Wackestone	
36.7	Os, Bz, Cl	N/A	3	none	subhoriz.	mod.	mod.-poor	2 mm	Wackestone	
36.9	Os, Tr, Br, Bz, Ce, Cl	N/A	6	none	subhoriz.	mod.	poor	5 mm	Packstone	
37.2	Os, Br, Bz, Cr	Platystrophia Strophomena	5	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	Whitewater Formation
37.6	Br, Bz, Tr, Pe, Os	Pterinea Platystrophia Strophomena Zygospira	7	none	subhoriz.	mod.	mod.-poor	3 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Brookville North 37.8	Br, Bz, Tr	N/A	3	color mottling	subhoriz.	high	mod.-well	1 mm	Wackestone	
38.0	Os, Ga, Pe	N/A	3	none	subhoriz.	high	mod.-well	1 mm	Wackestone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
KY. 445(I) A.0 (c)	(Cr), Br, Bz, Tr, Ga	*Cyclora*	5	none	random	high	well	2 mm	Grainstone	KY. 445 / I-275 East composite section (Basal Kope Fm.)
A.4 (s)	(Tr), Bz, Br, Cr	*Onniella* *Sowerbyella* *Zygospira*	6	none	subhoriz.	low	poor	5 mm	Packstone	
A.7 (s)	N/A	N/A	N/A	vertical tubes (escape?)	N/A	N/A	N/A	N/A	Siltstone	tool marks on base of bed.
A.94 (s)	Br, Bz, Cr, Tr	*Onniella* *Sowerbyella* *Zygospira*	6	none	subhoriz.	mod.-high	mod.-well	4 mm	Packstone	
B.75 (s)	Br, Bz, Cr, Tr	*Flexicalymene* *Onniella* *Sowerbyella*	5	none	subhoriz.	low	poor	7 mm	Packstone	
B.99 (s)	Br, Bz, Cr, Tr	*Onniella* *Sowerbyella*	5	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
C.2 (s)	Br, Bz, Cr, Tr	*Onniella* *Sowerbyella* *Zygospira*	6	none	subhoriz.	low	poor	7 mm	Packstone	
D.2 (s)	(Bz), Br, Cr, Tr	*Onniella* *Sowerbyella*	5	none	random	low	poor	6 mm	Packstone	silty matrix
D.45 (s)	(Br), (Bz), Cr, Tr	*Onniella* *Sowerbyella*	5	none	subhoriz.	low	poor	5 mm	Packstone	
E.1 (c)	Cr, Br, Bz, Tr	N/A	4	none	inclined (45°); good parall.	high	well	2 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
KY.445(I) E.36 (c)	(Bz), Br, Tr, Cr	Onniella Sowerbyella	5	none	subhoriz.	mod.	poor	Bimodal: 12 mm/ 2 mm	Packstone	
F.3 (s)	Br, Bz, Tr, Cr	Onniella Sowerbyella	5	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
F.9 (s)	N/A	N/A	N/A	color mottling	N/A	N/A	N/A	N/A	Siltstone	
G.1 (c)	(Cr), Br, Bz, Tr	Onniella	4	none	inclined (50°)	high	well	1.5 mm	Grainstone	
G.4 (s)	(Ga), (Pe), Ce, Tr, Br, Bz, Cr	Onniella	7	none	subhoriz.	low	poor	11 mm	Packstone	
G.9 (c)	(Cr), Br, Bz, Tr	Sowerbyella	4	none	random	high	very well	1 mm	Grainstone	
H.1 (c)	(Cr), Br, Bz, Tr	Sowerbyella	4	none	subhoriz.	high	well	3 mm	P/G	
H.7 (s)	(Cr), Br, Bz, Tr, Ga	Cryptolithus Onniella	5	none	subhoriz.	mod.-high	mod.-well	3 mm	Wackestone / Packstone	(cr-poor) / (cr-rich) abrupt contact
I.4 (c)	Cr, Br, Bz, Tr	Onniella Rafinesquina	5	none	subhoriz.	mod.	mod.	3 mm	P/G	
I.7 (c)	(Cr), Br, Bz, Tr	Cryptolithus	4	none	random	high	well	1.5 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
KY. 445 (I) I.9 (c)	Cr, Br, Bz, Tr	*Cryptolithus* *Sowerbyella*	4	none	subhoriz.	high	well	2 mm	P/G	
J.4 (s)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Siltstone	laminated; sole marks on base.
M.8 (c)	(Cr), Br, Bz, Tr	*Cryptolithus*	4	none	random	high	well	1.5 mm	Grainstone	
M.99 (c)	(Cr), Bz, Br, Ga, Tr	*Cyclora*	5	none	random	high	well	2 mm	Grainstone	
O.3 (s)	Bz, Br, Tr, Cr, Ga, Pe	*Zygospira*	6	none	subhoriz.	mod.	poor	6 mm	Packstone	
P.1 (c)	(Cr), Br, Bz, Tr	*Sowerbyella*	4	none	random.	high	well	2 mm	Grainstone	
P.7 (s)	Ga, Bz, Tr, Br, Cr	*Lophospira* *Sowerbyella*	5	none	subhoriz.	mod.-low	poor	5 mm	Packstone	
Q.1 (s)	(Cr), Br, Bz, Tr, Ga	N/A	5	none	subhoriz.	mod.-high	mod.-well	3 mm	Packstone	
R.7 (c)	(Cr), Br, Bz, Tr	N/A	4	none	random	high	well	3 mm	Grainstone	
S.3 (s)	Br, Cr, Tr	*Onniella*	3	none	random	mod.-high	mod.	3 mm	Packstone	textural inversion

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
KY. 445(I) S.95 (c)	(Cr), Br, Bz, Ga, Tr, Pe	Cyclora Onniella Sowerbyella	7	none	subhoriz. (good parall.)	very high	very well	2 mm	Grainstone	
U.6 (c)	(Tr), Br, Cr, Ga, Bz	Onniella Sowerbyella	6	none	subhoriz.	mod.-high	mod.-well	3 mm	Packstone	
V.7 (c)	(Cr), Br, Ga, Tr, Bz	Cyclora Onniella Sowerbyella	6	none	random	mod.-high	mod.-well	3 mm	Grainstone	mud chips
W.2 (s)	(Bz), Br, Tr	N/A	3	none	subhoriz.	low	poor	6 mm	Packstone	possible organic baffle
W.5 (s)	Br, Bz, Tr, Cr, Ga, Pe	N/A	6	none	Subhoriz.	mod.	poor	Bimodal: 8 mm/ 1.5 mm	Packstone	
X.5 (c)	(Cr), Br, Bz, Tr	Onniella Sowerbyella	5	none	random	high	well	2 mm	Grainstone	
X.7 (c)	Cr, Br, Bz, Tr	Cryptolithus	4	none	subhoriz. (good parall.)	very high	very well	1 mm	Grainstone	
X.86 (c)	Br, Bz, Cr, Tr	Onniella Sowerbyella	5	none	Subhoriz.	mod.-low	poor	5 mm	Packstone	
EZ.1 (c)	Cr, Br, Tr	Onniella	3	none	random	mod.-high	mod.-well	4 mm	Grainstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
I-275(I) 1.0 (s)	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	base of I-275 outcrop
1.18 (s)	Br, Cr, Tr	N/A	3	none	horizontal	high	well	1.5 mm	Packstone	
2.2 (s)	N/A	N/A	N/A	vertical tubes	N/A	N/A	N/A	N/A	Siltstone	cross-laminated; rippled.
2.6 (s)	Br, Bz, Cr, Tr	N/A	4	none	subhoriz.	mod.-low	poor	5 mm	Packstone	
3.02 (s)	Br, Bz	Onniella (line base of bed)	2	none	horizontal	N/A	N/A	N/A	Siltstone	cross-laminated
4.0 (c)	Cr, Br, Bz, Ga, Tr	Onniella	5	none	random	mod.-high	mod.-well	2.5 mm	Grainstone	
4.16 (c)	Br, Tr	Onniella	2	none	horizontal	high	mod.-well	3 mm	Packstone	
4.48 (s)	Br, Bz, Tr, Ga	Cyclora Onniella	4	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
4.7 (c)	Br, Bz, Tr, Ga	Cyclora Onniella	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
4.8 (c)	(Tr), Bz, Br, Cr	N/A	4	none	subhoriz.	mod.-high	mod.	2.5 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
I-275 (I) 5.1 (c)	Cr, Br, Bz, Tr	Onniella	4	none	subhoriz.	mod.-high	mod.	3.5 mm	P/G	
5.72 (s)	N/A	N/A	N/A	Diplocraterion	N/A	N/A	N/A	N/A	Siltstone	
6.4 (c)	Cr, Br, Bz, Tr, Ga, Os	Cyclora	6	none	random	high	well	2 mm	Packstone	silty matrix; textural inversion
6.6 (c)	Cr, Br, Bz, Tr	N/A	4	none	horizontal (good parall.)	very high	well	1 mm	Grainstone	
6.8 (s)	Br, Bz, Tr, Cr	Onniella	4	none	subhoriz.	low	poor	6 mm	Packstone	
8.3 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Siltstone	
8.8 (s)	Br, Bz, Tr, Ga, Cr	Onniella	5	none	subhoriz.	low	poor	5 mm	Packstone	
9.2 (s)	Cr, Br, Bz, Tr, Os, Gr	Climacograptus Onniella	6	none	horizontal (good parall.)	very high	well	0.8 mm	Grainstone	
9.6 (s)	Br, Bz, Cr, Tr, Ga	Onniella	5	color mottling	random	mod.	mod.-poor	4.5 mm	Packstone	
10.15 (s)	Bz, Cr	N/A	2	Chondrites (vertical, 10%)	N/A	N/A	N/A	N/A	Siltstone	body fossils on top of bed only.

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
I-275 (I) 10.46 (s)	Br, Bz, Tr, Cr, Ga	N/A	5	none	subhoriz.	mod.	poor	4.5 mm	Packstone	
11.1 (s)	Br, Bz, Cr, Tr, Os	Cryptolithus	5	Chondrites (horizontal and vertical)	N/A	N/A	N/A	N/A	Siltstone	fossils occur only on base of bed.
11.2 (s)	(Cr), Br, Bz, Tr, Ga, Os	Cyclora	6	none	subhoriz.	high	well	1 mm	Grainstone	
11.3 (c)	Cr, Br, Bz, Tr, Os	Onniella	5	none	subhoriz.	high / very high	well / very well	3 mm / 0.5 mm	Grainstone	---abrupt contact
11.5 (c)	Cr, Br, Bz, Tr	Onniella, Rafinesquina	5	none	random	mod.-high	mod.-well	5.5 mm	Grainstone	
12.4 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Micstone	
12.5 (c)	Cr, Br, Bz, Tr	Onniella	4	none	inclined (10°)	high	well	3 mm	Grainstone	
12.75 (c)	Cr, Br, Bz, Tr	Onniella	4	none	subhoriz.	high	well	1.5 mm	P/G	silty matrix
13.82 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Micstone	
13.9 (c)	Br, Bz, Cr, Tr, Ga	Cyclora, Onniella	5	none	subhoriz.	mod.-high	mod.	2 mm	Packstone	silty matrix

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
I-275 (I) 14.75 (c)	Cr, Br, Bz, Tr, Ga	*Cyclora*	5	none	horizontal (good parall.)	very high	very well	1 mm	Grainstone	
15.54 (s)	Br, Bz, Tr, Cr	*Onniella*	4	none	subhoriz.	low	poor	6 mm	Packstone	silty matrix
16.5 (c)	(Cr), (Tr), Ga	*Cyclora*	3	none	subhoriz.	mod.-low	poor	4.5 mm	Packstone	silty matrix
16.6 (c)	Bz, Cr, Tr, Ga	*Cyclora* unknown Ga genus	5	none	subhoriz.	mod.	mod.	3.5 mm	Packstone	silty matrix
16.8 (c)	Br, Bz, Tr, Cr	N/A	4	none	subhoriz.	low	poor	5 mm	Packstone	
16.94 (c)	(Cr), Br, Bz, Tr, Ga	*Cyclora* *Onniella*	5	none	random	mod.-high	mod.-well	2 mm	Grainstone	
17.25 (s)	(Bz), Br, Tr, Cr, Pe, Ga	*Ambonychia* *Lophospira*	6	none	subhoriz.	low	very poor	6 mm	Packstone	encrusting Bz
18.3 (c)	Cr, Br, Bz, Tr, Ga	*Cyclora*	5	none	subhoriz.	high	well	2 mm	Grainstone	
20.14 (c)	Cr, Br, Bz, Tr	*Onniella*	4	none	random	high	well	1 mm	Grainstone	
20.3 (c)	Br, Bz, Tr, Cr	*Onniella*	4	none	subhoriz.	low	poor	7 mm	Packstone	

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
I-275 (I) 20.42 (c)	Br, Bz, Cr, Gr	N/A	4	none	subhoriz.	mod.	mod.	3 mm	Wackestone	
21.0 (s)	(Bz), Br, Tr	Onniella	3	none	random	low	poor	7 mm	Wackestone	
21.24 (s)	Br, Bz, Cr, Tr	Onniella	4	none	subhoriz.	mod.-low	poor	4.5 mm	Packstone	
21.4 (c)	Br, Bz, Cr, Tr	Onniella	4	none	random	mod.	mod.-poor	5 mm	P/G	
22.25 (s)	(Br), (Bz), Tr, Cr	Onniella Rafinesquina Zygospira	6	none	subhoriz.	low	poor	6 mm	Packstone	
22.7 (s)	Br, Bz, Tr	Onniella Rafinesquina	4	none	subhoriz.	low	poor	8 mm	Packstone	
22.9 (c)	(Br), (Bz), Cr	Onniella Rafinesquina	4	none	horizontal	low	very poor	8 mm	Packstone	silty matrix
23.1 (c)	Br, Cr, Bz, Tr	Rafinesquina	4	none	horizontal	very high	very well	0.6 mm	Grainstone	
23.2 (c)	Cr, Br, Bz, Tr, Ga	Cyclora	5	none	subhoriz.	very high	well	0.8 mm	Grainstone	
23.3 (c)	Br, Bz, Cr, Tr Ga	Cyclora	5	Trichophycus (on base of bed)	subhoriz.	very high	well	1 mm	P/G	

SAMPLE	FOSSILS				TEXTURE				ROCK	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	NAME	
I-275 (I) 23.5 (c)	Br, Bz, Cr, Tr, Ga	Cyclora Onniella	5	none	subhoriz.	mod.-low	mod.-poor	8 mm	Packstone	
25.3 (s)	Br, Bz, Cr, Tr	N/A	4	Diplocraterion Trichophycus Chondrites	N/A	N/A	N/A	N/A	Siltstone	cross-laminated; all fossils on base of bed.
25.7 (s)	Br, Bz, Cr, Tr	Onniella	4	none	horizontal	mod.	mod.	4 mm	Packstone	
26.9 (c)	Br, Bz, Cr, Tr	Onniella	4	none	subhoriz.	mod.	mod.	4 mm	Packstone	
27.0 (c)	Br, Bz, Cr, Tr	Onniella	4	none	subhoriz.	mod.	mod.	3.5 mm	Packstone	
28.99 (s)	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Micstone	
29.36 (c)	Cr, Tr, Br	N/A	3	none	random	very high	well	1 mm	Grainstone	
29.6 (c)	Br, Bz, Cr, Tr, Ga	Cyclora Onniella	5	none	subhoriz.	high	well	1.5 mm	Packstone	matrix poor
29.94 (c)	(Bz), Br	Onniella	2	none	random	low	mod.-poor	15 mm	Wackestone	
32.2 (c)	Cr, Br, Bz, Ga, Pe	Cyclora Onniella	5	none	random	high	well	2 mm	Grainstone	mud chips

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Middletown 1.05	Br, Bz, Tr, Ga, Pe	Cyclora Rafinesquina Zygospira	6	none	subhoriz.	mod.-low	mod.-poor	4 mm	Packstone	Corryville Formation
1.4	Br, Bz, Cr, Tr	Flexicalymene Zygospira	4	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
1.75	Bz, Tr	N/A	2	none	N/A	very high	very well	0.4 mm	Calcisiltite	
2.1	Br, Bz, Cr, Tr	Platystrophia Rafinesquina Zygospira	6	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
2.4	Br, Bz, Cr, Tr, Ga	Cyclora Rafinesquina	5	none	subhoriz.	mod.-low	mod.-poor	6 mm	Packstone	
2.76	Br, Bz, Tr, Pe	Rafinesquina	4	none	horizontal	low	mod.-poor	7 mm	Packstone	
2.8	N/A	N/A	N/A	none	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
3.2	Br	Rafinesquina	1	none	N/A	N/A	N/A	N/A	Siltstone	laminated
3.46	Br, Tr, Bz	Rafinesquina	3	none	horizontal	high	mod.-well	2.5 mm	P/G	
3.6	Br, Tr, Bz	Rafinesquina	3	none	horizontal	mod.-high	mod.	3 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Middletown 4.0	Br, Bz, Cr, Tr	Rafinesquina	4	Chondrites (top of bed)	subhoriz.	mod.-high	mod.-poor	4.5 mm	Packstone	1 cm thick siltstone layer on top.
4.15	Br, Pe, Tr	Ambonychia Rafinesquina Zygospira	4	none	horizontal	mod.-low	poor	15 mm	Packstone	articulated brachiopods
4.3	Br, Bz, Tr	Rafinesquina Zygospira	4	none	subhoriz.	mod.-low	poor	7 mm	Packstone	
4.55	Br, Bz, Tr	Rafinesquina Zygospira	4	none	inclined (40°)	mod.	mod.	6.5 mm	Packstone	
4.6	Br	Rafinesquina	1	none	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
5.35 (c)	Br, Bz, Ga	Rafinesquina Zygospira	4	none	inclined (10°)	mod.	mod.	6 mm	Grainstone	
5.6 (s)	Br, Bz, Tr	Rafinesquina	3	none	subhoriz.	mod.-high	mod.	5 mm	Packstone	
5.95	Br, Bz, Tr	Rafinesquina	3	none	subhoriz.	low	poor	8 mm	Packstone	
6.3	Br, Ga	Cyclora Platystrophia Rafinesquina	3	none	random	high	mod.	3 mm	Wackestone	Mt. Auburn Fm. (argillaceous)
6.8	Br, Tr, Ga.	Cyclora Zygospira	3	none	random	high	well	1 mm	Wackestone	argillaceous

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Middletown 7.3	Br, Bz, Tr	Platystrophia Rafinesquina	4	none	subhoriz.	mod.	poor	6 mm	Packstone	
7.6	Br, Bz, Cr, Tr	Rafinesquina	4	none	horizontal	mod.-low	poor	6 mm	Packstone	
7.7	Br, Tr, Ga	Cyclora Zygospira	3	none	random	high	mod.-well	2 mm	Packstone	
7.9	Br, Cr, Ga, Tr	Cyclora Rafinesquina Zygospira	5	none	random	mod.-high	mod.	3 mm	Wackestone	argillaceous
8.35	Br, Bz, Cr, Tr, Ga	Cyclora Zygospira	4	none	random	high	mod.-well	2 mm	Grainstone	
8.5	Br, Bz	Rafinesquina Zygospira	3	none	subhoriz.	mod.	mod.-poor	3 mm	Packstone	
8.65	Br, Bz	Platystrophia Rafinesquina	3	none	random	low	poor	20 mm	Wackestone	
8.9	Br, Bz, Ga	Cyclora Lophospira	4	none	random	high	well	2.5 mm	Grainstone	
9.1	Br, Ga, Tr	Cyclora Platystrophia Zygospira	4	none	subhoriz.	very high	well	1 mm	Packstone	textural inversion
9.15	Br, Bz, Tr, Ga, Pe	Zygospira	5	none	subhoriz.	mod.	poor	5 mm	Packstone	

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Middletown 9A	Br, Bz, Ga	Cyclora Platystrophia Zygospira	4	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	highly abraded and bored Br.
9B	Cr, Br, Bz, Tr	Platystrophia Rafinesquina Zygospira	6	none	subhoriz.	mod.-low	poor	6 mm	Packstone	argillaceous
9C	Br, Bz	Platystrophia Rafinesquina Zygospira	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	argillaceous
10.1	Br, Bz, Tr, Ga	Cyclora Rafinesquina	4	none	random	mod.-low	poor	6 mm	Packstone	
10.5	Br, Bz, Tr	Zygospira	3	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
10.6(c)	Br, Bz, Cr, Tr, Ga	Rafinesquina Zygospira	6	none	subhoriz.	mod.-high	mod.	3.5 mm	P/G	Sunset Fm.
10.99(s)	Br, Bz, Tr, Ga	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
11.25(s)	Br, Bz, Tr, Ga	Cyclora unknown Ga genus Rafinesquina	5	none	subhoriz.	low	mod.-poor	15 mm	Packstone	
11.35(s)	Br, Bz, Tr	Rafinesquina Trematis Zygospira	5	none	horizontal	low	mod.-poor	12 mm	Packstone	
11.5(c)	Br, Bz, Tr, Ga	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	mod.	mod.	3.5 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Middletown 11.6	Br	Rafinesquina Zygospira	2	vertical tubes	horizontal (good parall)	very high	very well	0.3 mm	Calcisiltite	
11.7	N/A	N/A	N/A	vertical tubes	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
11.8	Br, Bz, Cr, Tr, Ga, Pe	Rafinesquina	6	none	horizontal (good parall.)	mod.-high	mod.-well	2 mm	Packstone	
11.9	Br, Bz, Tr	Rafinesquina Zygospira	4	color mottling	subhoriz.	mod.	poor	7 mm	Packstone	
12.0	Br, Bz	Rafinesquina	2	none	imbricated brachiopods	low	poor	15 mm	Grainstone	
12.2	Br, Bz, Tr, Pe	Rafinesquina Zygospira	5	none	subhoriz.	high	mod.	2 mm	Grainstone	
12.3	Br, Cr, Tr	Flexicalymene Rafinesquina Zygospira	4	none	subhoriz.	mod.-high	well	4 mm	Grainstone	
12.6	Cr, Br, Bz, Tr	Rafinesquina Zygospira	5	none	subhoriz.	high	well	2 mm	Grainstone	
12.9	Br, Bz, Cr, Tr	Rafinesquina Zygospira	5	none	subhoriz.	mod.-low	poor	10 mm	Packstone	
13.0	Br, Bz, Cr, Tr, Ga, Pe	Cyclonema Rafinesquina Zygospira	7	none	horizontal	mod.	poor	8 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Richmond 1.4	Cr, Br, Be, Tr, Pe, Ga, Cl, Os, Sc	Platystrophia, Cyclora	9	none	subhoriz.	mod.-high	mod.	5.5 mm	Grainstone	Whitewater Formation
1.5	Cr, Br, Be, Ga, Tr, Sc	Zygospira, Cyclora	6	none	subhoriz.	high	mod.-well	4 mm	P/G	
1.7	Cr, Br, Be, Tr, Ga, Os, Sc	Strophomena, Zygospira, Cyclora	8	none	subhoriz.	high	mod.-well	3 mm	Grainstone	argillaceous
1.8	Cr, Br, Be, Tr, Os, Ga, On	Platystrophia, Strophomena, Zygospira, Cyclora	9	none	random	mod.-high	mod.-poor	5 mm	Grainstone	
2.0	Cr, Br, Be, Ga, Tr, On	Platystrophia, Zygospira, Cyclora	7	none	subhoriz.	high	very well	Bimodal: 1cm / 0.5mm	Grainstone	
2.4	Cr, Br, Be, Tr, Ga, Cl	Strophomena, Zygospira, Grewinkia, Cyclora	7	none	subhoriz.	high	mod.-well	1 mm	Grainstone	encrusting bryozoans
2.6	Br, Be, Cr, Tr, Ga, On	Platystrophia, Cyclora, Ga (unknown genus)	7	none	subhoriz.	high	mod.-poor	3.5 mm	Packstone	encrusting bryozoans
2.9	Cr, Br, Be, Tr, Ga, Sc, Os	Platystrophia, Strophomena, Cyclora	8	none	subhoriz.	mod.-high	poor	3 mm	Grainstone	
3.3	Cr, Br, Be, Ga, Tr, Os	Plaesiomys, Strophomena, Cyclora	7	none	subhoriz.	high	mod.-poor	1.5 mm	Grainstone	encrusting bryozoans
3.7	Br, Be, Ga, Tr, Sc	Zygospira, Cyclora	5	none	subhoriz.	mod.-high	mod.	4 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Richmond 3.8	Cr, Br, Bz, Ga, Tr, Os	Platystrophia, Strophomena, Cyclora	7	none	subhoriz.	high	mod.	2 mm	Grainstone	
4.16	Cr, Br, Bz, Tr, Pe, Ga	Plaesiomys, Rhynchotrema, Strophomena	8	none	subhoriz.	high	poor	2 mm	P/G	
4.3	Cr, Br, Bz, Tr, Ga, Os	Zygospira, Cyclora	6	none	subhoriz.	high	mod.-well	2 mm	P/G	
4.5	(Cr), Br, Bz, Tr, Ga	Rhynchotrema, Cyclora	5	none	subhoriz.	high	well	1 mm	Grainstone	
4.6	Br, Bz, Cr, Tr, Ga	Platystrophia, Rhynchotrema, Cyclora	6	none	subhoriz.	high	mod.-poor	3 mm	Grainstone	
4.9	Cr, Br, Bz, Tr	Holtedahlina, Plaesiomys, Rhynchotrema	6	none	subhoriz.	mod.	poor	4.5 mm	Grainstone	
5.1	Cr, Br, Bz, Tr, Ga, Pe, Sc	Holtedahlina, Platystrophia, Zygospira, Ambonychia	9	none	subhoriz.	mod.-high	poor	5 mm	Grainstone	
5.3	Cr, Br, Bz, Tr, Sc	Platystrophia, Rhynchotrema, Strophomena	7	none	subhoriz.	high	mod.-poor	Bimodal: 10 mm / 0.7 mm	Grainstone	
5.5	Br, Bz, Cr, Tr, Sc	Platystrophia, Zygospira	6	none	subhoriz.	high	mod.-well	2 mm	Packstone	
5.7	Br, Bz, Cr, Tr, Os	Rhynchotrema	5	vertical tube (4mm wide, cuts across bed. Silt-rich)	random	high	well	1 mm	Packstone	argillaceous

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Richmond 6.3	Br, Bz, Tr, Cr, Ga, Os	Strophomena Zygospira	7	none	random	high	well	2 mm	Packstone	encrusting bryozoans
6.5	Br, Bz, Pe, Tr, On	Zygospira	5	none	subhoriz.	mod.-high	mod.	4 mm	Grainstone	
6.64	Cr, Br, Bz, Os, On, Tr, Ga, Sc	Platystrophia Strophomena	9	none	subhoriz.	high	mod.	2 mm	Grainstone	encrusting bryozoans
6.9	Cr, Br, Bz, Tr, On, Os, Sc	Platystrophia Zygospira	8	none	subhoriz.	high	mod.-well	1 mm	Grainstone	
7.2	Cr, Br, Bz, Tr, Os, Sc, Pe, On	Platystrophia Strophomena	9	none	subhoriz.	high	poor	1.5 mm	Grainstone	
7.5	Cr, Br, Bz, Pe, Ga, Sc, On	Platystrophia Rhynchotrema	8	none	subhoriz.	high	mod.-well	Bimodal: 10 mm / 0.5 mm	Grainstone	encrusting bryozoans
7.75	Cr, Br, Bz, Pe, Ga, Tr, On, Os, Cl	Platystrophia Strophomena	10	none	subhoriz.	high	mod.	2 mm	Grainstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke A.1 (c)	Cr, Br, Bz, Tr	N/A	4	color mottling	random	high	mod.-well	2 mm	Grainstone	Corryville Formation
A.2 (c)	(Tr), (Bz), Br, Pe	N/A	4	none	random	low	mod.-poor	4 mm	Packstone	
A.5 (s)	(Pe), Tr, Br, Bz, Cr	N/A	5	none	subhoriz.	very low	poor	8 mm	Packstone	
A.88 (s)	Cr, Br, Bz, Ga	Zygospira	4	none	random	very high	very well	0.7 mm	Grainstone	pellet nests
B.0 (s)	(Pe), Cr, Bz, Ga, Tr	N/A	5	none	subhoriz.	mod.	poor	6 mm	P/G	
B.34 (c)	Br, Bz, Tr, Cr	N/A	4	none	random	high	mod.-high	Bimodal: 15 mm/ 1 mm	Grainstone	
B.45 (c)	Cr, Br, Bz	Zygospira	3	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
B.54 (c)	Bz, Tr, Pe, Br	N/A	4	none	subhoriz	mod.	poor	5 mm	Packstone	pyrite
B.64 (c)	Cr, Br, Bz, Tr, Pe	N/A	5	none	subhoriz.	mod.	mod.-poor	5 mm	P/G	
B.7 (c)	Cr, Bz	Monticulipora	2	none	N/A	very high	very well	0.2 mm	Calcisiltite	Bz mound on top of bed.

SAMPLE NUMBER	FOSSILS: TYPES	FOSSILS: GENERA	FOSSILS: GENERIC DIVERSITY	BIOTURBATION	TEXTURE: ORIENTATION	TEXTURE: DEGREE OF BREAKAGE	TEXTURE: SORTING	TEXTURE: GRAIN SIZE	ROCK NAME	COMMENTS
Rumpke B.8 (c)	Cr, Br, Bz, Tr, Pe	Platystrophia, Rafinesquina, Zygospira	7	none	subhoriz.	low	poor	8 mm	P/G	
B.9 (c)	Cr, Br, Pe, Bz, Tr	Platystrophia, Rafinesquina	6	none	subhoriz.	mod.-high	mod.-well	4 mm	Grainstone	
C.05 (c)	Cr, Br, Bz, Ga, Tr	Platystrophia, Zygospira	6	none	subhoriz.	mod.-high	well	4 mm	Grainstone	
C.25 (c)	Br, Bz, Cr, Tr	Platystrophia, Zygospira	5	none	subhoriz.	mod.	mod.	8 mm	Packstone	
C.34 (s)	Br, Bz, Tr, Ga, Cr	Cyclora, Platystrophia, Rafinesquina	6	none	subhoriz.	mod.	mod.	4 mm	Packstone	
C.5 (s)	Br, Bz, Tr, Ga, Pe, Cr	Cyclora, Platystrophia, Zygospira	7	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	
C.62 (s)	Br, Bz, Tr, Cr	Platystrophia, Rafinesquina	5	none	subhoriz.	mod.	mod.-poor	6 mm	Packstone	
C.9 (c)	(Bz), Tr, Br, Cr	Zygospira	4	none	subhoriz.	low	poor	7 mm	Packstone	
D.1 (c)	Br, Bz, Tr, Cr	N/A	4	none	subhoriz.	mod.-low	poor	4 mm	Packstone	
D.2 (c)	Cr, Br, Tr, Bz	N/A	4	none	random	mod.	mod.	3 mm	P/G	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke D.4 (s)	Cr, Br, Bz, Pe	Platystrophia	4	none	random	mod.-high	mod.-poor	4 mm	Grainstone	
D.68 (s)	Cr, Br, Bz, Tr	Platystrophia Rafinesquina	5	none	subhoriz.	high	mod.-well	2.5 mm	Grainstone	
D.75 (s)	Br, Bz, Tr, Ga	Cyclora Rafinesquina	4	none	subhoriz.	mod.-high	mod.-well	3 mm	Packstone	
E.0 (c)	Br, Bz, Cr, Tr	Rafinesquina	4	none	subhoriz.	mod.-low	poor	10 mm	Packstone	
E.28 (c)	Br, Bz, Tr, Pe	Zygospira	4	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
E.32 (c)	(Bz), Tr, Br, Cr	Flexicalymene	4	none	subhoriz.	mod.-low	poor	4 mm	Packstone	
E.4 (c)	Br, Bz	N/A	2	Chondrites (5%, horizontal)	N/A	N/A	N/A	N/A	Siltstone	
E.5 (c)	Br, Bz, Tr, Cr	Platystrophia	4	none	subhoriz.	mod.	mod.-poor	5 mm	Packstone	
E.75 (s)	Br, Bz, Tr, Pe	Platystrophia	4	none	inclined (10°)	mod.	mod.-poor	5 mm	Packstone	
F.0 (s)	Br, Bz, Tr	N/A	3	none	subhoriz.	low	poor	6 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke F.1 (s)	Bz, Ga, Br, Tr, Cr	Cyclonema	5	none	subhoriz.	mod.	mod.-poor	4 mm	Packstone	
F.5 (s)	Br, Bz, Tr, Cr	Hebertella	4	none	subhoriz.	mod.	poor	5 mm	Packstone	
F.68 (s)	(Tr), Bz, Br, Pe, Ga, Cr	Flexicalymene Platystrophia Zygospira	7	none	subhoriz.	mod.	poor	6 mm	Packstone	
F.8 (s)	Br, Bz, Tr, Cr	Platystrophia Zygospira	5	none	subhoriz.	mod.-low	poor	5 mm	Packstone	
G.1 (s)	Br, Cr, Ga, Bz, Tr	Zygospira	5	none	subhoriz.	mod.-low	mod.-poor	3 mm	P/G	
G.4 (c)	Cr, Br, Bz, Tr	N/A	4	none	subhoriz.	mod.	mod.	4 mm	P/G	
G.6 (c)	(Bz), Br, Tr	N/A	3	none	subhoriz.	mod.	poor	4 mm	Packstone	
G.8 (s)	(Bz), Br, Tr	N/A	3	none	random	mod.	mod.-poor	4 mm	Packstone	
H.0 (s)	(Bz), Br, Tr, Cr	Rafinesquina	4	none	inclined (10°)	mod.-high	mod.	2.5 mm	Packstone	
H.3 (c)	Br, Bz, Tr, Cr	Rafinesquina	4	none	subhoriz.	mod.-low	poor	5 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke 1.15 (c)	Br, Bz, Tr, Os	Rafinesquina	4	none	subhoriz.	mod.-low	poor	4 mm	Packstone	
1.55 (s)	?	N/A	N/A	Chondrites (5%, horizontal)	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
2.62 (s)	Br, Bz, Tr, Cr	N/A	4	none	random	mod.-high	mod.	3 mm	Packstone	
2.7 (s)	(Tr), Br, Bz	N/A	3	none	horizontal (good parall.)	very high	very well	1 mm	Packstone	
3.1	Bz, Br, Cr, Ga	Platystrophia Zygospira	5	none	subhoriz.	mod.-low	poor	5 mm	Wackestone	
4.32	Bz, Br, Tr, Ga	Cyclora Platystrophia Rafinesquina	5	none	subhoriz.	mod.	poor	7 mm	Packstone	
4.8	Bz, Br, Tr, Cr, Ga	Cyclora Platystrophia Rafinesquina Zygospira	7	none	subhoriz.	mod.-high	mod.	6 mm	Packstone	
5.47	Br, Bz, Tr	Rafinesquina Zygospira	4	snail trail (top of bed)	subhoriz.	mod.-high	mod.	3 mm	Grainstone	fines upward to 0.5 mm
5.65	Br, Bz, Tr	Hebertella Rafinesquina Zygospira	5	none	subhoriz.	mod.-low	poor	8 mm	Wackestone	
6.75	Cr, Br, Bz, Ga	Cyclora Rafinesquina	4	none	random	very high	well	2.5 mm	P/G	Mt. Auburn Formation

SAMPLE	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
NUMBER	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke 7.05	Cr, Br, Bz, Tr, Ga	*Cyclora* *Hebertella* *Rafinesquina*	6	none	random	mod.	mod.-poor	4.5 mm	P/G	
7.35	Br, Bz, Tr, Ga, Cr	*Cyclora* *Hebertella* *Rafinesquina*	6	none	subhoriz.	mod.-high	mod.	2.5 mm	Packstone	
7.5	Br, Bz, Ga, Cr	*Cyclora*	4	none	subhoriz.	very high	well	1 mm	Packstone	
7.9	Cr, Br, Ga	*Cyclora* *Rafinesquina* *Zygospira*	4	none	subhoriz.	very high	well	1 mm	Grainstone	
8.17	Br, Cr, Ga, Bz	*Cyclora* *Rafinesquina* *Zygospira*	5	none	subhoriz.	high	mod.-well	2 mm	P/G	
8.5	Br, Bz, Ga	*Cyclora* *Zygospira*	3	none	subhoriz.	very high	well	2 mm	Packstone	
9.25	Br, Bz, Tr	*Platystrophia* *Zygospira*	4	none	subhoriz.	high	mod.	2.5 mm	Packstone	
9.5	Br, Ga	*Cyclora* *Zygospira*	2	none	random	very high	well	1 mm	Grainstone	
9.55	Cr, Br, Ga	*Cyclora* *Zygospira*	3	none	random	very high	very well	1 mm	Grainstone	
9.85	Cr, Br, Bz, Ga	*Cyclora* *Platystrophia* *Zygospira*	5	borings in *Platystrophia*	random	high	mod.	3.5 mm	P/G	high degree of abrasion

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke 9.9	Cr, Br, Bz	N/A	3	Chondrites (horizontal and vertical)	N/A	very high	well	0.4 mm	Calcisiltite	cross-laminated
10.37	Br, Bz, Cr, Pe	Rafinesquina Zygospira	5	Trichophycus (top of bed)	subhoriz.	low	poor	6 mm	Packstone	
10.55	Br, Bz, Ga, Cr	Cyclora Platystrophia Rafinesquina Zygospira	6	none	subhoriz.	mod.-high	mod.	2.5 mm	Packstone	
10.99(c)	(Br), Bz, Ga	Cyclora Rafinesquina	3	none	inclined (45°)	low	poor	20 mm	Packstone	Sunset Formation
11.26(c)	Cr, Br, Bz, Ga	Cyclora Rafinesquina	4	none	subhoriz.	mod.	mod.-poor	5 mm	P/G	
11.84(c)	Cr, Br, Bz	Rafinesquina Zygospira	4	none	subhoriz.	mod.-low	poor	6 mm	Packstone	
12.19(s)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Siltstone	cross-laminated
12.6(s)	(Br), (Bz), Tr	Platystrophia Zygospira	4	none	subhoriz.	mod.-low	mod.-poor	6 mm	Packstone	
12.7(s)	N/A	N/A	N/A	none	N/A	very high	very well	0.4 mm	Calcisiltite	laminated
13.21(c)	Br, Bz, Ga, Cr	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	mod.	mod.-poor	4.5 mm	Packstone	possible hardground on top of bed.

SAMPLE	FOSSILS				TEXTURE				ROCK	
NUMBER	TYPES	GENERA	GENERIC DIVERSITY	BIOTURBATION	ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE	NAME	COMMENTS
Rumpke 13.65 (c)	Br, Bz, Ga, Cr	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	low	poor	6 mm	Packstone	
13.95 (c)	Br, Bz, Ga, Cr	Cyclora Rafinesquina	4	none	inclined (45°)	very low	poor	20 mm	Packstone	
14.78 (c)	Br, Bz, Tr, Cr, Ga	Cyclora Rafinesquina	5	none	inclined (45°)	mod.	mod.-poor	7 mm	Packstone	

SAMPLE NUMBER	FOSSILS			BIOTURBATION	TEXTURE				ROCK NAME	COMMENTS
	TYPES	GENERA	GENERIC DIVERSITY		ORIENTATION	DEGREE OF BREAKAGE	SORTING	GRAIN SIZE		
Rumpke 13.65 (c)	Br, Bz, Ga, Cr	Cyclora Rafinesquina Zygospira	5	none	subhoriz.	low	poor	6 mm	Packstone	
13.95 (c)	Br, Bz, Ga, Cr	Cyclora Rafinesquina	4	none	inclined (45°)	very low	poor	20 mm	Packstone	
14.78 (c)	Br, Bz, Tr, Cr, Ga	Cyclora Rafinesquina	5	none	inclined (45°)	mod.	mod.-poor	7 mm	Packstone	

APPENDIX 5A

CARBONATE PETROGRAPHIC DATA

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
I A.0 (C)*	Kope	63	0	0	0	1	36	0	Tr	Tr	0	Fine Grainstone
I G.1 (C)	Kope	47	0	0	0	6	47	0	Tr	Tr	0	P/G
I G.4 (C)	Kope	62	2	0	0	30	6	0	Tr	Tr	0	Packstone
I 0.3 (S)	Kope	54	0	0	0	34	3	0	1	6	2	Packstone
I P.7 (C)	Kope	63	Tr	0	0	29	8	Tr	Tr	Tr	0	Packstone
I V.7 (C)	Kope	48	0	0	0	Tr	52	Tr	Tr	Tr	0	Fine Grainstone
I X.86 (C)	Kope	59	0	0	0	28	7	5	1	0	0	Packstone
I 2.2 (S)	Kope	2	0	0	0	0	16	14	3	48	17	Dolomitic Siltstone
I 4.7 (C)	Kope	54	0	0	0	21	23	0	1	1	0	Packstone
I 11.5 (C)	Kope	49	0	0	0	0	49	2	Tr	0	0	Coarse Grainstone
I 13.9 (C)	Kope	65	0	0	0	30	3	2	Tr	Tr	0	Packstone

*Sample numbering system can be decoded from this sample: I = outcrop location (I-275/KY 445 composite)--see Appendix 1 for official abbreviations; A.0 = meter *A*, 0.0 m up from its base; (C) = megacycle designation (C = carbonate hemicycle; S = shale hemicycle).

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
I 16.6 (C)	Kope	64	0	0	0	16	19	Tr	1	Tr	0	Packstone
I 22.25 (C)	Kope	54	0	0	0	23	21	1	1	Tr	0	Packstone
I 25.3 (S)	Kope	6	0	0	0	0	28	10	1	46	9	Siltstone
Ru A.1 (C)	Corry-ville	58	0	1	0	0	35	1	Tr	5	0	Fine Grainstone
Ru A.5 (C)	Corry-ville	52	0	0	0	38	6	1	Tr	3	0	Packstone
Ru B.34 (C)	Corry-ville	73	0	0	0	3	18	1	2	3	0	Fine Grainstone
Ru C.5 (S)	Corry-ville	62	0	0	0	24	3	10	1	Tr	0	Packstone
Ru D.68 (S)	Corry-ville	54	0	24	0	0	22	Tr	Tr	Tr	0	Fine Grainstone
Ru F. 68 (S)	Corry-ville	62	0	0	0	30	3	3	2	Tr	0	Packstone
Ru 5.47 (S)	Corry-ville	62	0	0	0	0	16	1	3	18	0	Sandy, Fine Grainstone
M 4.0 (S)	Corry-ville	55	0	0	0	14	20	Tr	1	10	0	Silty Packstone
M 5.35	Corry-ville	47	0	2	0	3	48	Tr	Tr	0	0	Coarse Grainstone

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
B1 S2	Mt. Auburn	58	0	8	0	4	18	2	Tr	9	1	Coarse Grainstone
B1 S9	Mt. Auburn	51	0	0	0	44	3	0	1	1	0	Packstone
M 6.3	Mt. Auburn	36	0	0	0	61	1	1	Tr	1	0	Wackestone
M 7.6	Mt. Auburn	64	0	0	0	16	19	0	Tr	1	0	Packstone
M 9A	Mt. Auburn	65	0	0	0	17	12	5	Tr	1	0	Packstone
Ru 7.9	Mt. Auburn	71	0	0	0	0	28	0	Tr	1	0	Fine Grainstone
Ru 9.25	Mt. Auburn	65	0	7	0	4	21	0	Tr	3	0	Coarse Grainstone
Ru 9.55	Mt. Auburn	63	0	8	0	Tr	29	0	Tr	0	0	Fine Grainstone
Ru 9.9	Mt. Auburn	55	0	0	0	0	33	1	1	10	0	Calci-siltite
Ru 10.37	Mt. Auburn	69	0	1	0	7	14	8	Tr	1	0	P/G
A 2.4 (S)	Sunset	9	0	0	0	0	21	Tr	Tr	20	0	Silty Cal-cisiltite

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
A 2.8 (C)	Sunset	62	0	14	0	1	23	0	Tr	0	0	Fine Grainstone
B1 S15 (C)	Sunset	62	0	4	0	2	31	1	Tr	Tr	0	Coarse Grainstone
B1 S16 (C)	Sunset	63	0	0	0	0	29	Tr	2	6	0	Fine Grainstone
B1 S19 (C)	Sunset	60	0	0	0	0	22	1	Tr	17	0	Silty Cal-cisiltite
B1 S25 (S)	Sunset	55	0	0	0	7	37	1	Tr	0	0	P/G
M 11.9 (C)	Sunset	53	0	0	0	0	25	16	1	5	0	Coarse Grainstone
M 12.6 (C)	Sunset	67	0	0	0	1	31	1	Tr	Tr	0	Fine Grainstone
Ru 12.7 (S)	Sunset	19	0	0	0	0	28	17	1	35	0	Fossilif. Siltstone
A 7.2	Ore-gonia	57	0	0	0	8	34	0	1	Tr	0	P/G
A 7.3 (bot.)	Ore-gonia	71	0	0	0	4	22	0	Tr	3	0	Fine Grainstone
A 7.3 (top)	Ore-gonia	51	0	0	0	39	7	0	1	2	0	Packstone

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
A 7.8	Ore-gonia	54	0	0	0	38	6	0	1	1	0	Packstone
A 8.2	Ore-gonia	56	0	0	0	0	40	Tr	1	3	0	Fine Grainstone
A 8.9 (bot.)	Ore-gonia	55	0	0	0	30	15	0	Tr	Tr	0	Packstone
A 8.9 (top)	Ore-gonia	74	0	0	0	0	24	0	2	Tr	0	Fine Grainstone
BD 38.1 (C)	Waynes-ville	57	0	0	0	23	12	4	4	0	0	Packstone
BD 38.8 (C)	Waynes-ville	50	0	0	0	1	47	1	1	0	0	Coarse Grainstone
BD 40.8 (C)	Waynes-ville	56	0	0	0	5	39	Tr	Tr	0	0	Coarse Grainstone
BD 44.86 (S)	Waynes-ville	66	0	0	0	0	32	Tr	2	0	0	Fine Grainstone
BD 50.5 (S)	Waynes-ville	65	0	0	0	5	20	4	3	3	0	Calci-siltite
BD 51.85 (C)	Waynes-ville	54	0	0	0	37	5	4	Tr	Tr	0	Packstone
BD 59.4 (C)	Waynes-ville	49	0	0	0	35	12	3	1	0	0	Packstone

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
BD 73.6 (C)	Liberty	50	0	0	0	39	10	Tr	1	Tr	0	Packstone
BD 75.9 (S)	Liberty	61	0	12	0	2	22	2	1	Tr	0	Fine Grainstone
BD 76.4 (C)	Liberty	54	0	0	0	0	44	1	1	0	0	Fine Grainstone
BD 76.85 (C)	Liberty	67	0	0	0	25	8	Tr	Tr	0	0	Packstone
BD 77.5 (C)	Liberty	61	0	0	0	1	37	1	Tr	0	0	Coarse Grainstone
BD 77.8 (C)	Liberty	51	0	0	0	0	39	2	1	6	1	Calci-siltite
BD 79.24 (S)	Liberty	38	0	0	0	0	29	4	2	22	3	Silty Cal-cisiltite
BD 81.7 (C)	Liberty	54	0	0	0	39	6	0	1	0	0	Packstone
Ri 1.7	White-water	77	0	0	0	1	18	4	Tr	0	0	Coarse Grainstone
Ri 3.3	White-water	64	1	12	4	1	15	3	Tr	0	0	Coarse Grainstone
Ri 4.5	White-water	64	0	Tr	4	0	32	Tr	Tr	0	0	Fine Grainstone
Ri 5.5	White-water	52	0	0	13	33	2	Tr	Tr	0	0	Packstone

APPENDIX 5A (continued)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
Ri 6.3	White-water	48	0	0	8	38	1	5	Tr	0	0	Packstone
Ri 6.64	White water	51	0	2	24	6	11	6	Tr	0	0	P/G
BN 33.3	Saluda	58	0	0	0	34	0	5	3	Tr	0	Packstone
BN 34.8	Saluda	45	0	0	0	48	1	5	Tr	1	0	Wackestone
BN 35.2	Saluda	56	29	0	0	4	10	Tr	Tr	1	0	Coarse Grainstone
BN 35.3	Saluda	11	0	0	0	84	0	0	Tr	5	0	Wackestone
BN 35.65	Saluda	48	0	1	4	35	11	Tr	1	0	0	Packstone
BN 36.2	Saluda	12	0	0	0	85	2	Tr	1	0	0	Wackestone
GA 0.51 (C)**	Kope	65	0	0	0	Tr	35	Tr	Tr	0	0	Fine Grainstone
GA 0.58 (C)	Kope	65	0	0	0	Tr	28	7	Tr	Tr	0	Fine Grainstone
GA 0.65 (C)	Kope	68	0	0	0	1	6	22	3	0	0	Packstone
GA 0.70 (C)	Kope	60	0	0	0	2	32	6	Tr	Tr	0	P/G

**GA* samples were taken from the upper Kope Formation at Reidlin Road, megacycle #3 (8.3 - 9.5). The numbers 0.51, 0.58, etc., refer to the vertical distance in meters from the base of megacycle #3.

APPENDIX 5A (concluded)

Sample No.	Formation	Bioclasts	Pellets	Intraclasts	Onkoids	Matrix	Spar	Dolomite	Pyrite	Quartz	Other	Rock Name
GA 0.75 (C)	Kope	75	0	0	0	4	10	10	1	Tr	0	P/G
BR-1***	Corry-ville	71	0	0	0	24	4	1	Tr	Tr	0	Packstone
BR-2	Corry-ville	57	0	0	0	29	9	1	4	Tr	0	Packstone
SL-1	Corry-ville	54	0	4	0	0	31	0	1	10	0	Silty Cal-cisiltite
44341	Corry-ville	57	0	0	0	0	30	2	Tr	9	2	Calci-siltite
44398	Corry-ville	59	0	0	0	0	24	1	2	12	2	Silty Cal-cisiltite

***The next five samples were taken from a crinoid-rich (*Iocrinus*) horizon in the upper Corryville Formation from two localities: Blue Rock Road (BR-1, BR-2), and Stonelick Creek (SL-1, 44341, 44398). This echinoderm "Lagerstatten" is described in detail in Meyer et al. (1981, Table 10).

APPENDIX 5B
CARBONATE BIOCLAST DATA

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
I A.0 (C)	19	21	30	0	6	0	19	0	Tr	Tr	0	0	5	7	Fine Grainstone
I G.1 (C)	49	8	33	0	2	2	4	0	0	Tr	0	0	2	7	P/G
I G.4 (C)	5	23	14	3	24	13	5	0	2	0	0	0	11	8	Packstone
I O.3 (S)	6	52	13	0	7	11	11	0	Tr	0	0	0	0	7	Packstone
I P.7 (C)	Tr	19	18	0	44	5	14	0	0	Tr	0	0	0	7	Packstone
I V.7 (C)	29	19	38	0	Tr	0	10	0	0	Tr	0	0	4	6	Fine Grainstone
I X.86 (C)	48	11	27	0	Tr	0	14	0	Tr	Tr	0	0	0	7	Packstone
I 2.2 (S)	20	0	0	0	0	0	0	0	0	0	0	0	80	1	Dolomitic Siltstone
I 4.7 (C)	15	57	7	0	2	0	17	0	2	0	0	0	0	6	Packstone
I 11.5 (C)	14	19	35	0	4	0	28	0	Tr	Tr	0	0	0	7	Coarse Grainstone
I 13.9 (C)	12	26	39	0	2	0	20	0	1	0	0	0	0	6	Packstone
I 16.6 (C)	3	33	30	0	11	13	9	0	1	Tr	0	0	0	8	Packstone
I 22.25 (C)	33	26	9	0	0	0	13	0	2	Tr	0	0	17	7	Packstone
I 25.3 (S)	0	10	0	0	0	0	0	0	0	0	0	0	90	1	Siltstone

APPENDIX 5B (continued)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
Ru A.1 (C)	29	28	22	0	0	0	16	0	3	2	0	0	0	6	Fine Grainstone
Ru A.5 (C)	8	40	2	0	0	40	10	0	0	0	0	0	0	5	Packstone
Ru B.34 (C)	21	27	41	0	0	0	11	0	Tr	Tr	0	0	0	6	Fine Grainstone
Ru C.5 (S)	19	27	13	0	5	34	2	0	Tr	Tr	0	0	0	8	Packstone
Ru D.68 (S)	20	35	30	0	Tr	0	7	0	5	3	0	0	0	7	Fine Grainstone
Ru F.68 (S)	2	44	11	0	0	32	11	0	0	Tr	0	0	0	6	Packstone
Ru 5.47 (S)	47	19	10	0	0	2	2	0	0	5	0	0	15	6	Sandy, Fine Grainstone
M 4.0 (S)	47	13	15	0	Tr	11	4	0	0	10	0	0	0	7	Silty Packstone
M 5.35	58	19	6	0	13	0	2	0	0	2	0	0	0	6	Coarse Grainstone
Bl S2	48	10	10	0	2	0	7	0	Tr	4	0	0	19	7	Coarse Grainstone
Bl S9	38	28	20	0	2	Tr	8	0	2	2	0	0	0	8	Packstone
M 6.3	28	17	14	0	6	0	6	0	1	6	0	0	22	7	Wackestone
M 7.6	11	23	31	0	9	16	8	0	2	Tr	0	0	0	8	Packstone

APPENDIX 5B (continued)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
M 9A	25	48	3	0	0	0	6	0	2	1	0	0	15	6	Packstone
Ru 7.9	37	11	7	0	0	14	9	0	4	4	0	0	14	7	Fine Grainstone
Ru 9.25	57	17	17	0	0	0	3	0	3	Tr	0	0	3	6	Coarse Grainstone
Ru 9.55	10	27	49	0	5	1	2	0	0	6	0	0	0	7	Fine Grainstone
Ru 9.9	31	6	9	0	0	0	7	0	7	2	0	0	38	6	Calci- siltite
Ru 10.37	17	22	16	0	0	23	4	0	0	3	0	0	15	6	P/G
A 2.4 (S)	7	17	20	0	0	0	3	0	5	2	0	0	46	6	Silty Cal- cisiltite
A 2.8 (C)	3	34	24	0	11	21	7	0	0	0	0	0	0	6	Fine Grainstone
B1 S15 (C)	18	34	23	0	13	10	2	0	0	Tr	0	0	0	7	Coarse Grainstone
B1 S16 (C)	27	30	22	0	3	0	3	0	Tr	Tr	0	0	15	7	Fine Grainstone
B1 S19 (C)	42	20	7	0	0	0	3	0	2	2	0	0	24	6	Silty Cal- cisiltite
B1 S25 (S)	38	29	18	0	Tr	6	9	0	0	Tr	0	0	0	6	P/G

APPENDIX 5B (continued)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
M 11.9 (C)	51	15	9	0	0	0	2	0	0	2	0	0	21	5	Coarse Grainstone
M 12.6 (C)	37	12	36	0	0	0	3	0	2	Tr	0	0	10	6	Fine Grainstone
Ru 12.7 (S)	21	11	5	0	0	0	Tr	0	5	5	0	0	53	6	Fossilif. Siltstone
A 7.2	37	9	32	0	4	5	5	0	Tr	4	0	0	4	8	P/G
A 7.3 (bot.)	34	14	32	0	1	0	1	0	1	1	0	0	16	7	Fine Grainstone
A 7.3 (top)	30	15	24	0	3	15	1	0	2	Tr	0	0	10	8	Packstone
A 7.8	41	26	11	0	1	Tr	6	0	4	0	0	0	11	7	Packstone
A 8.2	45	16	12	0	2	0	14	0	2	Tr	0	0	9	7	Fine Grainstone
A 8.9 (bot.)	33	7	18	0	0	0	9	0	11	2	0	0	20	6	Packstone
A 8.9 (top)	30	27	16	0	3	0	8	0	5	3	0	0	8	7	Fine Grainstone
BD 38.1 (C)	37	39	7	0	7	2	5	0	Tr	Tr	0	0	3	8	Packstone
BD 38.8 (C)	16	30	38	0	4	0	8	0	2	Tr	0	0	2	7	Coarse Grainstone
BD 40.8 (C)	34	32	23	0	2	0	7	0	Tr	2	0	0	0	7	Coarse Grainstone

APPENDIX 5B (continued)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
BD 44.86 (S)	32	11	30	0	0	6	1	0	3	3	0	0	14	7	Fine Grainstone
BD 50.5 (S)	20	18	13	0	9	2	1	0	5	1	0	0	31	8	Calci-siltite
BD 51.85 (C)	41	35	6	0	4	7	7	0	0	Tr	0	0	0	7	Packstone
BD 59.4 (C)	39	14	6	0	4	33	4	0	Tr	Tr	0	0	0	8	Packstone
BD 73.6 (C)	14	22	10	0	2	50	2	0	Tr	Tr	0	0	0	8	Packstone
BD 75.9 (S)	20	18	26	0	5	8	10	0	3	Tr	0	0	10	8	Fine Grainstone
BD 76.4 (C)	35	26	17	0	2	0	2	0	6	Tr	0	0	12	7	Fine Grainstone
BD 76.85 (C)	18	52	15	0	7	5	3	0	0	Tr	0	0	0	7	Packstone
BD 77.5 (C)	38	26	15	0	3	3	6	0	0	0	0	0	9	6	Coarse Grainstone
BD 77.8 (C)	4	4	10	0	0	0	0	0	8	0	0	0	70	5	Calci-siltite
BD 79.24 (S)	8	3	3	0	0	0	3	0	0	8	0	0	75	5	Silty Cal-cisiltite
BD 81.7 (C)	11	11	7	0	4	50	17	0	Tr	Tr	0	0	0	8	Packstone
Ri 1.7	10	74	7	0	Tr	0	3	0	3	0	0	3	0	7	Coarse Grainstone

APPENDIX 5B (continued)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
Ri 3.3	6	56	6	0	Tr	21	3	0	Tr	0	0	5	3	8	Coarse Grainstone
Ri 4.5	16	34	14	0	Tr	2	16	0	1	0	0	8	9	8	Fine Grainstone
Ri 5.5	19	38	10	0	6	6	2	0	2	0	0	6	11	8	Packstone
Ri 6.3	19	23	19	0	1	2	2	0	1	0	8	9	16	9	Packstone
Ri 6.64	12	31	18	0	2	2	Tr	0	Tr	Tr	0	26	9	9	P/G
BN 33.3	5	19	9	0	17	24	5	0	7	0	0	7	7*	9	Packstone
BN 34.8	4	22	Tr	0	49	4	Tr	4	7	0	0	Tr	10	9	Wackestone
BN 35.2	Tr	7	5	0	54	13	3	0	13	0	0	Tr	5	8	Coarse Grainstone
BN 35.3	0	10	10	0	18	0	Tr	0	18	Tr	0	0	44	6	Wackestone
BN 35.65	0	29	4	0	10	8	2	0	2	0	19	13	13	8	Packstone
BN 36.2	0	Tr	8	0	8	0	25	0	8	Tr	0	0	51	6	Wackestone
GA 0.51 (C)	42	35	11	0	3	0	9	0	0	Tr	0	0	0	6	Fine Grainstone
GA 0.58 (C)	52	25	14	0	1	0	8	0	0	Tr	0	0	0	6	Fine Grainstone

*5% unknown, plus 2% sponge spicules.

APPENDIX 5B (concluded)

Sample No.	Brachiopods	Bryozoans	Crinoids	Cephalopods	Gastropods	Pelecypods	Trilobites	Corals	Ostracods	Conodonts	Algae: Red	Algae: Blue-Green	Unknown	Diversity	Rock Name
GA 0.65 (C)	54	41	Tr	0	2	0	3	0	0	Tr	0	0	0	6	Packstone
GA 0.70 (C)	32	40	11	0	Tr	0	17	0	0	Tr	0	0	0	6	P/G
GA 0.75 (C)	24	63	3	0	1	0	9	0	0	Tr	0	0	0	6	P/G
BR-1	27	0	73	0	0	0	0	0	0	Tr	0	0	0	3	Packstone
BR-2	9	2	89	0	0	0	0	0	0	Tr	0	0	0	4	Packstone
SL-1	24	13	24	0	0	0	11	0	4	2	0	0	22	6	Silty Cal-siciltite
44341	30	21	14	0	0	0	5	0	9	3	0	0	18	6	Calci-siltite
44398	36	10	25	0	0	0	5	0	3	2	0	0	19	6	Silty Cal-cisiltite

APPENDIX 5C

CARBONATE TEXTURAL DATA

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
I A.0 (C)	1.23	mod.-well	mod.-high	subhoriz.	none	none	Fine Grainstone
I G.1 (C)	1.28	well	high	incl. (40°)	none	none	P/G
I G.4 (C)	4.92	poor	mod.-low	subhoriz.	none	none	Packstone
I 0.3 (S)	3.97	very poor	mod.-low	subhoriz.	none	none	Packstone
I P.7 (C)	3.81	poor	mod.-low	subhoriz.	none	none	Packstone
I V.7 (C)	1.31	well	high	random	none	none	Fine Grainstone
I X.86 (C)	2.32	mod.-poor	mod.	subhoriz.	none	none	Packstone
I 2.2 (S)	N/A	N/A	very high	N/A	none	none	Dolomitic Siltstone
I 4.7 (C)	1.92	poor	mod.	subhoriz.	none	none	Packstone
I 11.5 (C)	1.93	mod.	mod.-high	random	none	none	Coarse Grainstone
I 13.9 (C)	1.32	mod.-well	mod.-high	subhoriz.	none	none	Packstone
I 16.6 (C)	2.52	poor	mod.	subhoriz.	none	none	Packstone
I 22.25 (C)	1.99	poor	mod.	subhoriz.	none	none	Packstone
I 25.3 (S)	N/A	N/A	high	N/A	none	none	Siltstone
Ru A.1 (C)	0.71	well	high	subhoriz.	none	1.5-0.3 mm	Fine Grainstone

APPENDIX 5C (continued)

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
Ru A.5 (C)	4.26	poor	low	subhoriz.	none	5-1 mm	Packstone
Ru B.34 (C)	1.21	well	high	subhoriz.	yes	none	Fine Grainstone
Ru C.5 (S)	1.99	mod.-poor	mod.-low	subhoriz.	none	none	Packstone
Ru D.68 (S)	0.98	very well	very high	subhoriz.	none	none	Fine Grainstone
Ru F.68 (S)	2.49	mod.-poor	low	subhoriz.	none	none	Packstone
Ru 5.47 (S)	0.56	well	high	horizontal	none	1-0.2 mm	Sandy, Fine Grainstone
M 4.0 (S)	0.92	mod.-well	high	horizontal	none	1-0.4 mm	Silty Packstone
M 5.35	2.39	mod.-poor	mod.-low	incl. (10°)	yes	none	Coarse Grainstone
B1 S2	2.80	mod.-poor	high	incl. (15°)	none	none	Coarse Grainstone
B1 S9	0.74	mod.-well	high	random	none	none	Packstone
M 6.3	0.35	very well	very high	incl. (30°)	none	none	Wackestone
M 7.6	1.76	mod.-poor	high	incl. (45°)	none	none	Packstone
M 9A	4.42	mod.-poor	high	random	none	none	Packstone
Ru 7.9	0.92	mod.-poor	high	random	none	none	Fine Grainstone
Ru 9.25	2.16	poor	mod.-low	subhoriz.	yes	none	Coarse Grainstone

APPENDIX 5C (continued)

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
Ru 9.55	0.81	well	high	subhoriz.	yes	none	Fine Grainstone
Ru 9.9	0.17	very well	very high	subhoriz.	none	none	Calci-siltite
Ru 10.37	6.32	very poor	mod.	subhoriz.	none	none	P/G
A 2.4 (S)	0.27	very well	very high	subhoriz.	none	none	Silty Cal-cisiltite
A 2.8 (C)	1.46	well	high	random	yes	none	Fine Grainstone
B1 S15 (C)	1.96	poor	mod.-low	vertical	yes	none	Coarse Grainstone
B1 S16 (C)	0.61	very well	very high	subhoriz.	none	2-0.5 mm	Fine Grainstone
B1 S19 (C)	0.24	very well	very high	horizontal	none	none	Silty Cal-cisiltite
B1 S25 (S)	2.66	poor	low	incl. (10°)	yes	none	P/G
M 11.9 (C)	6.87	poor	moderate	subhoriz.	none	none	Coarse Grainstone
M 12.6 (C)	0.70	mod.-well	high	subhoriz.	none	none	Fine Grainstone
Ru 12.7 (S)	0.24	very well	very high	subhoriz.	none	none	Fossilif. Siltstone
A 7.2	0.89	mod.-well	high	subhoriz.	none	none	P/G

APPENDIX 5C (continued)

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
A 7.3 (bot.)	0.71	very well	high	subhoriz.	none	none	Fine Grainstone
A 7.3 (top)	0.94	mod.	mod.-high	random	none	none	Packstone
A 7.8	2.55	mod.-poor	mod.	subhoriz.	none	none	Packstone
A 8.2	0.56	very well	very high	subhoriz.	none	none	Fine Grainstone
A 8.9 (bot.)	0.40	mod.-well	high	random	none	none	Packstone
A 8.9 (top)	0.61	very well	very high	subhoriz.	none	none	Fine Grainstone
BD 33.1 (C)	2.72	poor	low	subhoriz.	none	none	Packstone
BD 38.8 (C)	1.95	mod.-well	mod.-high	subhoriz.	none	none	Coarse Grainstone
BD 40.8 (C)	2.02	mod.	mod.-high	subhoriz	none	none	Coarse Grainstone
BD 44.86 (S)	0.58	well	high	random	none	0.9-0.3 mm	Fine Grainstone
BD 50.5 (S)	0.49	very well	very high	subhoriz.	yes	0.9-0.1 mm	Calci-siltite
BD 51.85 (C)	2.44	mod.-poor	low	subhoriz.	none	none	Packstone
BD 59.4 (C)	3.08	poor	low	subhoriz.	none	none	Packstone
BD 73.6 (C)	5.09	mod.-poor	very low	subhoriz.	none	none	Packstone
BD 75.9 (S)	1.27	mod.	high	subhoriz.	yes	1.8-0.4 mm	Fine Grainstone

APPENDIX 5C (continued)

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
BD 76.4 (C)	0.77	well	high	incl. (10°)	none	none	Fine Grainstone
BD 76.85 (C)	2.36	poor	low	subhoriz.	none	none	Packstone
BD 77.5 (C)	1.84	poor	mod.-high	subhoriz.	none	none	Coarse Grainstone
BD 77.8 (C)	0.14	very well	very high	random	none	mone	Calci-siltite
BD 79.24 (S)	0.10	very well	very high	subhoriz.	none	none	Silty Cal-cisiltite
BD 81.7 (C)	3.02	very poor	low	subhoriz.	none	none	Packstone
Ri 1.7	3.34	very poor	mod.-low	random	none	none	Coarse Grainstone
Ri 3.3	3.80	mod.-poor	mod.-low	subhoriz.	none	none	Coarse Grainstone
Ri 4.5	0.74	well	high	subhoriz.	none	none	Fine Grainstone
Ri 5.5	3.19	poor	mod.-low	random	none	none	Packstone
Ri 6.3	0.73	mod.-well	high	random	none	none	Packstone
Ri 6.64	1.61	mod.-poor	mod.-high	subhoriz.	none	none	P/G
BN 33.3	2.44	poor	mod.	subhoriz.	none	none	Packstone
BN 34.8	2.32	very poor	mod.-low	random	none	none	Wackestone
BN 35.2	1.71	mod.	mod.-high	subhoriz.	yes	none	Coarse Grainstone

APPENDIX 5C (concluded)

Sample No.	Grain Size (mm)	Sorting	Breakage	Fossil Orientation	Micrite Envelopes	Grading	Rock Name
BN 35.3	0.17	well	very high	random	none	none	Wackestone
BN 35.65	2.59	mod.-well	mod.-low	subhoriz.	yes	3-0.8 mm	Packstone
BN 36.2	0.40	well	high	random	none	none	Wackestone
GA 0.51 (C)	1.06	well	high	random	none	none	Fine Grainstone
GA 0.58 (C)	1.61	mod.-well	high	random	none	none	Fine Grainstone
GA 0.65 (C)	1.60	poor	mod.-high	subhoriz.	none	none	Packstone
GA 0.70 (C)	2.20	mod.-poor	mod.-high	subhoriz.	none	none	P/G
GA 0.75 (C)	2.60	poor	mod.	subhoriz.	none	none	P/G
BR-1	2.00	mod.-well	mod.-low	subhoriz.	none	none	Packstone
BR-2	1.90	mod.-well	low	subhoriz.	none	none	Packstone
SL-1	0.30	very well	very high	horizontal	none	none	Silty Cal-cisiltite
44341	0.16	very well	very high	incl. (50°)	none	0.2-0.1 mm	Calci-siltite
44398	0.15	very well	very high	incl. (45°)	none	yes	Silty Cal-cisiltite

APPENDIX 6A
SHALE COMPOSITIONS

Sample No.	Formation	Quartz	Feldspar	Heavies	Clays + Micas	Fossils	Dolomite	Pyrite	Other	Q + F/ C + M/ Ca + Do	Silt/ Clay Ratio	Rock Name
I A.2 (S)*	Kope	41	Tr	1	37	0	17	4	0	43/39/18	1.11	Dolomitic Mudstone
I F.8 (S)	Kope	42	Tr	2	39	Tr	11	6	Tr	46/42/12	1.08	Dolomitic Mudstone
I N.1 (S)	Kope	36	0	4	49	Tr	7	4	0	39/53/8	0.74	Mudstone
I 0.8 (S)	Kope	40	Tr	1	41	1	14	3	0	42/43/15	0.98	Dolomitic Mudstone
I 4.2 (C)	Kope	26	0	2	68	1	Tr	3	Tr	28/71/1	0.38	Claystone
I 5.2 (S)	Kope	42	0	1	53	Tr	Tr	4	Tr	44/55/1	0.79	Mudstone
I 6.0 (S)	Kope	42	0	3	46	1	2	6	0	47/51/2	0.91	Mudstone
I 11.6 (S)	Kope	41	Tr	3	46	0	5	4	1	44/49/7	0.89	Mudstone
I 12.3 (S)	Kope	41	Tr	1	48	Tr	1	8	1	45/53/2	0.85	Mudstone
I 23.4 (C)	Kope	29	0	4	61	0	1	5	0	32/67/1	0.48	Claystone
Ba 4.0 (S)	Kope	57	2	2	25	Tr	12	2	Tr	62/25/13	2.36	Dolomitic Mudstone

*Sample numbering system can be decoded from this example: I = outcrop location (I-275/KY 445 composite)--see Appendix 1 for official abbreviations; A.2 = meter *A*, 0.2 m up from its base; (S) = megacycle designation (C = carbonate hemicycle; S = shale hemicycle).

APPENDIX 6A (continued)

Sample No.	Formation	Quartz	Feldspar	Heavies	Clays + Micas	Fossils	Dolomite	Pyrite	Other	Q + F/ C + M/ Ca + Do	Silt/ Clay Ratio	Rock Name
Re S1 (C)	Fairview	6	0	2	86	0	3	3	0	6/91/3	0.07	Claystone
Re S2 (C)	Fairview	25	Tr	2	63	Tr	3	7	0	28/69/3	0.41	Claystone
Re S3 (S)	Fairview	23	Tr	2	57	0	13	5	0	25/61/14	0.41	Dolomitic Claystone
Re S4 (S)	Fairview	30	0	2	58	0	8	2	0	31/61/8	0.52	Claystone
Re S5 (C)	Fairview	39	Tr	1	45	0	10	5	0	41/48/11	0.88	Dolomitic Mudstone
Re S6 (S)	Fairview	19	0	3	67	1	7	3	0	20/72/8	0.28	Claystone
Re S7 (S)	Fairview	40	Tr	1	39	0	17	3	0	42/40/18	1.04	Dolomitic Mudstone
Re S8 (S)	Fairview	62	Tr	1	31	1	3	2	0	65/32/3	2.02	Mudstone
Re S9 (S)	Fairview	31	0	3	48	0	17	1	0	32/50/18	0.65	Dolomitic Claystone
Re S10 (C)	Fairview	39	Tr	1	49	0	7	4	0	41/52/7	0.81	Mudstone
Ru A.35 (C)	Corryville	32	1	2	55	Tr	6	4	0	35/59/6	0.60	Mudstone
Ru D.6 (S)	Corryville	38	Tr	1	32	1	24	4	0	41/34/25	1.19	Dolomitic Mudstone
Ru F.3 (S)	Corryville	46	Tr	2	26	Tr	23	3	0	49/27/24	1.77	Dolomitic Mudstone
Ru 1.75 (S)	Corryville	31	0	2	48	0	18	1	0	32/49/19	0.65	Dolomitic Claystone
A 3.05 (C)	Sunset	31	Tr	1	55	Tr	0	1	12	36/64/0	0.56	Mudstone

APPENDIX 6A (continued)

Sample No.	Formation	Quartz	Feldspar	Heavies	Clays + Micas	Fossils	Dolomite	Pyrite	Other	Q + F/ C + M/ Ca + Do	Silt/ Clay Ratio	Rock Name
A 3.7 (S)	Sunset	38	Tr	2	47	1	0	Tr	12	45/55/0	0.81	Mudstone
A 8.1	Oregonia	37	Tr	1	50	0	9	3	0	39/52/9	0.74	Mudstone
BD 32.7 (S)	Waynesville	34	0	1	59	Tr	5	1	Tr	35/60/5	0.58	Mudstone
BD 34.8 (S)	Waynesville	36	0	1	48	0	8	7	0	39/52/9	0.75	Mudstone
BD 38.7 (C)	Waynesville	18	0	1	74	0	2	5	0	19/79/2	0.24	Claystone
BD 40.5 (S)	Waynesville	36	0	Tr	55	2	4	3	0	38/58/4	0.66	Mudstone
BD 50.46 (C)	Waynesville	18	0	2	54	1	19	6	0	20.59.21	0.33	Dolomitic Claystone
BD 54.1 (S)	Waynesville	42	Tr	2	32	Tr	23	1	0	43/33/24	1.31	Dolomitic Mudstone
BD 62.6 (C)	Waynesville	22	0	3	59	0	13	3	0	23/63/14	0.37	Dolomitic Claystone
BN 20.7 (S)	Liberty	35	0	1	36	0	27	1	0	36/36/28	0.97	Dolomitic Mudstone
BN 24.5 (S)	Liberty	34	0	Tr	32	0	33	1	0	34/33/33	1.06	Very Dolomitic Mudstone
BN 30.9 (S)	Liberty	14	0	0	7	0	14	3	62	15/7/78	N/A	Silty Micstone
Ri 6.6	Whitewater	13	0	0	75	8	1	3	0	15/84/1	0.17	Fossilif. Claystone

APPENDIX 6A (concluded)

Sample No.	Formation	Quartz	Feldspar	Heavies	Clays + Micas	Fossils	Dolomite	Pyrite	Other	Q + F/ C + M/ Ca + Do	Silt/ Clay Ratio	Rock Name
GA 0.73 (C)**	Kope	7	0	1	82	0	10	Tr	0	7/83/10	0.09	Dolomitic Claystone
GA 0.95 (S)	Kope	25	0	1	66	0	6	2	0	26/68/6	0.38	Claystone
GA 1.08 (S)	Kope	37	Tr	3	47	Tr	9	4	0	40/50/10	0.80	Dolomitic Mudstone

***GA* samples were taken from the upper Kope Formation at Reidlin Road, megacycle #3 (8.3-9.5). The numbers 0.73, 0.95, and 1.08 refer to the vertical distance in meters from the base of megacycle #3.

APPENDIX 6B

SHALE TEXTURES

Sample No.	Formation	Rock Name	Grain Shape*	Sphericity*	Grain Size (in microns) Mean/Median	Bioturbation
I A.2 (S)	Kope	Dolomitic Mudstone	very elongate (.583)	very low (.583)	33/29	none
I F.8 (S)	Kope	Dolomitic Mudstone	very elongate (.538)	very low (.538)	30/28	none
I N.1 (S)	Kope	Mudstone	very elongate (.599)	very low (.588)	29/28	none
I 0.8 (S)	Kope	Dolomitic Mudstone	elongate (.620)	very low (.620)	27/25	none
I 4.2 (C)	Kope	Claystone	subequant (.692)	high (.692)	19.19	none
I 5.2 (S)	Kope	Mudstone	subelongate (.633)	low (.633)	24/21	none
I 6.0 (S)	Kope	Mudstone	subequant (.712)	high (.712)	24/24	none
I 11.6 (S)	Kope	Mudstone	very elongate (.563)	very low (.563)	26/25	none
I 12.3 (S)	Kope	Mudstone	very elongate (.580)	very low (.580)	25/25	none
I 23.4 (C)	Kope	Claystone	elongate (.600)	very low (.600)	16/15	none

Grain shape and *sphericity* are determined from the ratio of width/length, using the scale of Folk (1974, pp. 10-11).

APPENDIX 6B (continued)

Sample No.	Formation	Rock Name	Grain Shape	Sphericity	Grain Size (in microns) Mean/Median	Bioturbation
Ba 4.0 (S)	Kope	Dolomitic Mudstone	intermediate (.667)	moderate (.667)	32/35	none
Re S1 (C)	Fairview	Claystone	subequant (.702)	high (.702)	16/13	none
Re S2 (C)	Fairview	Claystone	elongate (.602)	very low (.602)	24/25	none
Re S3 (S)	Fairview	Dolomitic Claystone	very elongate (.594)	very low (.594)	19/15	none
Re S4 (S)	Fairview	Claystone	subelongate (.631)	low (.631)	24/24	none
Re S5 (C)	Fairview	Dolomitic Mudstone	intermediate (.672)	moderate (.672)	30/30	*Chondrites* (9%)
Re S6 (S)	Fairview	Claystone	intermediate (.666)	moderate (.666)	21/18	none
Re S7 (S)	Fairview	Dolomitic Mudstone	very elongate (.598)	very low (.598)	28.25	none
Re S8 (S)	Fairview	Mudstone	very elongate (.534)	very low (.534)	44/45	*Chondrites* (8%)
Re S9 (S)	Fairview	Dolomitic Claystone	very elongate (.556)	very low (.556)	18/15	none
Re S10 (C)	Fairview	Mudstone	intermediate (.668)	moderate (.668)	29/25	none
Ru A.35 (C)	Corryville	Mudstone	very elongate (.595)	very low (.595)	26/25	none
Ru D.6 (S)	Corryville	Dolomitic Mudstone	elongate (.600)	very low (.600)	29/25	none

APPENDIX 6B (continued)

Sample No.	Formation	Rock Name	Grain Shape	Sphericity	Grain Size (in microns) Mean/Median	Bioturbation
Ru F.3 (S)	Corryville	Dolomitic Mudstone	subelongate (.644)	low (.644)	32/30	none
Ru 1.75 (S)	Corryville	Dolomitic Mudstone	subelongate (.639)	low (.639)	23/20	none
A 3.05 (C)	Sunset	Mudstone	elongate (.607)	very low (.607)	37/36	none
A 3.7 (S)	Sunset	Mudstone	subelongate (.659)	low (.658)	44/39	none
A 8.1	Oregonia	Mudstone	elongate (.636)	very low (.636)	27/23	none
BD 32.7 (S)	Waynesville	Mudstone	elongate (.624)	very low (.624)	23/20	none
BD 34.8 (S)	Waynesville	Mudstone	very elongate (.540)	very low (.540)	20/18	none
BD 38.7 (C)	Waynesville	Claystone	subelongate (.645)	low (.645)	15/15	none
BD 40.5 (S)	Waynesville	Mudstone	elongate (.622)	very low (.622)	20/20	none
BD 50.46 (C)	Waynesville	Dolomitic Mudstone	subequant (.706)	high (.706)	17/15	none
BD 54.1 (S)	Waynesville	Dolomitic Mudstone	subelongate (.653)	low (.653)	23/19	none
BD 62.6 (C)	Waynesville	Dolomitic Claystone	subequant (.696)	high (.696)	20/19	none
BN 20.7 (S)	Liberty	Dolomitic Mudstone	elongate (.618)	very low (.618)	22/20	none

APPENDIX 6B (concluded)

Sample No.	Formation	Rock Name	Grain Shape	Sphericity	Grain Size (in microns) Mean/Median	Bioturbation
BN 24.5 (S)	Liberty	Very Dolomitic Mudstone	subelongate (.648)	low (.648)	22/20	none
BN 30.8 (S)	Liberty	Silty Micstone	N/A	N/A	N/A	none
Ri 6.6	Whitewater	Fossilif. Claystone	intermediate (.689)	moderate (.689)	16/15	none
GA 0.73 (C)	Kope	Dolomitic Claystone	intermediate (.678)	moderate (.678)	17/14	none
GA 0.95 (S)	Kope	Claystone	elongate (.601)	very low (.601)	21/20	none
GA 1.08 (S)	Kope	Dolomitic Mudstone	subelongate (.652)	low (.652)	26/25	*Chondrites* (12%)

APPENDIX 7
PALEOCURRENT DATA

Outcrop (meter)	Formation	Megacycle Subdivision	Rock Type	Type of Structure	Azimuth Orientation
A (6.6)	Sunset	carbonate	P/G	gutter cast	15°
A (7.9)	Oregonia	N/A	calcisiltite	gutter cast	25°
BD (C.2)	Corryville	shale	siltstone	gutter cast	136°
BN (19.2)	Liberty	carbonate	grainstone	flute mark	111°
I (J.4)	Kope	shale	siltstone	gutter cast	43°
I (T.0)	Kope	carbonate	grainstone	ripple	59°*
I (11.1)	Kope	shale	siltstone	ripple	23°*
I (23.1)	Kope	carbonate	grainstone	ripple	74°*
Re (5.7)	Kope	carbonate	grainstone	gutter cast	5°*
Re (31.9)	Fairview	N/A	wackestone	ripple	4°*
Re (33.3)	Fairview	carbonate	grainstone	ripple	-6°*
Ri (4.5)	Whitewater	N/A	grainstone	oriented cephalopod	45° (current to SW)

*Orientation perpendicular to crest of ripple.

APPENDIX 7 (continued)

Outcrop (meter)	Formation	Megacycle Subdivision	Rock Type	Type of Structure	Azimuth Orientation
Ru (5.1)	Corryville	shale	shale	oriented cephalopod	132° (current to NW)
Ru (7.9)	Mt. Auburn	N/A	grainstone	oriented cephalopod	92° (current to W)
Ru (8.1)	Mt. Auburn	N/A	P/G	oriented cephalopod	145°
Ru (8.8)	Mt. Auburn	N/A	packstone	oriented cephalopod	160°
Ru (9.2)	Mt. Auburn	N/A	packstone	oriented cephalopod	0°
Ru (9.4)	Mt. Auburn	N/A	packstone	oriented cephalopod	80°
Ru (10.8)	Mt. Auburn	N/A	shale	oriented cephalopod	156°
Clifton Ave. (8.6)	Fairview	shale	siltstone	ripple	28°*
Clifton Ave. (12.3)	Fairview	shale	siltstone	ripple	34°*
Clifton Ave. (20.9)	Fairview	carbonate	grainstone	ripple	25°*
Clifton Ave. (22.6)	Fairview	carbonate	packstone	flute mark	53°
Clifton Ave. (24.9)	Fairview	carbonate	packstone	ripple	109°*

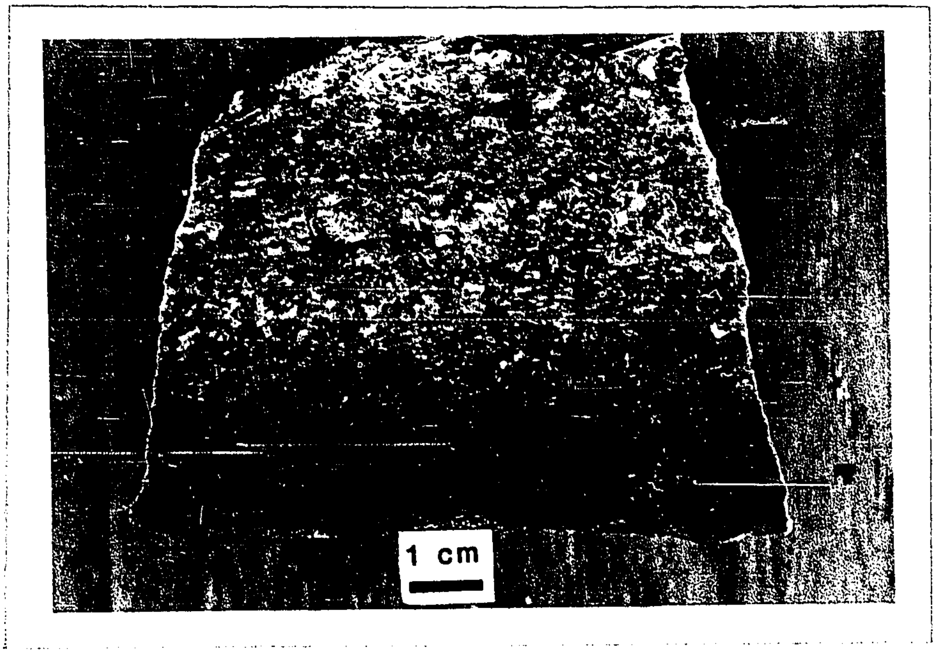
APPENDIX 7 (concluded)

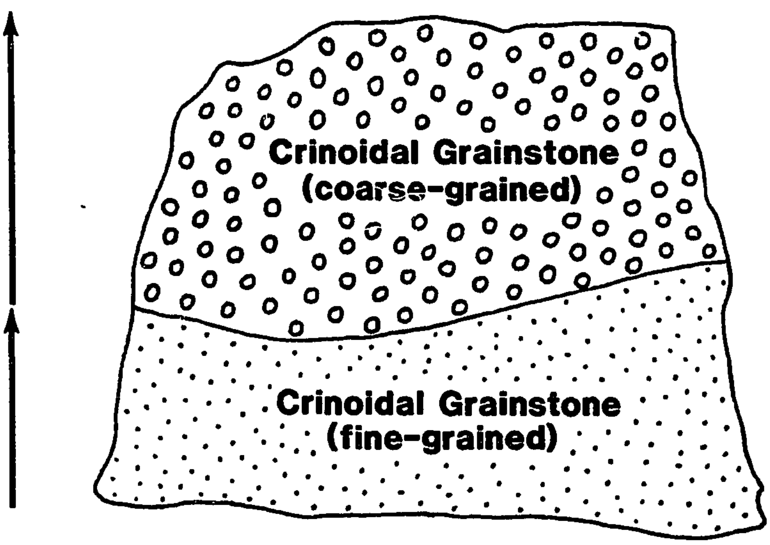
Outcrop (meter)	Formation	Megacycle Subdivision	Rock Type	Type of Structure	Azimuth Orientation
Clifton Ave. (31.6)	Miamitown	N/A	siltstone	gutter cast	82°
Lawrenceburg (22.0)	Fairview	shale	siltstone	ripple	111° (current to NW)
Lawrenceburg (23.2)	Fairview	carbonate	packstone	ripple	104°*
Lawrenceburg (30.4)	Miamitown	N/A	siltstone	gutter cast	11°
Maysville, KY (?)	Fairview	carbonate	grainstone	ripple	149°*
Muddy Creek (3.3)	Miamitown	N/A	packstone	gutter cast	4°
Winton Lake (12.2)	Fairview	carbonate	packstone	flute mark	17°
Winton Lake (13.5)	Fairview	shale	siltstone	flute mark	160°
Winton Lake (27.2)	Fairview	shale	siltstone	ripple	65°*

APPENDIX 8

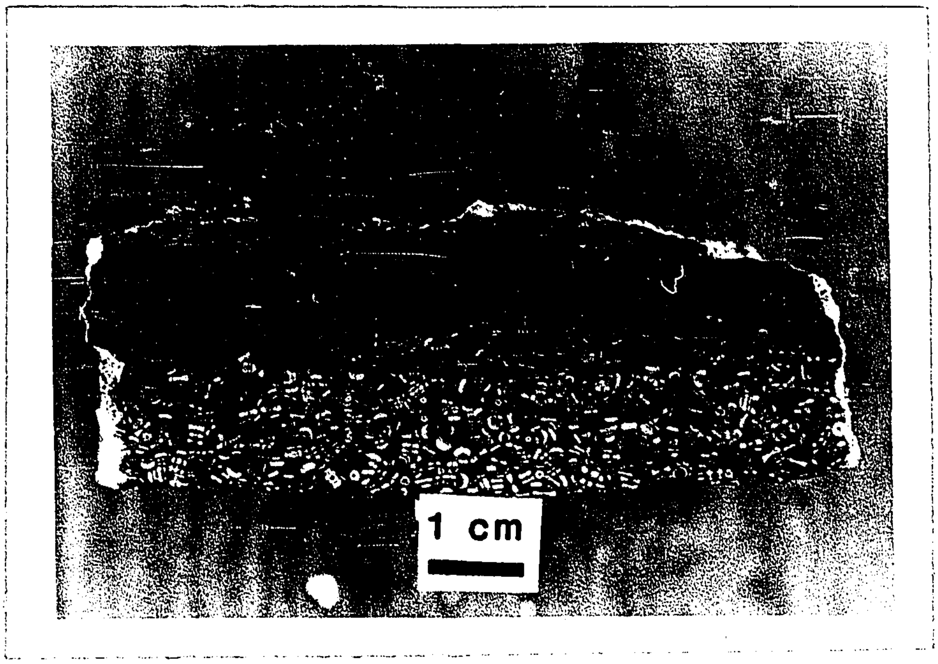
EXAMPLES OF DISCONTINUOUS SEDIMENTATION FROM LIMESTONE POLISHED SLABS

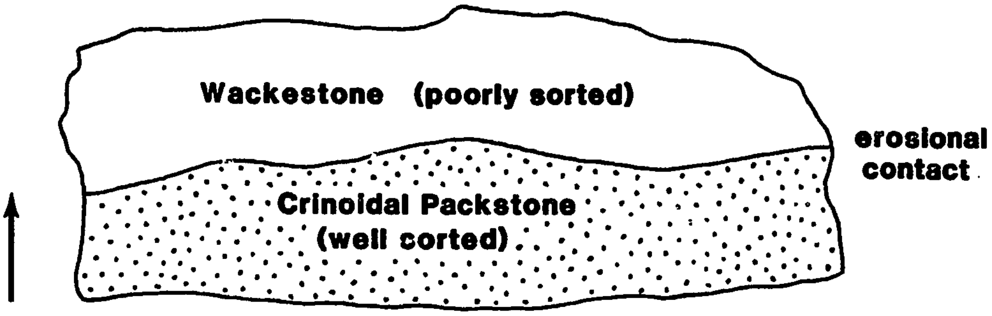
(Arrows denote inferred storm events)



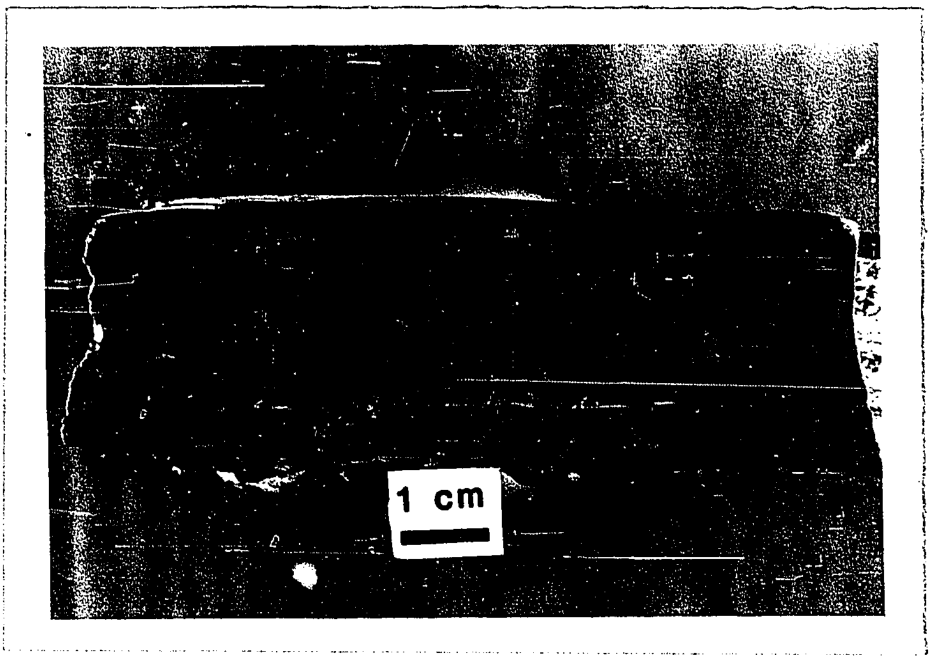


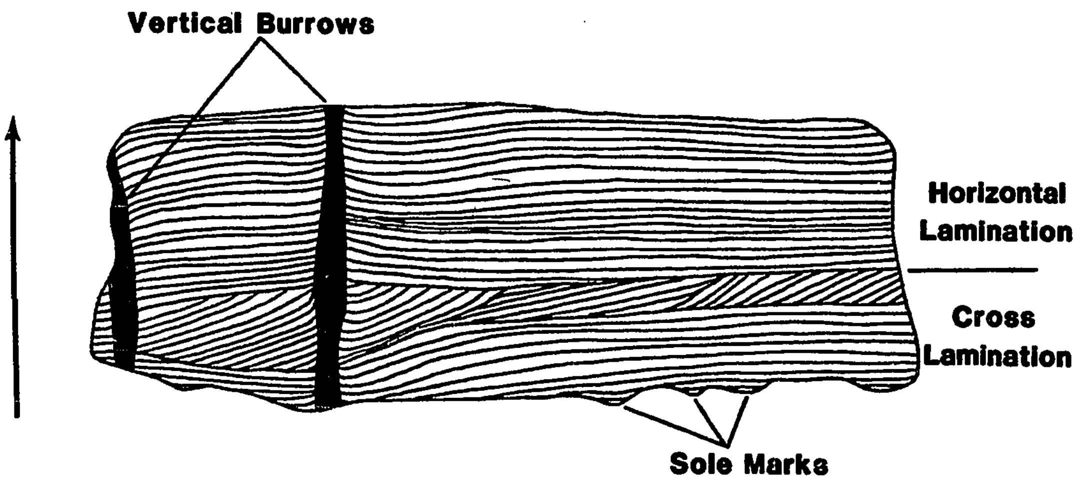
GRAINSTONE - UNIT A



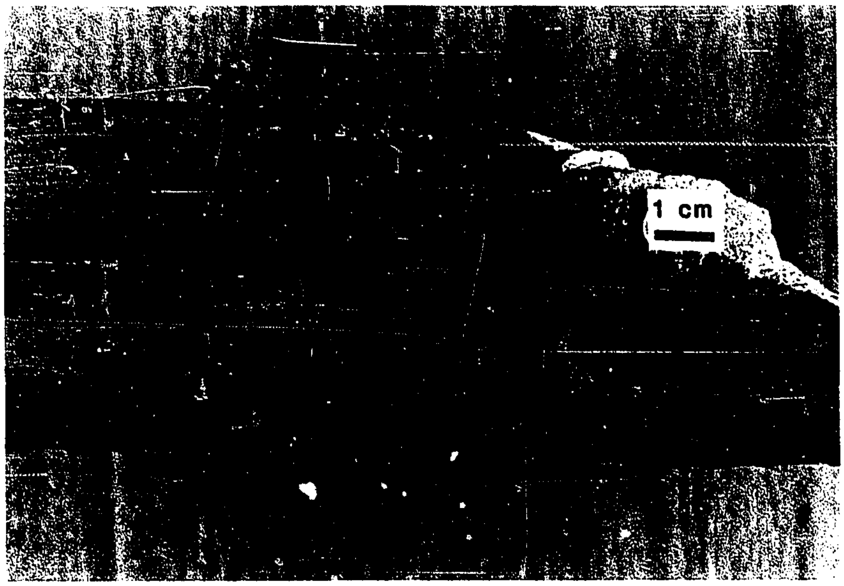


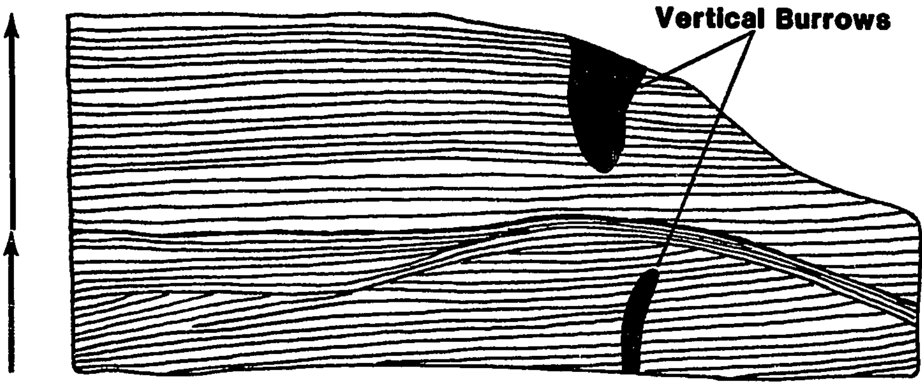
PACKSTONE - UNIT B



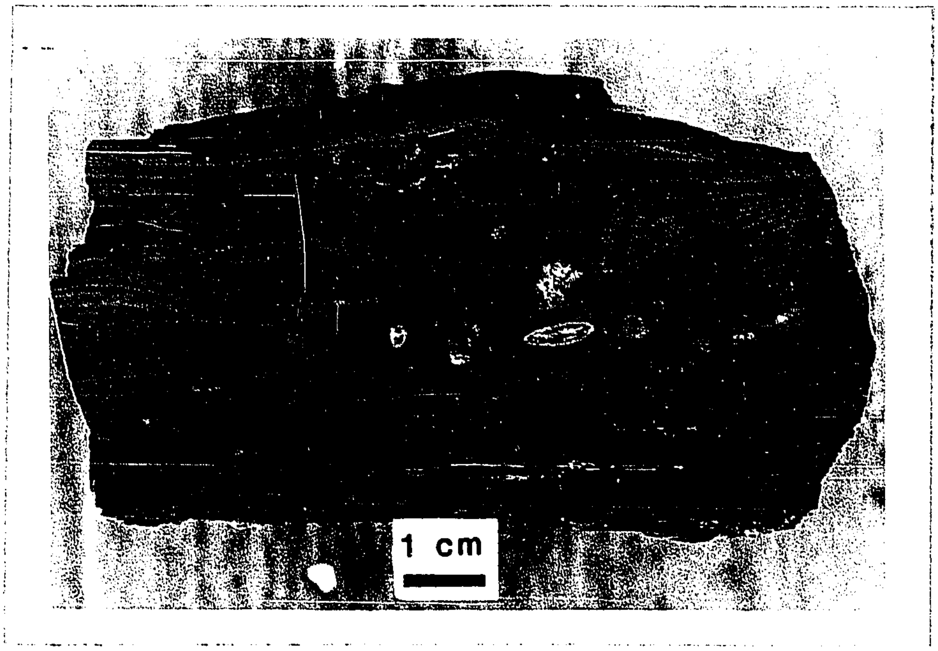


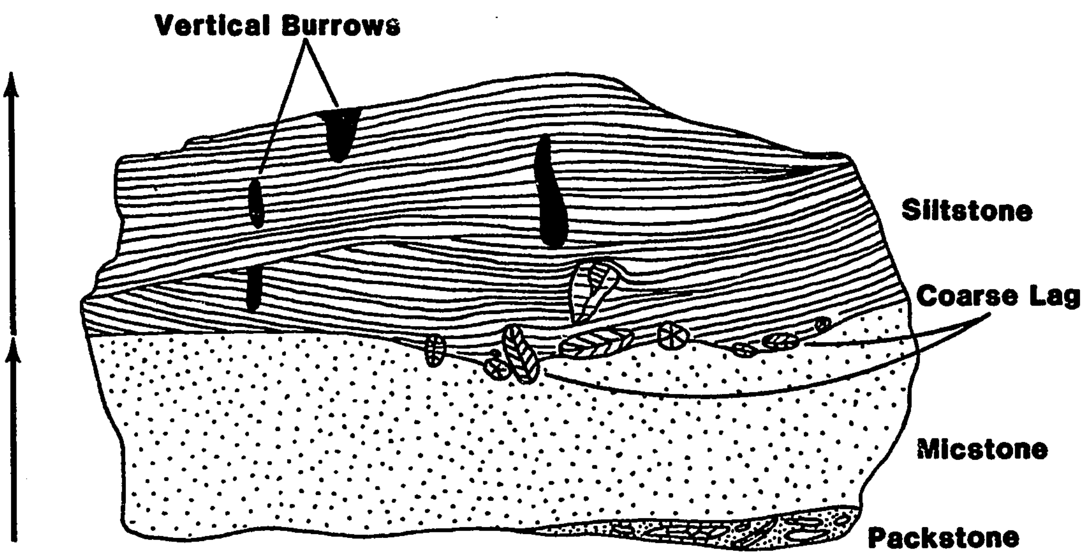
SILTSTONE - UNIT C





SILTSTONE - UNIT C





SILTSTONE - UNIT C

APPENDIX 9
MEGACYCLE DATA

Cycle Number*	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
BK/K/1	2.76	0.52	2.24	no	27	84	--	3P, 1G	3P, 1W, 7S, 1G
BK/K/2	2.48	0.42	2.06	yes	24	85	3G	1P	9S
BK/K/3	0.96	0.37	0.59	no	11	100	3G	--	--
I/K/1	4.00	0.12	3.88	no	0	80	1G	--	13P, 4S, 1M
I/K/2	2.00	0.38	1.62	yes	42	84	1G	2P	3S, 2M, 2P
I/K/3	0.84	0.16	0.68	no	0	88	1G	--	1P, 1M
I/K/4	1.32	0.34	0.98	yes	18	89	1G	1P/G	3P, 1W, 1M
I/K/5	0.46	0.26	0.20	no	23	80	--	2P, 1P/G	1S
I/K/6	1.30	0.28	1.02	yes	50	67	1G	1P/G	3S, 3M
I/K/7	2.30	0.24	2.06	no	25	75	2G	--	7S, 2M, 3P
I/K/8	2.54	0.20	2.34	no	0	90	1G	--	5P
I/K/9	1.32	0.18	1.14	no	0	77	1G	--	2P, 1S, 1M
I/K/10	1.20	0.20	1.00	no	0	86	--	1P	3M, 1S
I/K/11	1.80	0.20	1.60	no	0	81	1G	--	5P, 1S, 2M
I/K/12	2.50	0.38	2.12	yes	42	93	3G	2P	3M, 2S, 1W
I/K/13	3.90	0.14	3.76	no	0	90	1G	--	6P, 6S, 1M

*Numbering system is as follows: BK/K/1 means Bald Knob Hill locality, Kope Formation, cycle number 1 (see Appendix 3 for all abbreviations).

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
I/K/14	0.54	0.26	0.28	yes	27	89	2G	1P	1P
I/K/15	0.48	0.26	0.22	no	23	68	--	2P	1P, 2W
I/K/16	1.28	0.14	1.14	no	0	91	1P/G	--	1S, 1M
I/K/17	4.92	0.12	4.80	no	0	88	--	1P	4G, 4P, 6S, 1W
I/K/18	1.14	0.24	0.90	no	0	96	1G	--	2S
I/K/19	1.42	0.34	1.08	yes	0	92	1G	1P/G	1P, 2S
I/K/20	0.88	0.18	0.70	no	0	91	--	1P	1G, 2P/G
I/K/21	1.78	0.10	1.68	no	0	96	1G	--	1P, 1M, 1S
I/K/22	1.74	0.46	1.28	no	30	94	--	3P, 1G	1P
I/K/23	1.86	0.16	1.70	no	0	100	1G	--	--
I/K/24	1.20	0.34	0.86	yes	53	84	1G	1P, 1W	2W, 1P
I/K/25	1.60	0.28	1.32	no	14	87	--	1P, 1P/G	6P, 1S
I/K/26	3.88	0.66	3.22	no	33	85	--	2P, 2G, 1P/G	10P, 3S
I/K/27	2.74	0.66	2.08	yes	63	95	1G	2P, 1W	2S
I/K/28	0.90	0.32	0.58	yes	13	100	1G	2P	--
Re/K/1	2.70	0.68	2.02	no	38	83	5G	--	4M, 3S
Re/K/2	2.60	0.52	2.08	yes	23	86	1G	3P	6S, 2M
Re/K/3	1.20	0.56	0.64	yes	14	94	1G	2P	1M, 1S
G/K/1	1.90	0.32	1.58	yes	37	87	1G	3P	3S, 1M, 2P
G/K/2	0.80	0.27	0.53	no	15	89	3G	--	1S

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
G/K/3	2.94	0.24	2.70	yes	8	90	1G	1P	9S, 1M, 1P
G/K/4	0.66	0.18	0.48	no	0	100	--	1P	--
Ba/K/1	1.40	0.52	0.88	yes	42	91	2G	1W	1W
Ba/K/2	1.40	0.40	1.00	no	25	90	2G	--	1W, 2M
Ba/K/3	1.44	0.36	1.08	no	33	87	1P/G, 1G	--	2P, 2M, 1S
Ba/K/4	1.60	0.26	1.34	yes	31	94	1P/G	1P	1P, 1W
Ba/K/5	1.54	0.84	0.70	yes	31	91	3G	2P	1P, 1S
Ba/K/6	1.74	0.12	1.62	no	0	91	--	1P	1S, 2M, 1P/G
Ba/K/7	2.86	0.14	2.72	no	14	91	1G, 1P/G	--	2S, 3M, 1P
Ba/K/8	0.84	0.22	0.62	no	9	84	--	2P	2P
Ba/K/9	1.32	0.20	1.12	no	0	89	1G	--	2S
Ba/K/10	1.54	0.38	1.16	no	42	95	1G, 1P/G	--	1P, 1W
Re/F/4	0.50	0.14	0.36	no	0	78	--	1P	2P/G
Re/F/5	0.50	0.14	0.36	no	0	61	1G	--	2P
Re/F/6	0.24	0.10	0.14	no	0	93	1G	--	1P
Re/F/7	0.66	0.18	0.48	yes	22	58	1P/G	1P	4P, 2W
Re/F/8	0.50	0.40	0.10	no	10	100	1G, 1P/G	--	--
Re/F/9	0.48	0.24	0.24	no	0	75	1G	--	1G
Re/F/10	0.46	0.20	0.26	no	0	62	--	1P	1P
Re/F/11	0.50	0.20	0.30	no	0	47	1G	--	3P

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Tran-sition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
Re/F/12	1.64	0.38	1.26	no	21	79	--	2P	2C, 1P
Re/F/13	1.68	0.74	0.94	yes	30	94	2G	4P	1C
Re/F/14	0.6+	0.50	0.1+	yes	12	?	1G	2P	?
Re/F/15	0.80	0.30	0.50	yes	27	84	1G	1P	1P
Re/F/16	0.52	0.26	0.26	yes	31	100	1P/G	1P	--
Re/F/17	0.40	0.08	0.32	no	0	63	--	1P	1P, 2M, 1C
Re/F/18	0.60	0.44	0.16	no	32	100	--	3P	--
Re/F/19	0.66	0.46	0.20	no	17	80	--	4P, 1M	1S
Re/F/20	0.78	0.22	0.56	no	27	70	--	2P	2P, 1S
Re/F/21	0.42	0.10	0.32	no	0	63	--	1P	2P
Re/F/22	0.88	0.12	0.76	no	0	50	--	1P	3P, 1C, 1M
Re/F/23	0.66	0.36	0.30	no	11	87	--	2P	1S
Re/F/24	0.34	0.10	0.24	no	0	88	1P/G	--	1M
Re/F/25	1.00	0.42	0.58	no	24	69	--	2P, 1G	1S, 4P, 1W
Re/F/26	0.60	0.32	0.28	no	19	71	--	3P	1C
Re/F/27	0.50	0.28	0.22	no	0	82	--	1P	1G
Re/F/28	0.56	0.38	0.18	yes	21	78	1G	1P	2P
Re/F/29	0.78	0.42	0.36	no	19	67	1G, 2C, 1P/G	--	1W, 1G, 2S
Re/F/30	0.66	0.36	0.30	no	28	80	3G	--	1S, 1P
Re/F/31	0.72	0.16	0.56	no	0	50	--	1P	1M, 1P, 1C

APPENDIX 9 (continued)

Cycle Number	Thickness (m)			A/B Tran-sition	Percent Shale		Carbonate Beds		
	Total	Carb. Hemi.	Shale Hemi.		Carb. Hemi.	Shale Hemi.	Unit A	Unit B	Unit C
Re/F/32	0.58	0.44	0.14	no	9	100	--	2P, 1G	--
Re/F/33	0.70	0.22	0.48	no	18	71	--	2P	2P/G, 1S
Re/F/34	0.68	0.12	0.56	no	0	61	1G	--	2S, 1P, 3W
Re/F/35	1.24	0.16	1.08	no	0	44	--	1P	6P, 1S
Re/F/36	0.88	0.12	0.76	no	0	68	1G	--	3P, 1S
Re/F/37	0.40	0.10	0.30	no	0	80	--	1P	1M
Re/F/38	0.70	0.20	0.50	no	0	40	1G	--	1G, 5P, 1S
Re/F/39	0.54	0.14	0.40	no	0	80	1G	--	2M
Re/F/40	0.62	0.12	0.50	no	0	84	--	1P	4S
G/F/5	0.40	0.14	0.26	no	0	39	1C	--	2M
G/F/6	0.90	0.26	0.64	yes	8	58	2G	1P	4M, 1S, 1P, 1W
G/F/7	0.62	0.20	0.42	no	0	62	--	2P	4M, 2P, 1S
G.F/8	0.48	0.17	0.31	no	0	77	--	1P	1P, 1M, 1C
G/F/9	1.22	0.60	0.62	no	10	68	3C	--	1P, 2M, 1S, 1G
G/F/10	0.36	0.22	0.14	no	0	86	1G	--	1S
G/F/11	0.20	0.12	0.08	no	0	63	--	1P	2M
G/F/12	1.30	0.56	0.74	yes	7	37	2G	1P	4S, 2M, 3P, 1W
Ru/C/1	1.32	0.30	1.02	yes	13	78	1G	2P	2P, 4G, 1P/G
Ru/C/2	1.52	0.98	0.54	no	31	59	6G, 1C, 4P	--	7P
Ru/C/3	1.16	0.28	0.88	no	28	54	--	4P	4G, 1P/G, 8P

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
Ru/C/4	1.94	0.74	1.20	no	36	67	--	6P, 1M	13P
Ru/C/5	0.44	0.06	0.38	no	0	55	--	1P	9P/G
Ru/C/6	0.72	0.30	0.42	yes	7	76	1P/G	1P	2P
Ru/C/7	1.18	0.50	0.68	yes	60	81	1P/G	4P	4M
M/C/1	0.62	0.11	0.51	no	0	82	1G	--	4P
G/C/A	0.80	0.26	0.54	yes	15	63	2G	1P	3P, 2S
G/C/B	0.44	0.26	0.18	no	8	78	--	1P, 1G, 1M	1P, 1M
G/C/C	0.48	0.34	0.14	no	18	86	--	2P, 1G	1S
G/C/D	0.52	0.08	0.44	no	0	73	1G	--	1S, 4G
G/C/E	0.66	0.30	0.36	yes	27	61	1G	1P	2S, 1M, 1C
G/C/F	0.92	0.20	0.72	yes	10	67	1G	1P, 1S	4S, 3P
G/C/G	0.50	0.32	0.18	no	25	89	--	2P	1P
BD/C/1	2.4+	?	2.4+	?	?	92	?	?	1M, 2S, 1P
BD/C/2	1.52	0.60	0.92	no	23	67	--	7P	3M, 1P
BD/C/3	0.78	0.56	0.22	no	14	100	--	3P, 1G	--
BD/C/4	1.04	0.30	0.74	no	0	60	1G	--	5P, 3G
BD/C/5	2.3+	0.48	1.8+	yes	8	?	2G	1P	?
BD/C/6	1.54	0.58	0.96	no	31	97	--	3P, 2W	2W, 1S
Ru/S/8	2.05	1.00	1.05	no	8	72	--	3P, 2P/G, 1G	2S, 1C, 1W, 1P
Ru/S/9	1.52	1.10	0.42	no	11	54	--	9P	7P

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
M/S/2	0.90	0.10	0.80	no	0	62	1P/G	--	5P
A/S/1	0.78	0.68	0.10	yes	25	100	4G	7P	--
A/S/2	0.98	0.30	0.68	no	23	31	2P/G, 1G	--	4C, 4P
A/S/3	1.04	0.24	0.80	no	0	84	1G	--	2P, 1M
A/S/4	1.72	0.28	1.44	no	21	63	2G, 1C	--	10G, 1S, 8P
A/S/5	0.60	0.26	0.34	no	23	65	--	3P	2S, 1P
A/S/6	0.88	0.24	0.64	no	0	77	1G	--	1P, 1P/G
B1/S/1	0.72	0.18	0.54	no	22	78	1G, 1P/G	--	2W, 1M
B1/S/2	1.40	0.56	0.84	yes	35	67	3C	2P	1C, 2P
BD/S/7	1.22	0.28	0.94	no	7	60	2G	--	8P
BD/S/8	2.18	0.50	1.68	yes	28	73	1G	2P	9P, 1G, 2W
BD/S/9	1.00	0.32	0.68	no	31	71	--	4P	6P, 1S
BD/S/10	0.38	0.10	0.28	no	0	79	1G	--	1P/G, 2P
BD/S/11	0.54	0.30	0.24	no	20	92	--	2P	1S
BD/S/12	1.02	0.16	0.86	no	0	72	--	1W	3P, 1S
BD/S/13	0.92	0.62	0.30	no	35	87	--	5P	1P
BD/S/14	0.72	0.30	0.42	no	13	100	--	2P	--
BD/W/17	2.60	0.24	2.36	yes	0	81	1G	1P	6P, 1W, 3S
BD/W/18	1.28	0.24	1.04	no	17	80	--	1P, 2W	1M, 2S, 2P
BD/W/19	2.48	0.34	2.14	yes	41	83	1G, 1P/G	1P	7P, 1P/G, 1W

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
BD/W/20	2.74	0.94	1.80	no	37	76	--	5P, 2G	5W, 11P, 2S
BD/W/21	1.88	0.60	1.28	yes	57	98	1G	3P	1P, 1S
BD/W/22	0.64	0.06	0.58	no	0	86	1G	--	4P
BD/W/23	1.02	0.22	0.80	no	36	89	--	2P, 1S	6P
BD/W/24	1.78	0.22	1.56	yes	18	83	1P/G	1P	1G, 10P, 1S
BD/W/25	1.42	0.13	1.29	no	15	81	--	2P	6P
BD/W/26	0.98	0.30	0.68	no	40	75	--	3P	3P, 1W
BD/W/27	0.74	0.42	0.32	no	38	75	--	2P, 2W	2P
BD/W/28	0.96	0.10	0.86	no	0	66	1G	--	1W, 1G, 3P, 1S
BD/W/29	0.54	1.10	0.44	no	0	68	--	1P	3P, 3S
BD/W/30	0.68	0.42	0.26	yes	33	100	2G	5P	--
BD/W/31	0.66	0.26	0.40	no	12	70	4G	--	3P
BD/W/32	1.18	0.10	1.08	no	0	60	1G	--	12P, 1G
BD/W/33	1.12	0.20	0.92	no	15	80	--	2P	3P/G, 2P
BD/W/34	0.54	0.07	0.47	no	0	96	1G	--	1P
BD/W/35	2.94	1.44	1.50	no	30	75	--	12P, 1G	12P
BD/W/36	0.92	0.26	0.66	no	0	76	--	2P	1G, 3P
BD/W/37	0.78	0.12	0.66	no	0	65	1G	--	3P, 1W, 1P/G
BD/W/38	0.36	0.26	0.10	yes	23	100	1G	2P	--
BD/W/39	0.60	0.12	0.48	no	0	100	1P/G	--	--

APPENDIX 9 (continued)

Cycle Number	Thickness (m) Total	Carb. Hemi.	Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Shale Hemi.	Carbonate Beds Unit A	Unit B	Unit C
BD/W/40	1.42	0.32	1.10	yes	44	94	2G	1P	1P
BD/W/41	0.54	0.10	0.44	no	0	100	1G	--	--
BD/W/42	0.32	0.14	0.18	no	14	100	--	1P, 1W	--
BD/W/43	1.18	0.32	0.86	no	0	84	--	1P	1P, 1M, 1C
BN/W/1	0.80	0.16	0.64	no	0	73	--	1P	9P
BN/W/2	0.94	0.46	0.48	yes	30	71	1C	7P	4P
BN/W/3	0.82	0.12	0.70	no	0	64	--	1P	4P
BN/W/4	1.74	0.38	1.36	yes	26	85	3G	1P	5S, 1G
BD/L/44	1.30	0.68	0.62	no	35	100	--	4P, 1P/G	--
BD/L/45	0.75	0.38	0.37	yes	26	89	1G	2P	1P
BD/L/46	0.33	0.15	0.18	no	0	100	--	1P	--
BD/L/47	1.72	1.00	0.72	no	21	100	--	2P, 6G	--
BD/L/48	0.28	0.12	0.16	no	0	88	--	1P	1P
BD/L/49	1.14	0.40	0.74	no	15	62	2G	--	4G, 2P
BD/L/50	0.46	0.12	0.34	no	0	88	--	1P	1P
BD/L/51	0.50	0.10	0.40	no	0	100	--	1P	--
BD/L/52	2.20	1.38	0.82	no	33	90	6G, 2C	2P	1G
BD/L/53	1.20	0.80	0.40	yes	14	100	4G	3P	--
BD/L/54	1.58	0.88	0.70	no	21	100	3G, 2C	--	--
BD/L/55	1.92	0.58	1.34	no	31	94	--	4P, 1S	1G

APPENDIX 9 (concluded)

Cycle Number	Thickness (m) Total	Thickness (m) Carb. Hemi.	Thickness (m) Shale Hemi.	A/B Transition	Percent Shale Carb. Hemi.	Percent Shale Shale Hemi.	Carbonate Beds Unit A	Carbonate Beds Unit B	Carbonate Beds Unit C
BN/L/5	1.36	0.40	0.96	yes	25	90	1G	2P	1S, 1M, 1G
BN/L/6	0.94	0.44	0.50	no	14	62	--	3P, 1G	2P, 2G
BN/L/7	1.00	0.12	0.88	no	0	80	1C	--	3P
BN/L/8	0.92	0.46	0.46	no	0	65	--	1P	1P, 1P/G, 1G
BN/L/9	1.08	0.30	0.78	no	0	72	1G	--	3P, 1W, 1P/G
BN/L/10	0.60	0.12	0.48	no	0	88	1G	--	1M, 1S
BN/L/11	0.58	0.36	0.22	no	6	55	3G, 1S	--	1C, 1P
BN/L/12	1.20	0.82	0.38	no	11	53	4G, 2P/G	--	2G, 1P/G
BN/L/13	1.32	0.72	0.60	no	8	50	--	3P, 1M	3P, 1W, 2S, 1M
BN/L/14	0.66	0.28	0.38	no	14	68	--	2P	1G, 2S, 1P
BN/L/15	0.32	0.24	0.08	no	0	100	--	1P, 1S	--
BN/L/16	0.38	0.24	0.14	no	0	50	--	1W	3S
BN/L/17	0.50	0.34	0.16	no	12	75	--	2P	2P
BN/L/18	0.42	0.18	0.24	no	0	63	1P/G	--	3P
BN/L/19	0.36	0.28	0.08	no	14	100	3G	--	--
BN/L/20	1.08	0.56	0.52	no	37	73	--	3P, 2W, 1G	2P, 1S
BN/L/21	0.54	0.28	0.26	no	29	100	2P/G, 1P, 1G	--	--
BN/L/22	0.40	0.10	0.30	no	0	87	--	1P	1G
BN/L/23	0.32	0.08	0.24	no	0	75	1G	--	1P/G
BN/L/24	0.54	0.30	0.24	no	0	87	1G	--	1M
BN/L/25	0.28	0.20	0.08	no	10	100	--	2P	--

A P P E N D I X 1 0

STATISTICAL ANALYSIS OF CINCINNATIAN MEGACYCLES

(A) Transition matrix for carbonate hemicycles vs. shale hemicycles in the Kope Formation (location I, units U.5 - 22.9):

	carbonate	shale	Row Totals:
carbonate	0	16	16
shale	16	0	16
Column Totals:	16	16	32

⇨

8.0	8.0
8.0	8.0

⇨

-8.0	+8.5
+8.5	-8.0

Dominant Transition: Carbonate Hemicycle → Shale Hemicycle → Carbonate Hemicycle

(B) Transition matrix for carbonate hemicycles vs. shale hemicycles in the Fairview Formation (location Re, units 21.9 - 31.6):

	carbonate	shale	Row Totals:
carbonate	0	15	15
shale	15	0	15
Column Totals:	15	15	30

⇨

7.5	7.5
7.5	7.5

⇨

-7.5	+7.5
+7.5	-7.5

Dominant Transition: Carbonate Hemicycle → Shale Hemicycle → Carbonate Hemicycle

APPENDIX 10 (continued)

(C) Transition matrix for units A, B, and C of the "idealized" megacycle in the Kope Formation (location I, units U.5 - 22.9):

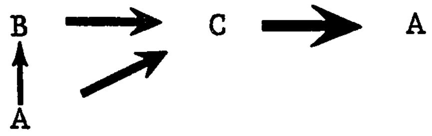
	unit A	unit B	unit C	Row Totals:
unit A	0	3	8	11
unit B	0	0	6	6
unit C	13	2	0	15
Column Totals:	13	5	14	32

4.5	1.7	4.8
2.4	0.9	2.6
6.1	2.3	6.6

-4.5	+1.3	+3.2
-2.4	-0.9	+3.4
+6.9	-0.3	-6.6

Ideal Prediction:

Dominant Transition:



(D) Transition matrix for units A, B, and C of the "idealized" megacycle in the Fairview Formation (location Re, units 21.9 - 31.6):

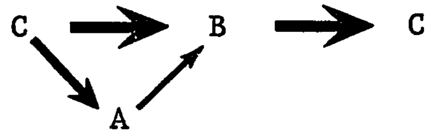
	unit A	unit B	unit C	Row Totals:
unit A	0	3	1	4
unit B	0	0	14	14
unit C	4	10	0	14
Column Totals:	4	13	15	32

0.5	1.6	1.9
1.8	5.7	6.6
1.8	5.7	6.6

-0.5	+1.4	-0.9
-1.8	-5.7	+7.4
+2.2	+4.3	-6.6

Ideal Prediction:

Dominant Transition:

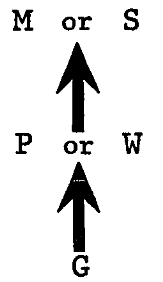


APPENDIX 10 (continued)

(E) Transition matrix for individual limestone beds in the Kope Formation (location I, units U.5 - 22.9):

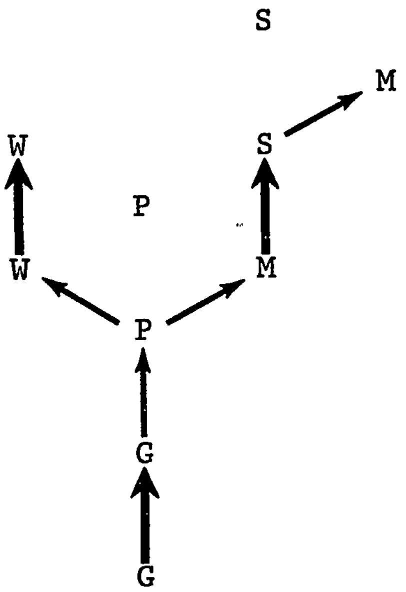
	G	P	W	M	S	Row Totals:
G	9	11	0	0	4	24
P	7	20	3	2	6	38
W	1	1	3	0	2	7
M	0	0	0	0	3	3
S	6	8	1	1	15	31
Column Totals:	23	40	7	3	30	103

Ideal Prediction:



5.4	9.3	1.6	0.7	7.0
8.5	14.8	2.6	1.1	11.1
1.6	2.7	0.5	0.2	2.0
0.7	1.2	0.2	0.1	0.9
6.9	12.0	2.1	0.9	9.0

Dominant Transitions:



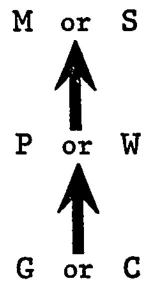
+3.6	+1.7	-1.6	-0.7	-3.0
-1.5	+5.2	+0.4	+0.9	-5.1
-0.6	-1.7	+2.5	-0.2	0
-0.7	-1.2	-0.2	-0.1	+2.1
-0.9	-4.0	-1.1	+0.1	+6.0

APPENDIX 10 (continued)

(F) Transition matrix for individual limestone beds in the Fairview Formation (location Re, units 21.9 - 31.6):

	G	P	W	C	M	S	Row Totals:
G	1	3	1	1	1	2	9
P	5	23	2	2	3	4	39
W	1	2	0	0	0	0	3
C	1	3	0	1	0	0	5
M	0	3	0	1	1	0	5
S	1	5	0	0	0	1	7
Column Totals:	9	39	3	5	5	7	68

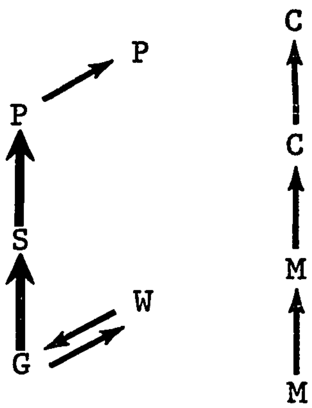
Ideal Prediction:



1.2	5.2	0.4	0.7	0.7	0.9
5.2	22.4	1.7	2.9	2.9	4.0
0.4	1.7	0.1	0.2	0.2	0.3
0.7	2.9	0.2	0.4	0.4	0.5
0.7	2.9	0.2	0.4	0.4	0.5
0.9	4.0	0.3	0.5	0.5	0.7

-0.2	-2.2	+0.6	+0.3	+0.3	+1.1
-0.2	+0.6	+0.3	-0.9	+0.1	0
+0.6	+0.3	-0.1	-0.2	-0.2	-0.3
+0.3	+0.1	-0.2	+0.6	-0.4	-0.5
-0.7	+0.1	-0.2	+0.6	+0.6	-0.5
+0.1	+1.0	-0.3	-0.5	-0.5	+0.3

Dominant Transitions:



APPENDIX 10 (continued)

(G) Transition matrix for <u>all beds</u> in the <u>Kope</u> Formation (location I, units U.5 - 22.9):

	G	P/G	P	W	M	S	Shale	Row Totals:
G	0	1	0	0	0	0	15	16
P/G	0	0	0	0	0	0	3	3
P	1	0	0	0	0	1	36	38
W	0	0	0	0	0	1	6	7
M	0	0	0	0	0	0	3	3
S	0	0	0	0	0	0	31	31
Shale	19	3	38	7	3	29	0	99
Column Totals:	20	4	38	7	3	31	94	197

1.6	0.3	3.1	0.6	0.2	2.5	7.6
0.3	0.1	0.6	0.1	0.1	0.5	1.4
3.9	0.8	7.3	1.4	0.6	6.0	18.1
0.7	0.1	1.4	0.3	0.1	1.1	3.3
0.3	0.1	0.6	0.1	0.1	0.5	1.4
3.2	0.6	6.0	1.1	0.5	4.9	14.8
10.1	2.0	19.1	3.5	1.5	15.6	47.2

-1.6	+0.7	-3.1	-0.6	-0.2	-2.5	+7.4
-0.3	-0.1	-0.6	-0.1	-0.1	-0.5	+1.6
-2.9	-0.8	-7.3	-1.4	-0.6	-5.0	+17.9
-0.7	-0.1	-1.4	-0.3	-0.1	-0.1	+2.7
-0.3	-0.1	-0.6	-0.1	-0.1	-0.5	+1.6
-3.2	-0.6	-0.6	-1.1	-0.5	-4.9	+16.2
+8.9	+1.0	+18.9	+3.5	+1.5	+13.4	-47.2

<u>Dominant Transition:</u>

Shale

↑

All carbonates

↑

Shale

APPENDIX 10 (concluded)

(H) Transition matrix for all beds in the Fairview Formation (location Re, units 21.9 - 31.6):

	G	P/G	P	W	C	M	Shale	S	Row Totals:
G	0	0	0	0	0	0	5	1	6
P/G	0	0	0	0	0	0	3	0	3
P	0	0	0	1	0	0	34	1	36
W	0	0	0	0	0	0	3	0	3
C	0	0	0	0	0	0	5	0	5
M	0	0	0	0	0	0	5	0	5
Shale	6	3	39	2	5	4	0	5	64
S	0	0	1	0	0	0	6	0	7
Column Totals:	6	3	48	3	5	4	61	7	129

0.3	0.1	2.2	0.1	0.2	0.2	2.8	0.3
0.1	0.1	1.1	0.1	0.1	0.1	1.4	0.2
1.7	0.8	13.4	0.8	1.4	1.2	17.0	2.0
0.1	0.1	1.1	0.1	0.1	0.1	1.4	0.2
0.2	0.1	1.9	0.1	0.2	0.2	2.4	0.3
0.2	0.1	1.9	0.1	0.2	0.2	2.4	0.3
3.0	1.5	23.8	1.5	2.5	2.0	30.3	3.5
0.3	0.2	2.6	0.2	0.3	0.2	0.3	0.4

-0.3	-0.1	-2.2	-0.1	-0.2	-0.2	+2.2	+0.7
-0.1	-0.1	-1.1	-0.1	-0.1	-0.1	+1.6	-0.2
-1.7	-0.8	-13.4	+0.2	-1.4	-1.2	+17.0	-1.0
-0.1	-0.1	-1.1	-0.1	-0.1	-0.1	+1.6	-0.2
-0.2	-0.1	-1.9	-0.1	-0.2	-0.2	+2.6	-0.3
-0.2	-0.1	-1.9	-0.1	-0.2	-0.2	+2.6	-0.3
+3.0	+1.5	+15.2	+0.5	+2.5	+2.0	-30.3	+1.5
-0.3	-0.2	-1.6	-0.2	-0.3	-0.2	+5.7	-0.4

Dominant Transitions: