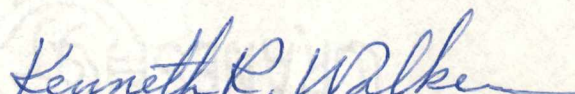
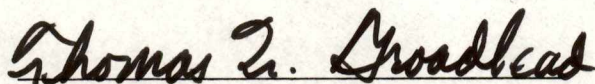


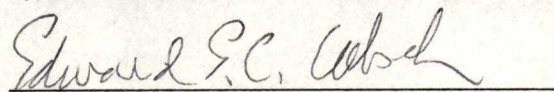
To the Graduate Council:

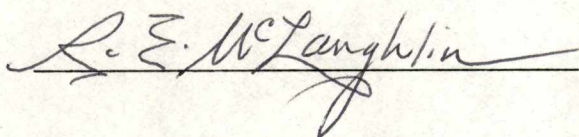
I am submitting herewith a dissertation written by Fritz Clayton Breland, Jr., entitled "Stratigraphic, Paleoenvironmental, and Echinoderm Distributional Patterns in an Unfaulted Middle Ordovician (Chickamauga Group) Shelf-Edge to On-Shelf Transect in East Tennessee." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geology.


Kenneth R. Walker, Major Professor

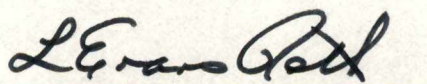
We have read this dissertation
and recommend its acceptance:







Accepted for the Council:


Vice Chancellor
Graduate Studies and Research

STRATIGRAPHIC, PALEOENVIRONMENTAL, AND ECHINODERM
DISTRIBUTIONAL PATTERNS IN AN UNFAULTED MIDDLE
ORDOVICIAN (CHICKAMAUGA GROUP) SHELF-EDGE TO
ON-SHELF TRANSECT IN EAST TENNESSEE

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Fritz Clayton Breland, Jr.

August 1980

3045021

ACKNOWLEDGEMENTS

I wish to thank my supervisor, Dr. Kenneth R. Walker, Professor and Head, Department of Geological Science, The University of Tennessee, Knoxville, who suggested this problem and advised all aspects of the study. Several of the ideas expressed in this work were developed directly or indirectly through consultation with him.

I would also like to express my appreciation to Dr. Thomas W. Broadhead, Assistant Professor of Geology, The University of Tennessee, Knoxville, who provided valuable assistance in the identification and preparation of echinoderms and for helpful criticism as a member of this dissertation committee. My sincere thanks go to Dr. R. E. McLaughlin, Professor of Geology and Dr. E. C. Clebsch, Professor of Botany/Ecology, both of The University of Tennessee, Knoxville, as members of this committee and for their many thoughtful suggestions during the preparation of the manuscript. Also, I wish to thank Dr. Garrett Briggs, Associate Dean of Liberal Arts, The University of Tennessee, Knoxville, who served for a time on the dissertation committee, for his encouragement and friendly advice during the course of my graduate study.

This research has been supported, in part, by National Science Foundation Grants (EAR 76-11808) to Walker and (EAR 79-27268) to Walker and Broadhead and by a grant to me from Sigma Xi. Additional support was provided to me by a Gulf Oil Foundation Graduate Fellowship.

ABSTRACT

Previous workers studying Middle Ordovician carbonate sequences in East Tennessee have attempted to study changes in lithotypes and faunas across regional strike (northeast-southwest), however, regional thrust faulting has masked many important depositional features and boundaries. In the study area, the carbonate rocks are fortuitously oriented in such a manner as to reveal lithofacies characteristic of carbonate shelf-edge and shelf environments. These lithofacies grade laterally in an unfaulted sequence from near shelf-edge lithotypes in the northeast to on-shelf "lagoon" environments to the southwest along strike. The major importance of the area is that it is possible, for the first time, to analyze the lithofacies and biofacies transitions which take place across the ancient shelf-edge onto the "shelf-lagoon" environments without having the facies patterns developed by these environments dissected by regional thrust faulting.

Detailed field studies of four measured sections (measured from the Knox unconformity to the base of the Moccasin Formation averaging 450 meters per section) and examination of 426 thin sections and more than 400 polished slabs and acetate peels reveal the complex nature of the faunal and lithofacies relationships in the Chickamauga Group. The Chickamauga Group is subdivided, in the study area, into 12 formations: Five Oaks, Tumbez, Fleanor, Lincolnshire, Rockdell, Chapman Ridge, Ottosee, Benbolt, Wardell, Bowen, Witten and Moccasin. These units are listed in stratigraphically ascending order although there are many complex lateral interfingering relationships. These formation names are applied to carbonate shelf, shallow water environments, with the

exception of the Chapman Ridge and Ottosee Formations, and represent a generally transgressive sequence. Determination of the time relationships of these units is based on environmental considerations, interfingering relationships and progradational cycles.

The line of measured stratigraphic sections oriented parallel to the regional southwest-northeast strike is interpreted to represent a transect across a portion of the Middle Ordovician shelf from near the shelf-edge in the northeast to the inner shelf in the southwestern portion of the study area. The complex lithofacies relationships observed in the shelf sediments are best summarized as lower, middle or upper stratigraphic packages. The lower stratigraphic package is composed of the Five Oaks, Tumbez, Fleanor and Lincolnshire Formations and was deposited in peritidal to shallow marine environments. This lower package is strongly influenced by the relief on the underlying post-Knox unconformity. The middle stratigraphic package consists of the Rockdell Formation which represents a generally transgressive sequence of near shelf margin and on-shelf patch reef environments. The lithofacies and biofacies transitions which take place near the shelf-edge and shelfward in this particular line of sections in the study area are well exemplified by the lateral facies changes within the Rockdell Formation. The upper stratigraphic package is dominated by carbonate rocks representing shallow marine (restricted lagoon) and peritidal environments of the Chapman Ridge, Ottosee, Wardell, Benbolt, Bowen and Witten Formations.

Bryozoan-red algal bound patch reefs observed in the study area have provided a means for recognizing and distinguishing on-shelf from shelf-edge carbonate buildups. The encrusting red alga, Solenopora sp.,

associated with these patch reefs was found to assume a morphology and a role in the build-up process that had previously not been observed in the Middle Ordovician carbonates of East Tennessee. It formed thin undulose layers and, along with encrusting bryozoans, bound muds of the reef core. Previously, Solenopora sp. was only known to be associated with shallow water lagoonal facies in the Middle Ordovician sequence (Moore, 1978).

Comparison of on-shelf patch reefs of the Rockdell Formation with the shelf-edge Holston reef complex has revealed some similarities in diagnostic lithofacies (e.g., reef flank and core), composition of reef flank material and mode of cementation and cement paragenesis. The major differences observed are in the size and geometry of the reefs and their organic composition. The Rockdell patch reefs are small in areal extent and circular whereas the Holston reef complex is large in areal extent with a linear geometry coincident with the shelf-edge. The binding and framework components of the Rockdell patch reefs are characterized by encrusting bryozoans and red algae in contrast to the bryozoans of the shelf-edge Holston reef complex.

Investigation of the different types of cements in the Rockdell patch reefs revealed a definite paragenetic sequence of cementation and internal sedimentation from which the diagenetic history of the patch reefs could be determined. The sequence of cementation was initiated by a low-iron content, radial fibrous marine cement which was generally followed by vadose silt and pendant cement. Primary and secondary pore space and cavities were finally filled with a late stage, high-iron content, blocky calcite cement. Initial partial cementation of sediments took place in the marine environment penecontemporaneously with

sedimentation in the patch reef. The patch reef sediments were subsequently subaerially exposed for a period of time during which dissolution, reprecipitation and internal sedimentation took place in a vadose diagenetic environment. Following a period of subaerial exposure, the remaining primary porosity and the secondary porosity produced in the vadose diagenetic environment were sealed by cementation in a fresh water phreatic diagenetic environment.

Documentation of the occurrence and stratigraphic distribution of echinoderms in the paleoenvironments of the study area has shown that echinoderms are abundant and relatively diverse (i.e., Crinoidea, Rhombifera, Paracrinoidea, Parablastoidea, Edrioasteroidea, Edrioblastoidea and Eocrinoidea). Echinoderms played a significant sedimentological role as major sediment producers and, as trappers and binders of sediment, were capable of modifying the environment by influencing local hydrodynamic conditions.

Much of the prior information on Middle Ordovician echinoderms from East Tennessee has come from the Benbolt Formation and from the Hogskin Member of the Lincolnshire Formation. A diverse assemblage of echinoderms collected from the Rockdell Formation in the present study contributes significantly to the informational gap between the Lincolnshire and Benbolt Formations and suggests that formational names assigned to many echinoderm specimens in the region may be in error. The study indicates that the parablastoid Meristoschisma hudsoni Sprinkle does not occur below the Benbolt and coeval units.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
General Background	1
Area of Study and Its Significance	2
Purpose and Limitations of the Study	5
Methods of Investigation	7
Format of the Dissertation	8
II. STRATIGRAPHY, CARBONATE PETROLOGY AND PALEODEPOSITIONAL ENVIRONMENTS OF A NEAR SHELF MARGIN TO ON-SHELF TRANSECT IN EAST TENNESSEE	9
Introduction	9
Methods of Study	13
Stratigraphy	13
Stratigraphic Nomenclature	13
Stratigraphic Framework	16
Carbonate Petrology and Paleodepositional Environments . .	18
Lower Stratigraphic Package—Peritidal to Shallow	
Marine Environments	19
Post Knox Unconformity	19
Five Oaks Formation	35
Tumbez Formation	37
Fleanor Formation	38
Lincolnshire Formation	41
Summary	44
Middle Stratigraphic Package—Near Shelf Margin and On-Shelf Patch Reef Environments	45
Rockdell Formation	47
Summary	58
Upper Stratigraphic Package—Shallow Marine (Restricted Lagoon) and Peritidal Environments	59
Chapman Ridge Formation	59
Ottosee Formation	63
Benbolt Formation	66
Wardell Formation	70
Bowen Formation	76
Witten Formation	77
Moccasin Formation	83
Summary	83
Summary and Conclusions	85
III. RED ALGAL BOUND PATCH REEF IN THE ON-SHELF ROCKDELL FORMATION, EAST TENNESSEE: COMPARISON WITH THE DOWN- SLOPE SHELF-EDGE HOLSTON FORMATION REEF COMPLEX, CEMENT PARAGENESIS AND DIAGENETIC HISTORY	86
Introduction	86
Red Algal Bound Patch Reef in the Lower Rockdell Formation	89

CHAPTER

PAGE

Comparison of On-Shelf Patch Reef of the Rockdell Formation and the Shelf Margin Reef Complex of the Holston Formation	99
Cement Paragenesis and Diagenetic History	105
Summary	114
IV. OCCURRENCE AND STRATIGRAPHIC DISTRIBUTION OF ECHINODERMS IN MIDDLE ORDOVICIAN INNER SHELF TO NEAR SHELF-EDGE ENVIRONMENTS IN EAST TENNESSEE	116
Introduction	116
Stratigraphic Framework	118
Occurrence and Stratigraphic Distribution of Echinoderms	119
Five Oaks Formation	123
Tumbez Formation	123
Fleanor Formation	123
Lincolnshire Formation	124
Rockdell Formation	124
Chapman Ridge Formation	128
Ottosee Formation	130
Benbolt Formation	130
Wardell Formation	132
Bowen Formation	134
Witten Formation	134
Summary	135
V. SUMMARY AND CONCLUSIONS	138
LITERATURE CITED	143
APPENDICES	153
A. DESCRIPTIONS OF STRATIGRAPHIC SECTIONS	154
B. PETROGRAPHIC CONSTITUENT ANALYSES	179
C. PETROGRAPHIC CONSTITUENT ANALYSIS OF THE PATCH REEF AT THE HARBISON LOCALITY	200
D. INSTRUMENT AND PHOTOGRAPHIC PARAMETERS USED IN CATHODOLUMINESCENCE STUDY	203
E. ECHINODERM PLATES WITH EXPLANATIONS	205
VITA	217

LIST OF TABLES

TABLE	PAGE
3.1. Summary of the characteristic properties of the Rockdell patch reefs and the Holston reef complex	106
4.1. Occurrence and stratigraphic distribution of echinoderms at the Dry Gap (DG), Halls Crossroads (HC), Harbison (HR) and Graveston (GA) localities	120
B-1. Constituent particle analysis (rock volume percent) for selected thin sections (DG1A-DG9A) at the Dry Gap stratigraphic section	181
B-2. Constituent particle analysis (rock volume percent) for selected thin sections (DG9C-DG14C) at the Dry Gap stratigraphic section	182
B-3. Constituent particle analysis (rock volume percent) for selected thin sections (DG15A-DG17C) at the Dry Gap stratigraphic section	183
B-4. Constituent particle analysis (rock volume percent) for selected thin sections (HC1A-HC3E) at the Halls Crossroads stratigraphic section	184
B-5. Constituent particle analysis (rock volume percent) for selected thin sections (HC4B-HC8A) at the Halls Crossroads stratigraphic section	185
B-6. Constituent particle analysis (rock volume percent) for selected thin sections (HC8C-HC13A) at the Halls Crossroads stratigraphic section	186
B-7. Constituent particle analysis (rock volume percent) for selected thin sections (HC13C-HC15E) at the Halls Crossroads stratigraphic section	187
B-8. Constituent particle analysis (rock volume percent) for selected thin sections (HC16B-HC21D) at the Halls Crossroads stratigraphic section	188
B-9. Constituent particle analysis (rock volume percent) for selected thin sections (HR1A-HR6E) at the Harbison stratigraphic section	189
B-10. Constituent particle analysis (rock volume percent) for selected thin sections (HR6G-HR9C) at the Harbison stratigraphic section	190

TABLE	PAGE
B-11. Constituent particle analysis (rock volume percent) for selected thin sections (HR9D-HR13A) at the Harbison stratigraphic section	191
B-12. Constituent particle analysis (rock volume percent) for selected thin sections (HR13C-HR17D) at the Harbison stratigraphic section	192
B-13. Constituent particle analysis (rock volume percent) for selected thin sections (HR17F-HR20B) at the Harbison stratigraphic section	193
B-14. Constituent particle analysis (rock volume percent) for selected thin sections (HR20C-HR21D) at the Harbison stratigraphic section	194
B-15. Constituent particle analysis (rock volume percent) for selected thin sections (GA1A-GA9A) at the Gravelston stratigraphic section	195
B-16. Constituent particle analysis (rock volume percent) for selected thin sections (GA11B-GA18B) at the Gravelston stratigraphic section	196
B-17. Constituent particle analysis (rock volume percent) for selected thin sections (GA19C-GA26C) at the Gravelston stratigraphic section	197
B-18. Constituent particle analysis (rock volume percent) for selected thin sections (GA27A-GA34D) at the Gravelston stratigraphic section	198
B-19. Constituent particle analysis (rock volume percent) for selected thin sections (GA34E-GA35B) at the Gravelston stratigraphic section	199
C-1. Constituent particle analysis (rock volume percent) for selected thin sections from the patch reef at Harbison (HR)	202

LIST OF FIGURES

FIGURE		PAGE
1.1.	Areal distribution of Middle Ordovician rocks in East Tennessee and the location of works completed in this area	3
1.2.	Area of study showing the locations of measured sections . .	4
1.3.	Generalized position of the shelf-edge and its relation to major faults in East Tennessee and to measured sections in the study area	6
2.1.	Reconstruction of regional facies patterns across a portion of the Middle Ordovician shelf, shelf margin and deep basin in East Tennessee	11
2.2.	Historical development of stratigraphic nomenclature used by workers in the Southern Appalachians	15
2.3.	Stratigraphic framework for a portion of the Middle Ordovician shelf in East Tennessee	17
2.4.	Stratigraphic distribution of nonfossil allochems in the measured section at Dry Gap, Tennessee	20
2.5.	Stratigraphic distribution of fossil allochems in the measured section at Dry Gap, Tennessee	21
2.6.	Stratigraphic occurrence of algae in the measured section at Dry Gap, Tennessee	22
2.7.	Stratigraphic distribution of nonfossil allochems in the measured section at Halls Crossroads, Tennessee	23
2.8.	Stratigraphic distribution of fossil allochems in the measured section at Halls Crossroads, Tennessee	24
2.9.	Stratigraphic occurrence of algae in the measured section at Halls Crossroads, Tennessee	25
2.10.	Stratigraphic distribution of nonfossil allochems in the measured section at Harbison, Tennessee	26
2.11.	Stratigraphic distribution of fossil allochems in the measured section at Harbison, Tennessee	27
2.12.	Stratigraphic occurrence of algae in the measured section at Harbison, Tennessee	28

FIGURE	PAGE
2.13. Stratigraphic distribution of nonfossil allochems in the measured section at Gravelston, Tennessee	29
2.14. Stratigraphic distribution of fossil allochems in the measured section at Gravelston, Tennessee	30
2.15. Stratigraphic occurrence of algae in the measured section at Gravelston, Tennessee	31
2.16. Lower stratigraphic package representing peritidal to shallow marine environments	32
2.17. Petrographic features of the Five Oaks and Tumbez Formations	33
2.18. Petrographic features of the Fleanor and Lincolnshire Formations	39
2.19. Middle stratigraphic package representing near shelf margin and on-shelf patch reef environments	48
2.20. Petrographic features of the Rockdell Formation	49
2.21. Petrographic features of the Rockdell and Chapman Ridge Formations	53
2.22. Upper stratigraphic package representing shallow marine (restricted lagoon) and peritidal environments	60
2.23. Petrographic features of the Ottosee and Benbolt Formations	64
2.24. Petrographic features of the Wardell and Bowen Formations	71
2.25. Petrographic features of the Witten Formation	78
3.1. Photomosaic of the bryozoan-algal bound patch reef deposits in the lower Rockdell Formation at the Harbison section . .	90
3.2. Petrographic features of the patch reef deposits in the lower Rockdell Formation	92
3.3. Petrographic features of the patch reefs and cements in the lower Rockdell Formation	96
3.4. Sketch of the patch reef in the lower Rockdell at the Harbison section showing the location and composition of samples from the two reef facies	102

FIGURE	PAGE
3.5. Sketch of small reef in the Holston along Alcoa Highway showing location and composition of samples from the two reef facies	103
3.6. Petrographic features observed in selected thin sections from the patch reef deposits in the lower Rockdell Formation as revealed under plane light and cathodoluminescence	108
3.7. Sequence of the stages of sedimentation, cementation and diagenetic alteration in the patch reef sediments	113
4.1. Occurrence and distribution of echinoderms in relation to the environmental and stratigraphic framework of the study area	136

LIST OF PLATES

PLATE	PAGE
E-1. Crinoidea Camerata	207
E-2. Crinoidea Inadunata	209
E-3. Crinoidea, Rhombifera, Edrioasteroidea, Edrioblastoidea and Eocrinoidea	211
E-4. Paracrinoidea and Parablastoidea	213
E-5. Columnals and holdfasts	215

CHAPTER I

INTRODUCTION

General Background

Exposures of Middle Ordovician rocks in the Southern Appalachians exhibit a complex mosaic of interfingering carbonate and terrigenous clastic facies. These rocks are exposed in a series of strike belts which have a regional northeast-southwest trend. Previous workers have attempted to correlate these lithofacies along strike and from one strike belt to the next using lithostratigraphic and biostratigraphic methods. Difficulties in solving lithostratigraphic problems have centered around the fact that many early workers viewed the lithofacies of the Southern Appalachian region as discrete formational units separated by disconformities rather than as complex interrelated facies subject to local environmental controls. Often times, workers based their biostratigraphic correlations upon a single taxon without apparent regard for the possibility that the taxon might be facies controlled. McLaughlin (1973) has pointed out some of the major limitations of this treatment of stratigraphy.

More recently, K. R. Walker and other workers at The University of Tennessee, Knoxville, have been involved in a program to re-evaluate the Middle Ordovician strata of East Tennessee using modern stratigraphic concepts and techniques. In 1973, Walker and Alberstadt proposed a paleoenvironmental model for the Middle Ordovician which has been continuously updated as new data have become available (Walker, 1977a).

This model has provided a framework around which the program of study has been coordinated and since its inception, numerous theses, reports, and papers have dealt with different aspects of the ecostratigraphy of these rocks. These studies have permitted considerable refinement of the model rather than substantially changing it.

The initial phases of the investigation (Figure 1.1) carried on by Walker and his coworkers concentrated on understanding the complex facies relationships in strike belts southeast of the Saltville Fault (Ferrigno, 1973; LaFollette, 1974; LeRoux, 1974; Shanmugam, 1978; Sitterly, 1976; Stephenson, 1973; McWilliams, 1975). More recently, others (Ratliff, 1974; Ruppel, 1979; Sickafoose, 1979) have examined in detail the shallow water shelf lithofacies observed in strike belts northwest of the Saltville Fault. The present study was undertaken in order to examine the ecostratigraphic character of similar shallow water shelf-type sediments but in an unfaulted sequence located in one of the northwest strike belts.

Area of Study and Its Significance

The study concentrates on carbonate rocks of the lower and middle Chickamauga Group (Rodgers, 1953) exposed along the strike belt in Beaver Valley and extending from Interstate Highway I-75 at the southwest of the study area approximately 15 miles northeast along strike to the town of Condon, Union County, Tennessee (Figure 1.2). This strike belt is bounded on the northwest by the Copper Creek Fault and on the southeast by the Beaver Valley Fault.

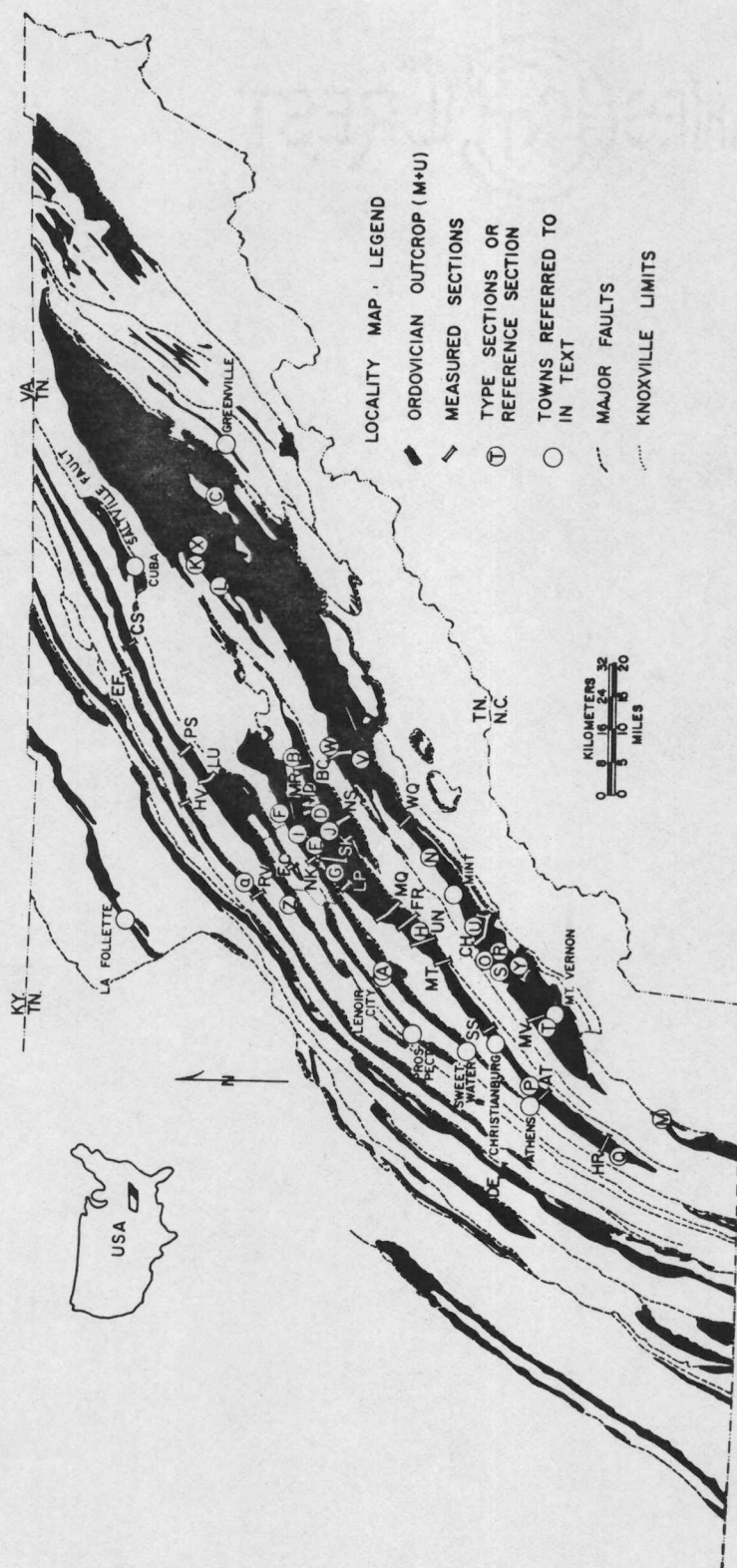


Figure 1.1. Areal distribution of Middle Ordovician rocks in East Tennessee and the location of works completed in this area. (Walker, 1977a)

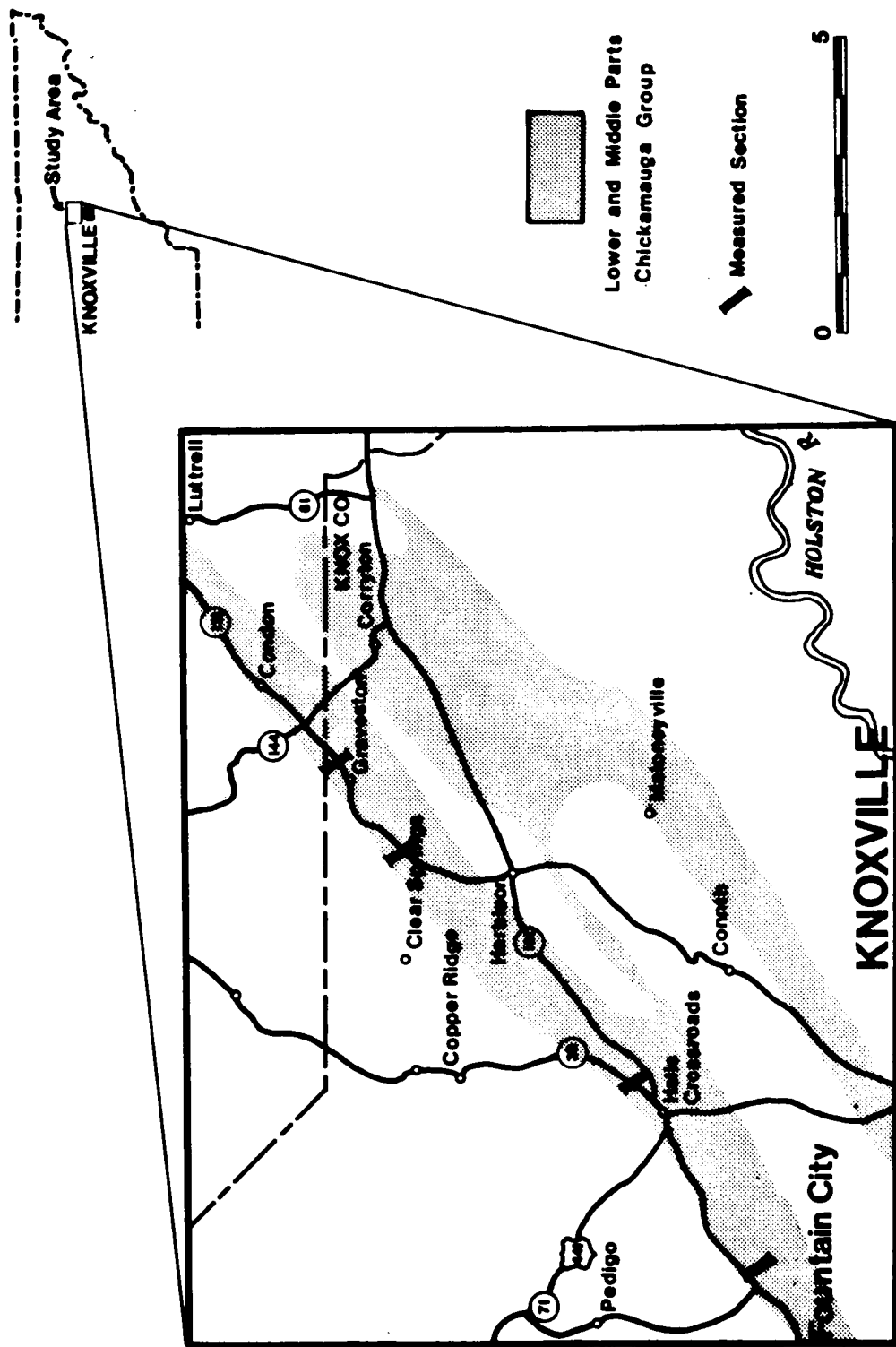


Figure 1.2. Area of study showing the location of measured sections.

In the study area the Middle Ordovician shelf-edge assumes an odd shape (Figure 1.3) because the shelf-edge deviates abruptly from its general northeast-southwest orientation to a position roughly normal to it. Thus, the shelf-edge boundary is oriented roughly northwest-southeast rather than paralleling the regional thrust faults as it does in other parts of the region. The area is therefore unique with respect to the investigation of Middle Ordovician carbonate environments in East Tennessee because analysis of these carbonate sequences in the study area affords, for the first time, an opportunity to examine the lithologic and paleontologic transitions from the near shelf-edge onto the shelf-lagoon environments without having the lithofacies patterns developed by these environments dissected by regional thrust faulting.

Purpose and Limitations of the Study

Although Walker and his colleagues have collected much valuable information contributing toward better understanding of the development and distribution of carbonate sequences in East Tennessee, many areas remain which need to be studied in much greater detail. The structural setting of the present study area makes it important for understanding several aspects of the sequence.

The purpose of this investigation is multifold:

1. Investigate in detail the shelf and near shelf-edge lithofacies.
2. Develop a working stratigraphic and environmental framework.
3. Determine the exact nature of the paleoenvironments.
4. Resolve, in general, the relationship of the biota to litho-type and environment.

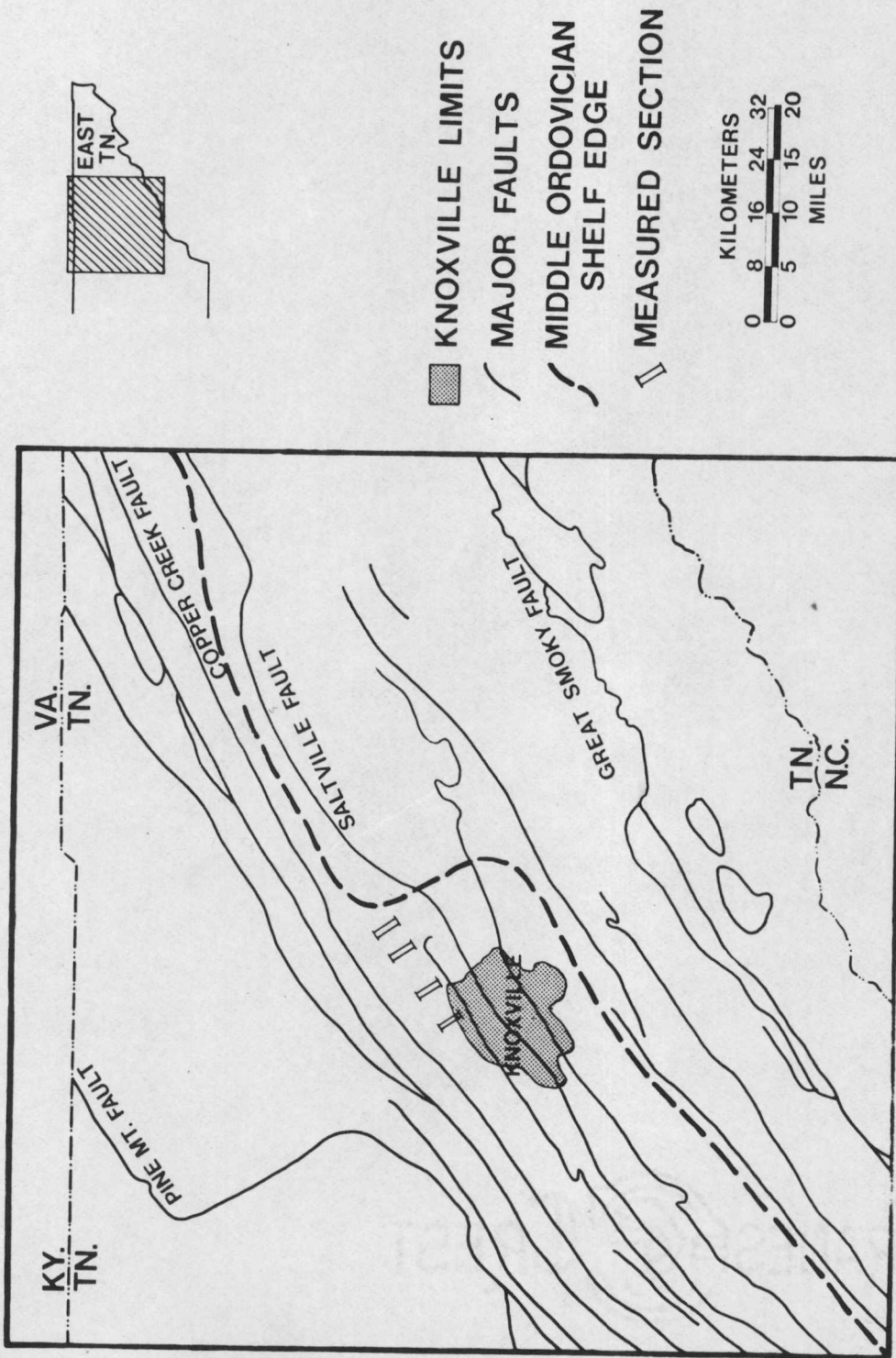


Figure 1.3. Generalized position of the shelf-edge and its relation to major faults in East Tennessee and to measured sections in the study area.

Position of the shelf-edge was determined by previous workers (e.g., Ratliff, 1974; Ruppel, 1979; Walker and Ferrigno, 1973; and others) and is represented here with displacement due to thrust faulting removed and on a nonpalinspastic base.

5. Study in detail the occurrence and distribution of echinoderms.

6. Test a portion of the regional working model first proposed by Walker and Alberstadt (1973), and updated by Walker (1977a).

Two major limitations to this study must be recognized. The first is imposed by the poorly exposed nature of the Middle Ordovician section in the area of study. The second limitation is that the area is not particularly suited to a detailed examination of the echinoderms also in part a consequence of poor exposures and in part due to the fortuitous circumstances required for high-quality preservation of echinoderms. As a general rule, echinoderms disarticulate upon death which places constraints upon the detailed systematic description of these organisms.

Methods of Investigation

The initial stage of the investigation consisted of detailed field examination and description of four stratigraphic sections (Figure 1.2 and Appendix A). Each measured section is approximately 450 meters in thickness and is bounded by the uncomfortable contact with the Lower Ordovician Knox Group at the base and the conformable contact with the upper Middle Ordovician Moccasin Formation at the top.

Bulk samples were collected at sites of particular interest or where there was a change in lithotype. Paleoenvironmental interpretation was based upon close examination of field descriptions of measured sections and laboratory analysis of approximately 450 thin sections and numerous polished slabs and acetate peels.

In an effort to better understand cement composition and paragenesis, nearly all thin sections were stained with Alizarin red-S

(modified from Friedman, 1959), and approximately 150 thin sections were stained with potassium ferricyanide (modified from Lindholm and Finkelman, 1972). Cathodoluminescence techniques were also applied to the determination of cement morphology and paragenesis.

Constituent particle analysis (Appendix B) of approximately 200 selected thin sections was undertaken by point count technique (modified from Chayes, 1954). These data were then plotted on diagrams designed to show the varying abundance of the constituents in relation to their stratigraphic position of both vertically and laterally. This method helps to illustrate the relationship of the constituent particles to the changing environmental patterns vertically through the measured sections and horizontally from one measured section to the next.

Study of the occurrence and distribution of echinoderms consisted of collecting rock slabs and individual specimens. Because of disarticulation and otherwise poor preservation of many of the echinoderms, classification of many specimens could not be extended below the familial or ordinal levels.

Format of the Dissertation

In keeping with the policies of the Department of Geological Sciences at The University of Tennessee, Knoxville, each chapter in this work has been prepared as a separate entity, each containing enough background information to be submitted for publication in a scientific journal. As a consequence, there is necessarily some overlap in information presented in the following chapters.

CHAPTER II

STRATIGRAPHY, CARBONATE PETROLOGY AND PALEODEPOSITIONAL ENVIRONMENTS OF A NEAR SHELF MARGIN TO ON-SHELF TRANSECT IN EAST TENNESSEE

Introduction

Exposure of Middle Ordovician rocks in the Southern Appalachians exhibit a complex mosaic of interfingering carbonate and terrigenous clastic facies. These rocks are exposed in a system of fault-bounded strike belts which have a regional northeast-southwest trend. The stratigraphy of these Middle Ordovician rocks has been studied for over 100 years and has stimulated considerable controversy (Rodgers, 1953). Much of the controversy has resulted from attempts by previous workers to correlate lithofacies along strike and from one strike belt to the next using lithostratigraphic and biostratigraphic methods. Difficulties in solving lithostratigraphic and biostratigraphic problems have centered around the fact that many early workers viewed the lithofacies of the Southern Appalachian region as discrete formational units separated by disconformities rather than as complex interrelated facies subject to local environmental conditions. Frequently, workers based biostratigraphic correlations upon a single taxon without apparent regard for the possibility that occurrence of the taxon might be facies controlled. McLaughlin (1973) has pointed out some of the major limitations of the treatment of stratigraphy.

More recently, K. R. Walker and other workers at The University of Tennessee, Knoxville, have been involved in a program to re-evaluate the stratigraphy and paleoenvironments of Middle Ordovician strata in East Tennessee using modern stratigraphic concepts and techniques. Walker and Alberstadt (1973) proposed a paleoenvironmental model for the Middle Ordovician which has been continuously updated as new data have become available (Walker, 1977a), and has provided a framework within which this program of study has been conducted. The program has concentrated on studying the stratigraphy of the region in terms of its depositional environments, permitting reconstruction of regional facies patterns for portions of the Middle Ordovician in East Tennessee (Figure 2.1). Facies patterns observed on a regional scale support this model in general and suggest that Middle Ordovician paleoenvironments were generally analogous to the environmental settings of South Florida today. One result of more recent research has been the recognition that in much of the region the boundaries between major environmental complexes (such as that between shelf and basin) commonly parallel the trend of the thrust-bounded strike belts. Not recognizing such boundaries, earlier workers encountered difficulties in correlating lithofacies and biofacies across the faults (Walker, Shanmugam and Ruppel, 1980). The location of the present study area is unique in this respect as is discussed below.

Initial investigations undertaken by Walker and his coworkers concentrated on examining the complex facies relationships of the shelf-edge, slope and deep basin sediments in strike belts southeast of the Saltville Fault (Ferrigno, 1973; LaFollette, 1974; LeRoux, 1974; Shanmugam, 1978; Sitterly, 1976; Stephenson, 1973; McWilliams, 1975). More

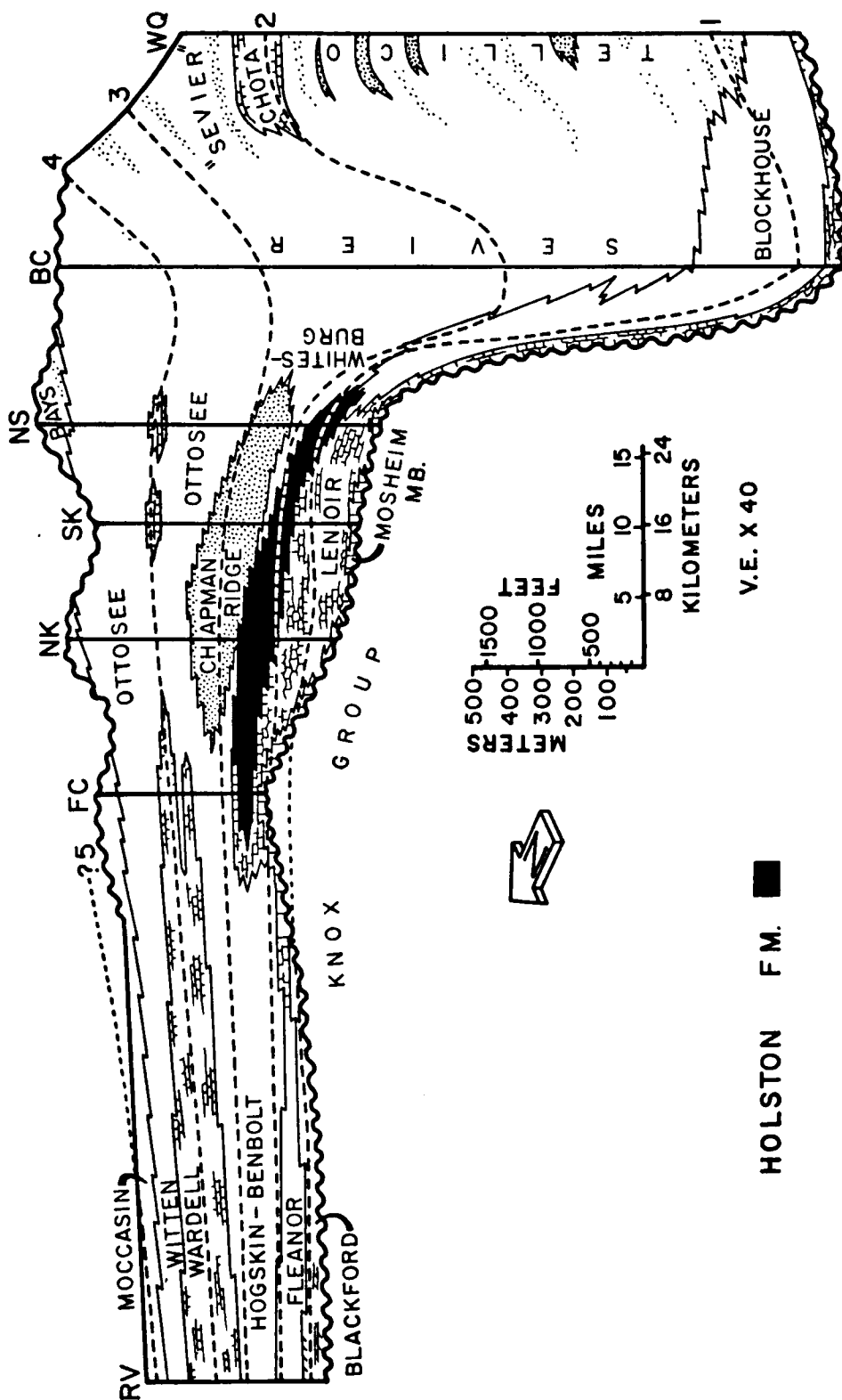


Figure 2.1. Reconstruction of regional facies patterns across a portion of the Middle Ordovician shelf, shelf margin and deep basin in East Tennessee.

Cross section is from Raccoon Valley (RV) through Fountain City (FC) and North Knoxville (NK) to Wildwood Quadrangle (WQ) (see Figure 1.1, page 3, for locations). Lines 1-5 are time lines based on lithostratigraphic, ecostratigraphic and biostratigraphic evidence (from Walker, 1977a).

recently workers (Ratliff, 1974; Ruppel, 1979; and Sickafoose, 1979) have examined in detail the shallow water shelf lithofacies observed in strike belts northwest of the Saltville Fault. This paper attempts to reveal the ecostratigraphic character of similar shallow water shelf-type sediments but in an unfaulted sequence located in one of the northwest strike belts.

The study focuses on carbonate rocks of the lower and middle Chickamauga Group (Rodgers, 1953) exposed along the strike belt at Beaver Valley from Interstate Highway I-75 at the southwest approximately 15 miles northeast along strike to the town of Condon, Union County, Tennessee (Figure 1.2, page 4). The strike belt is bounded to the northeast by the Copper Creek Fault and to the southeast by the Beaver Valley Fault.

The significance of the study area is related to the odd shape of the Middle Ordovician shelf-edge in the area of study (Figure 1.3, page 6) where it deviates abruptly from the general northeast-southwest orientation to a roughly southeast-northwest trend. In this area, then, this important environmental boundary is normal to the thrust faults rather than paralleling them as it does in other parts of the region. The area is unique with respect to the investigation of Ordovician carbonate environments in East Tennessee because it affords, for the first time, an opportunity to examine the lithologic and paleontologic transitions across the shelf-edge onto the shelf-lagoon environments without dissection of lithofacies and biofacies patterns by regional thrust faulting.

Methods of Study

The initial stage of the investigation consisted of detailed field descriptions of four stratigraphic sections (Figure 1.2, page 4, and Appendix A). Each measured section is approximately 450 meters thick and is bounded by the unconformable contact with the Lower Ordovician Knox Group at the base and the conformable contact with the upper Middle Ordovician Moccasin Formation at the top.

Bulk samples were collected at sites of particular interest or where there was a change in lithotype. Inference of the paleoenvironments was accomplished by close examination of field descriptions of measured sections and laboratory analysis of approximately 450 two by three petrographic thin sections, 150 acetate peels and 400 polished slabs. Constituent particle analyses (see Appendix B) of approximately 200 selected thin sections was undertaken by point count technique (modified from Chayes, 1954) to determine volume percentages of constituents.

Stratigraphy

Stratigraphic Nomenclature

The complex facies pattern of the Middle Ordovician sequence in East Tennessee is relatively well exposed but previous study has produced little agreement on the stratigraphy of these rocks. Hayes (1891) first defined the Chickamauga Limestone from exposures of bluish limestone along West Chickamauga Creek in Catoosa and Walker Counties, Georgia and Hamilton County, Tennessee. As originally defined, the Chickamauga included all strata between the underlying Knox Dolomite Group and the overlying Rockdell Formation (Hayes, 1894). Subsequent

work on the Chickamauga (Butts, 1940; Cooper, 1956; Cooper and Prouty, 1943; Prouty, 1946; Rodgers, 1953) resulted in the subdivision and correlation of units in Tennessee, Virginia and Alabama. Attempts to define and correlate these rocks have been based on lithologic evidence (Rodgers, 1953), paleontologic criteria (Cooper, 1956), or on a combination of both lithology and paleontology (Prouty, 1946). Figure 2.2 illustrates the chronological development of several schemes of stratigraphic nomenclature used by workers in this region.

These different schemes of nomenclature were developed in widely separated areas and presentation in Figure 2.2 is not meant to indicate equivalence. Each column in Figure 2.2 was developed primarily by studies in a single or few adjacent fault blocks. No two columns refer to exactly the same parts of the regional facies pattern because early workers lacked full knowledge of the different parts of the overall environmental pattern to which they were applying terms. For example, Cooper and Prouty (1943) developed their nomenclature while working on the stratigraphy of rocks now recognized as shallow water, shelf carbonates in Southwest Virginia and later attempted to correlate these units with assumed equivalent units in East Tennessee (Cooper, 1956; Prouty, 1946). In contrast, Cattermole (1958), working south of Knoxville, applied terms (some originally defined by Ulrich, 1911) to stratigraphic sequences representing shelf-edge and basin deposits. Since this paper is concerned primarily with the study of sediments deposited in shelf environments, it seems appropriate to utilize, with some modification, the stratigraphic terminology employed by Prouty (1946) and Cooper (1956) where comparative facies were encountered. Similarly, the terminology of Cattermole (1958) was used for shelf-edge facies.

Campbell 1894 Keith 1896 1901	Ulrich 1911	Prouty 1946	Rodgers 1953	Cooper 1956	Cattermole 1958	McLaughlin 1973	This Paper	
CHICKAMAUGA LIMESTONE	MOCCASIN	MOCCASIN	MOCCASIN	MOCCASIN	BAYS	ZONE IV	MOCCASIN	
	LOWVILLE	WITTEN		WITTEN	OTTOSEE		WITTEN	
	OTTOSEE	BOWEN	CHICKAMAUGA LS. UNIT 2	BOWEN			BOWEN	
		WARDELL		WARDELL	CHAPMAN RIDGE	ZONE III	WARDELL	
	HOLSTON	BENBOLT		BENBOLT			BENBOLT	
		THOMPSON VALLEY		ROCKDELL	HOLSTON	ZONE II	ROCKDELL	
				HOGSKIN				
	LENOIR MOSHEIM	LINCOLNSHIRE	CHICKAMAUGA LIMESTONE UNIT 1	EIDSON	FLEANOR	ZONE I	FLEANOR- LINCOLNSHIRE	
				ELWAY				
		FIVE OAKS- BLACKFORD	LOWER	TUMBEZ	LENOIR MOSHEIM		FIVE OAKS TUMBEZ	

Figure 2.2. Historical development of stratigraphic nomenclature used by workers in the Southern Appalachians.

It should be noted that each column was developed primarily by studies in a single or a few adjacent fault blocks and no two columns refer to exactly the same parts of the facies pattern.

Stratigraphic Framework

The initial objective of this treatise was to construct, from measured stratigraphic sections, an operable stratigraphic framework within which the other phases of the investigation might proceed. Four stratigraphic sections were measured in detail along strike: Dry Gap (DG), Halls Crossroads (HC), Harbison (HR) and Graveston (GA) (see Figure 1.2, page 4). The lower and middle Chickamauga Group were subdivided into 11 formations (Figure 2.3): Five Oaks, Tumbez, Fleanor, Lincolnshire, Rockdell, Chapman Ridge, Ottosee, Benbolt, Wardell, Bowen and Witten. These units are listed in stratigraphically ascending order although there are many complex lateral interfingering relationships. The formation names are terms which have been shown in recent research (Walker, 1977a) to generally apply to deposits formed in carbonate shelf, shallow water environments (with the exception of the Chapman Ridge and Ottosee Formations) and represent a broadly transgressive sequence. Determination of the physical stratigraphy of the units is based on environmental considerations, interfingering relationships and progradational cycles.

The Bowen Formation, as used in the framework stratigraphy, is an excellent example of the use of interfingering relationships and progradational cycles. The Bowen, which separates the Wardell and Witten Formations is a distinctive unit of thin bedded, fine grained, red mudstones which has a limited fauna and commonly contains mudcracks and vertical burrows. The Bowen was first named by Cooper and Prouty (1943) from Tazewell County, Virginia, and according to Read (1978) represents, in Virginia, a rapidly prograding deltaic lobe derived from the east.

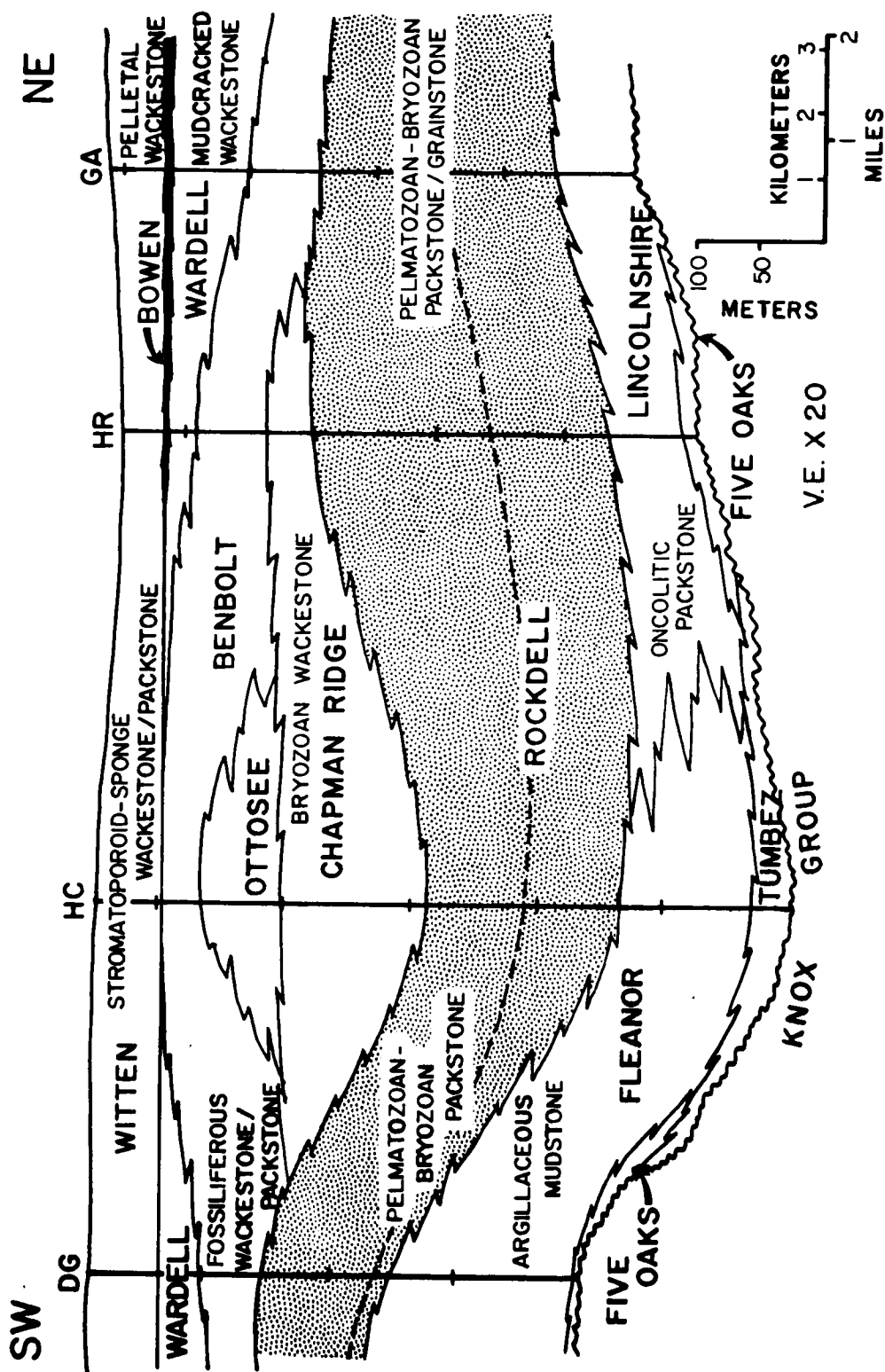


Figure 2.3. Stratigraphic framework for a portion of the Middle Ordovician shelf in East Tennessee.

Line of sections are located between Fountain City, Tennessee, to the southwest and Condon, Tennessee, to the northeast and oriented parallel to regional strike (but normal to the Middle Ordovician shelf-edge). The Bowen Formation is used as stratigraphic datum. Dashed line in the Rockdell, used as a time line, represents a thin unit of poorly developed oolite interpreted to have been deposited across the shelf in a brief period of time, perhaps by storm activity.

Evidence in East Tennessee suggests that the terrigenous sediments of the Bowen were derived from a northeast source (Walker, personal communication, 1980). Ruppel (1979) has observed similar lithofacies of the Bowen in East Tennessee and supports Read's interpretation. However, the Bowen is restricted to the northeastern part of the present study area and probably represents a brief period of regression in a generally transgressive sequence. In light of the fact that no previous biostratigraphic work has been attempted in the studied sections, the Bowen is used as a datum because it is a distinctive lithic unit with a brief duration of sedimentation. Extension of the Bowen datum across the study area corresponds to a general decrease in water depth which began in the Wardell and is roughly coincident with Bowen deposition. This shallowing event is associated with encroachment of basin sediments from the southeast onto the shelf (Shanmugam and Walker, 1978).

Carbonate Petrology and Paleodepositional

Environments

For the purpose of discussing in detail the physical stratigraphy, carbonate petrology and paleodepositional environments, the sequence can be separated into three distinct stratigraphic and paleoenvironmental packages. The lower stratigraphic package consists of a peritidal to shallow marine complex consisting of the Five Oaks, Tumbez, Fleanor and Lincolnshire Formations and is strongly influenced by the relief on the underlying post Knox unconformity. The middle stratigraphic package is dominated by pelmatozoan-bryozoan grainstones of the near shelf-edge and on-shelf patch reef environments in the Rockdell Formation. This package

shows the marked influence of the development and continuation of the shelf margin to the east and southeast. Finally, the upper stratigraphic package contains the intricate facies relationships of the shallow marine (restricted lagoon) and peritidal environments of the Benbolt, Chapman Ridge, Ottosee, Wardell, Bowen and Witten Formations. Figures 2.4-2.15, derived from constituent particle analysis (see Appendix B), illustrate the stratigraphic distribution, in each of the four measured sections, of fossil allochems (including algae in general), nonfossil allochems, and specific types of algae.

Lower Stratigraphic Package—Peritidal to Shallow Marine Environments

No biostratigraphic analyses have been made in this study area and therefore, the portrayal of lateral relationships (e.g., time relationships) has been based on environmental considerations, interfingering relationships and progradational cycles. The lower stratigraphic package is reconstructed in Figure 2.16. Evidence for this reconstruction is derived from the homotaxial relationships of the Fleanor and Lincolnshire Formations and their inferred interfingering relationships.

Post-Knox Unconformity. The post-Knox unconformity is poorly exposed everywhere except at Dry Gap (DG) where the contact with the overlying Five Oaks Formation was taken as the base of the Dry Gap section. The Knox at the contact is a dolomitic mudstone which contains abundant chert clasts (Figure 2.17A). Where the contact was not exposed, at Halls Crossroads (HC) and Harbison (HR), the base of the section was inferred to be in close proximity to the base of Copper Ridge. At

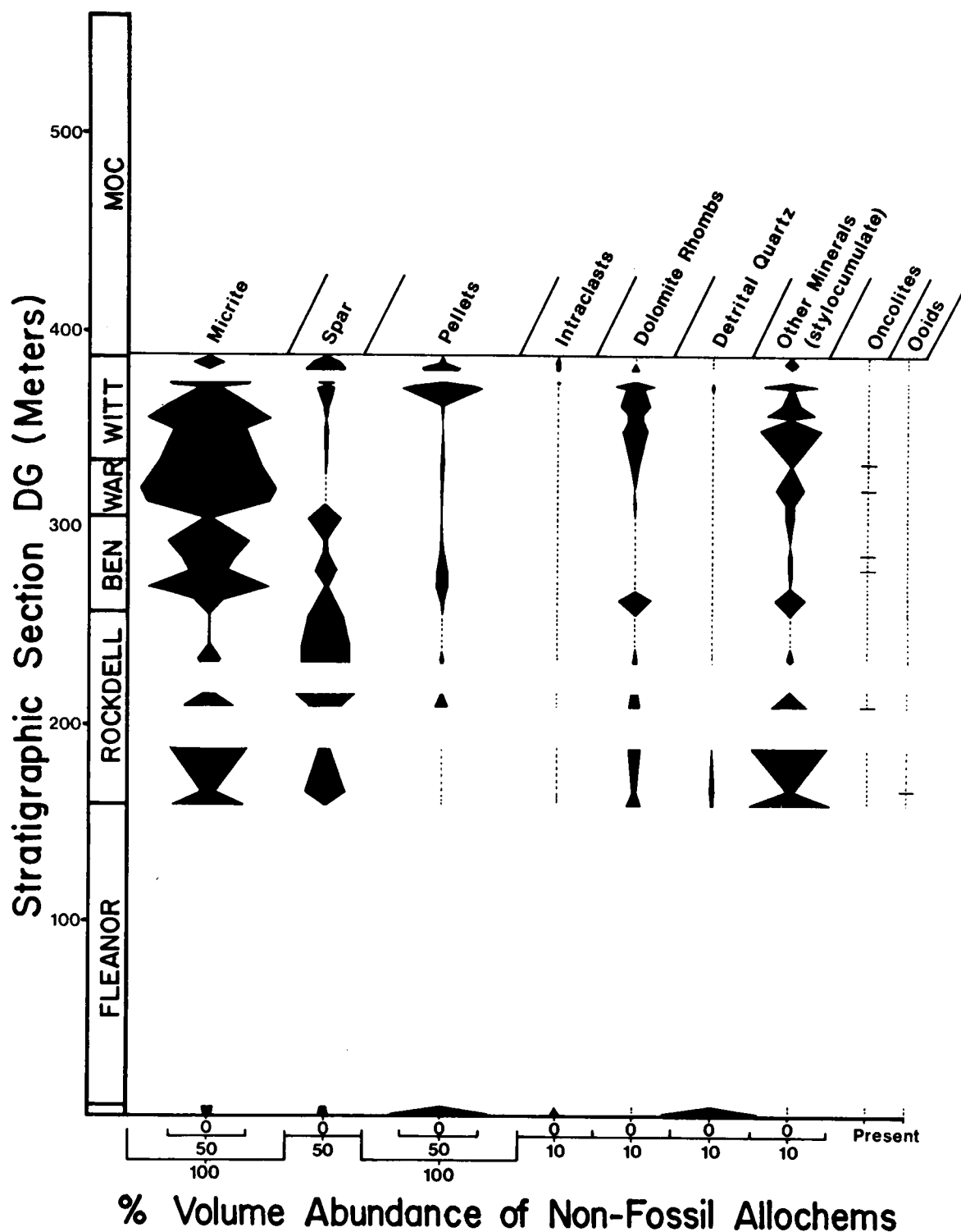


Figure 2.4. Stratigraphic distribution of nonfossil allochems in the measured section at Dry Gap, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).

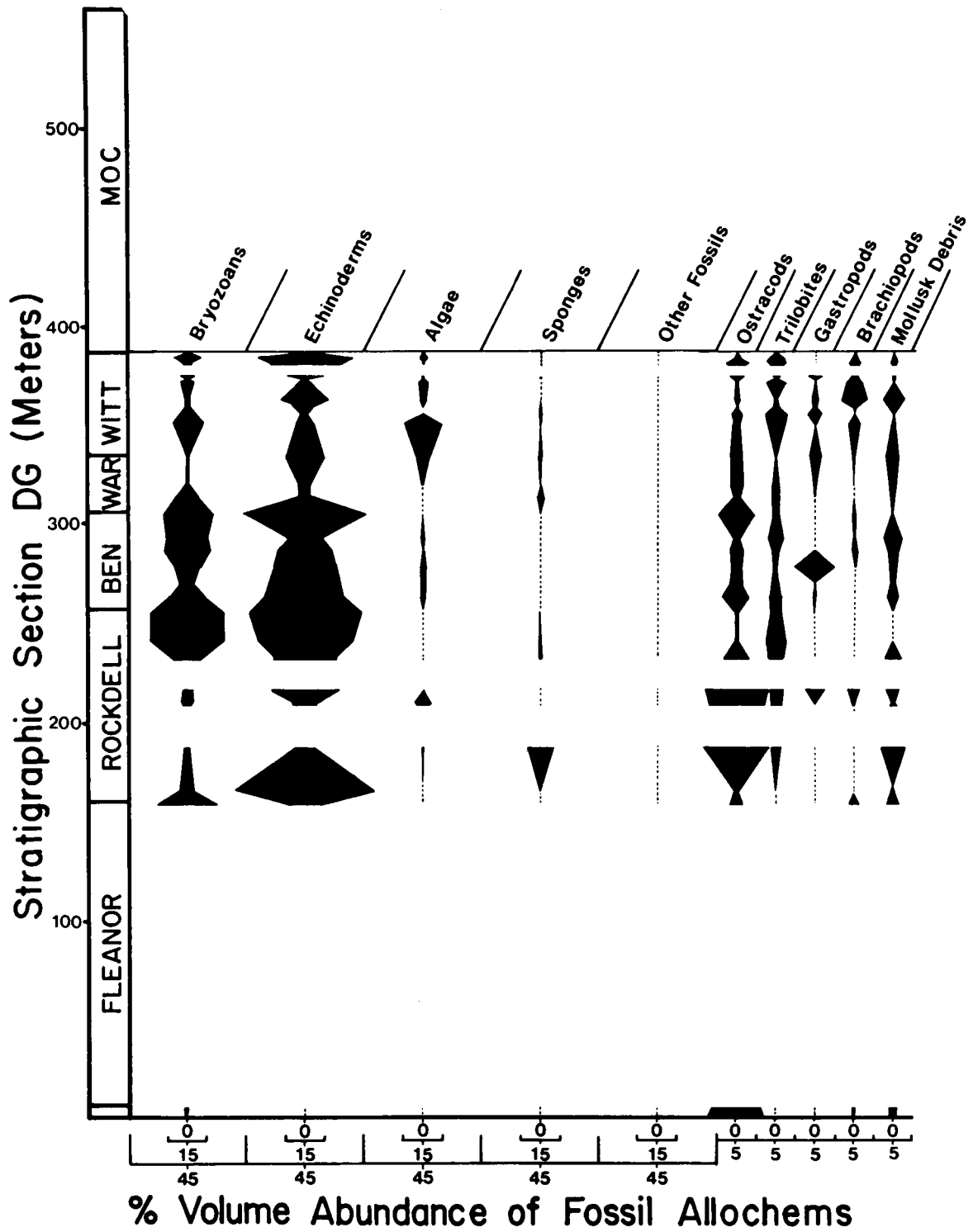
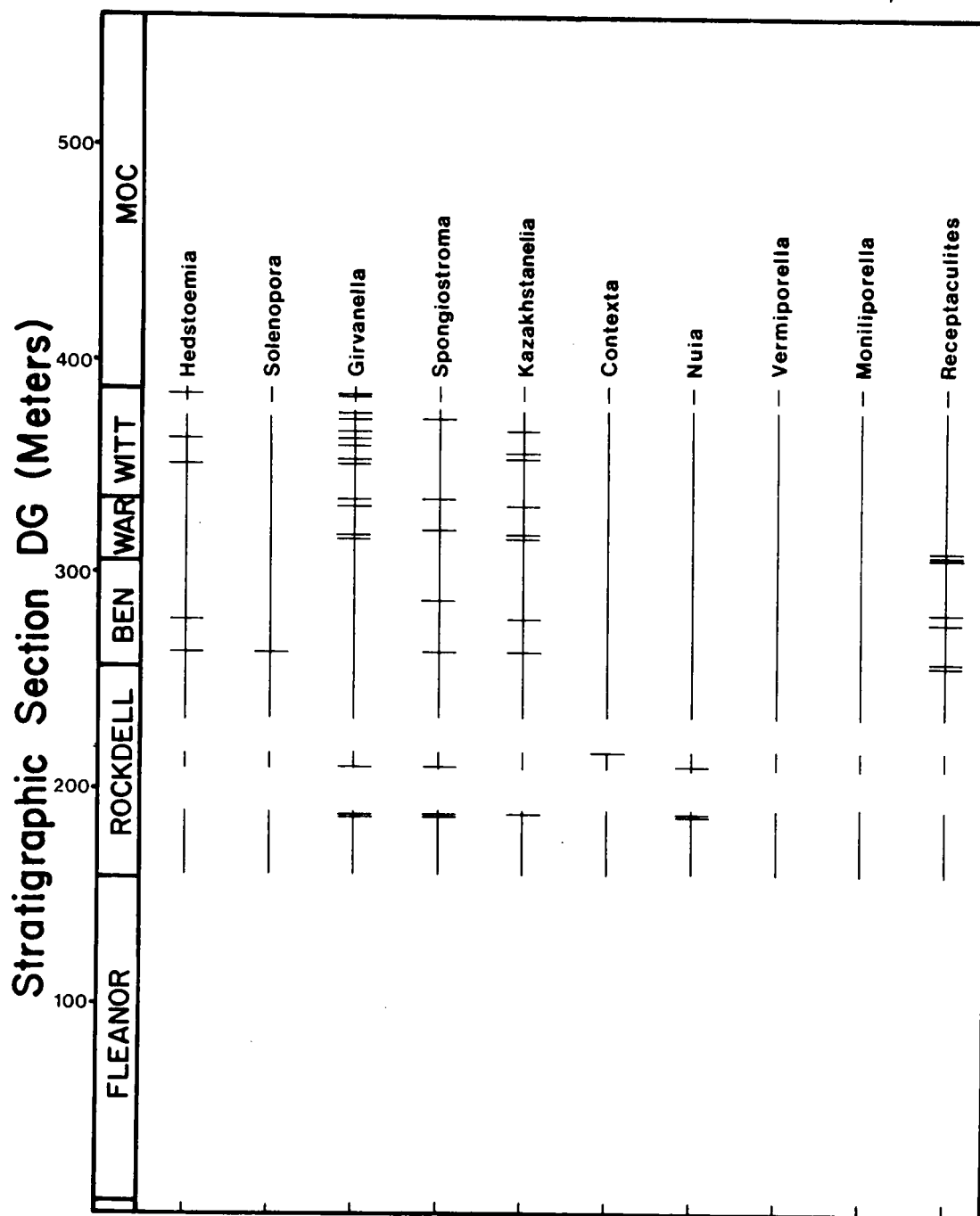


Figure 2.5. Stratigraphic distribution of fossil allochems in the measured section at Dry Gap, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).



Stratigraphic Occurrence of Algae

Figure 2.6. Stratigraphic occurrence of algae in the measured section at Dry Gap, Tennessee.

Each horizontal bar represents the occurrence of an alga at a particular stratigraphic interval as revealed by petrographic thin section examination. Vertical bars represent exposed portion of the measured section.

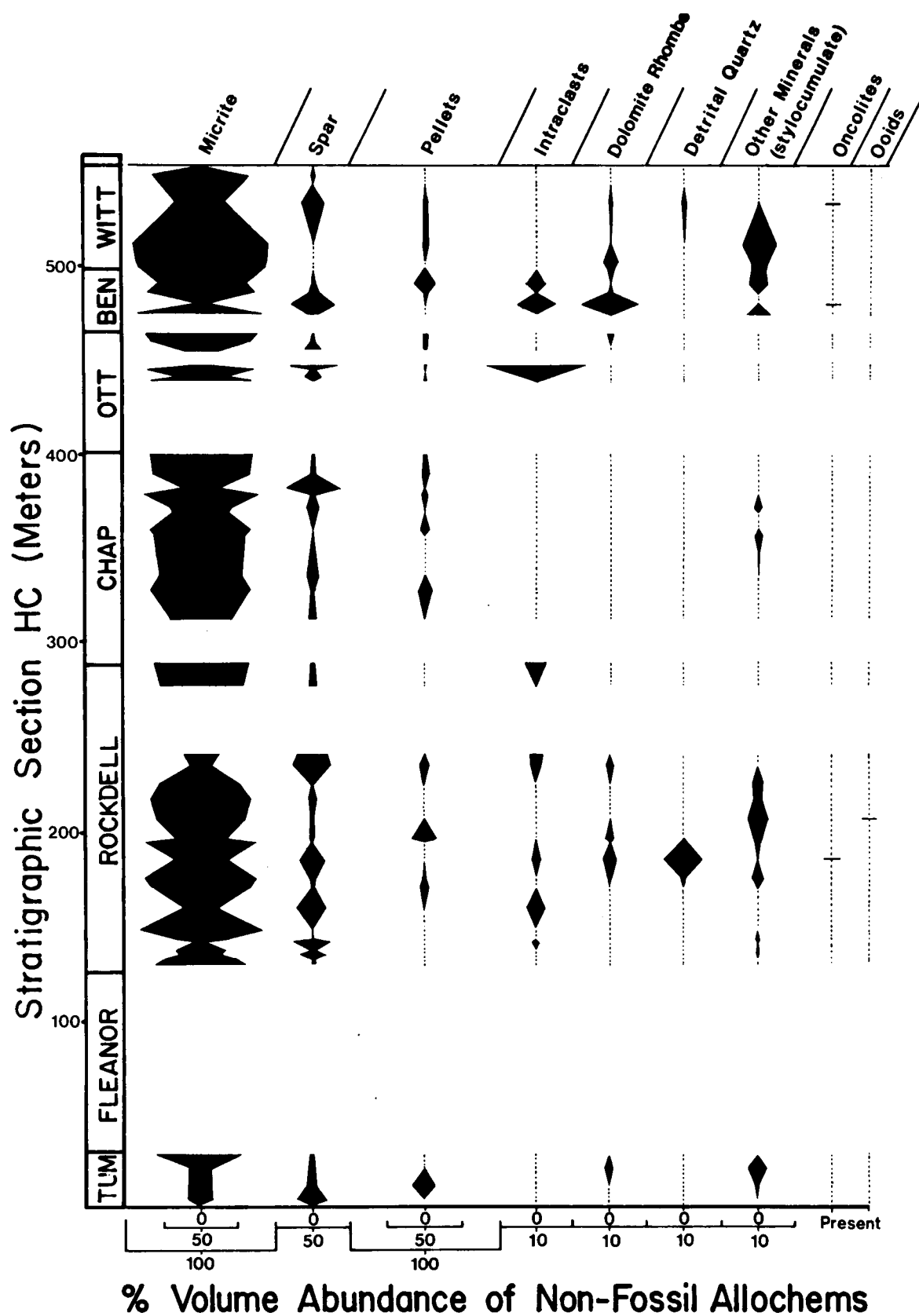


Figure 2.7. Stratigraphic distribution of nonfossil allochems in the measured section at Halls Crossroads, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).

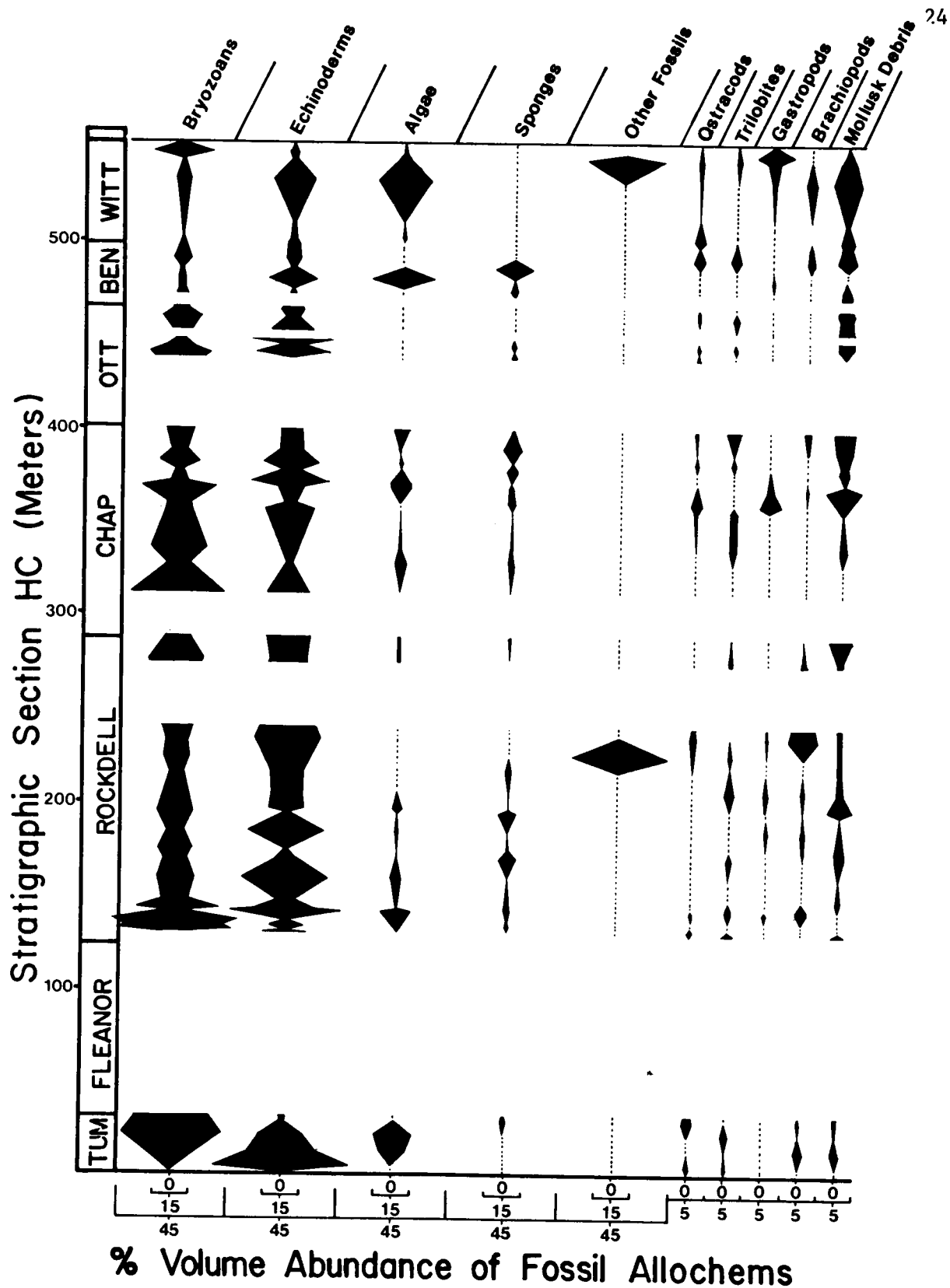
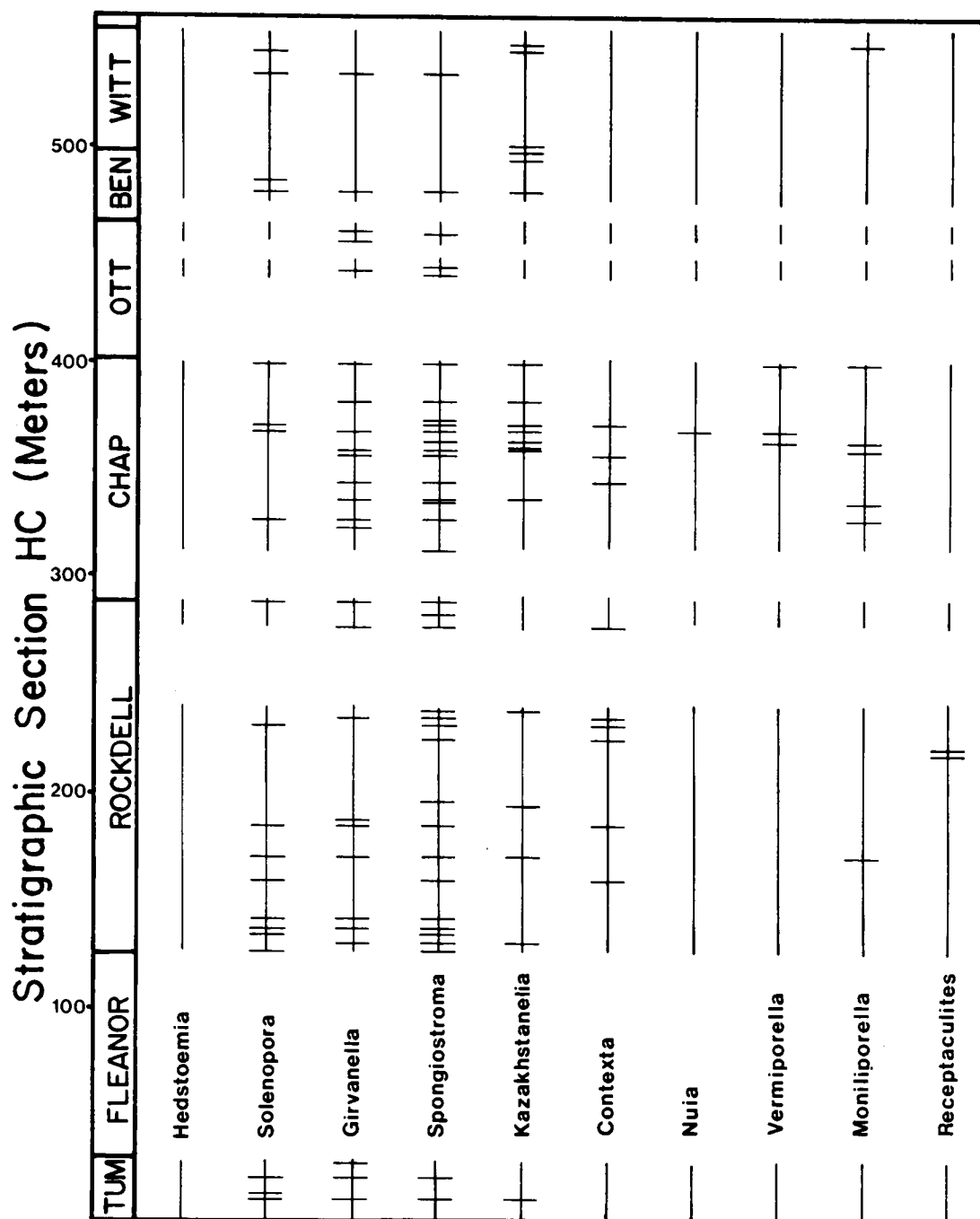


Figure 2.8. Stratigraphic distribution of fossil allochems in the measured section at Halls Crossroads, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of sample).



Stratigraphic Occurrence of Algae

Figure 2.9. Stratigraphic occurrence of algae in the measured section at Halls Crossroads, Tennessee.

Each horizontal bar represents the occurrence of an alga at a particular stratigraphic interval as revealed by petrographic thin section examination. Vertical bars represent exposed portion of the measured section.

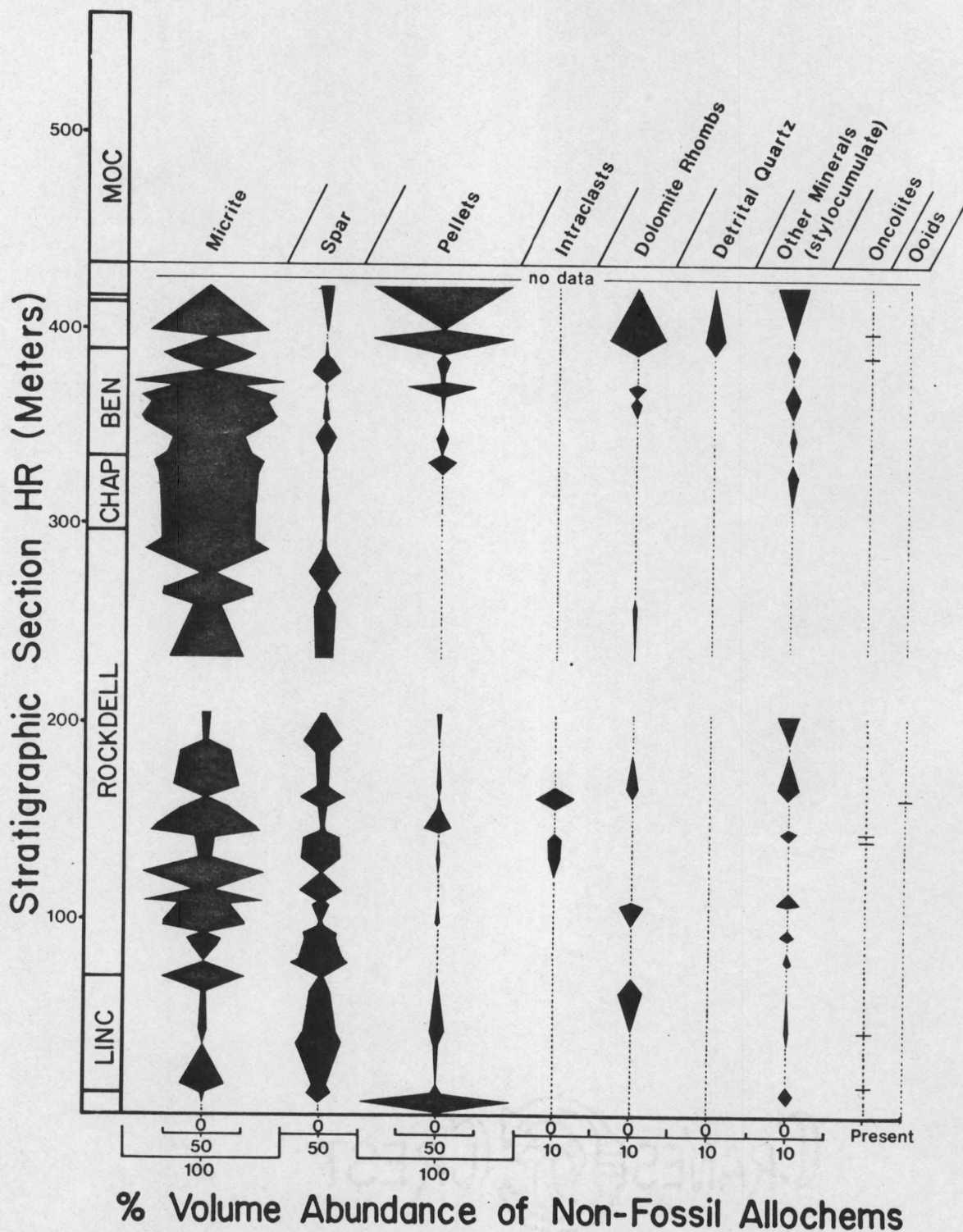


Figure 2.10. Stratigraphic distribution of nonfossil allochems in the measured section at Harbison, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).

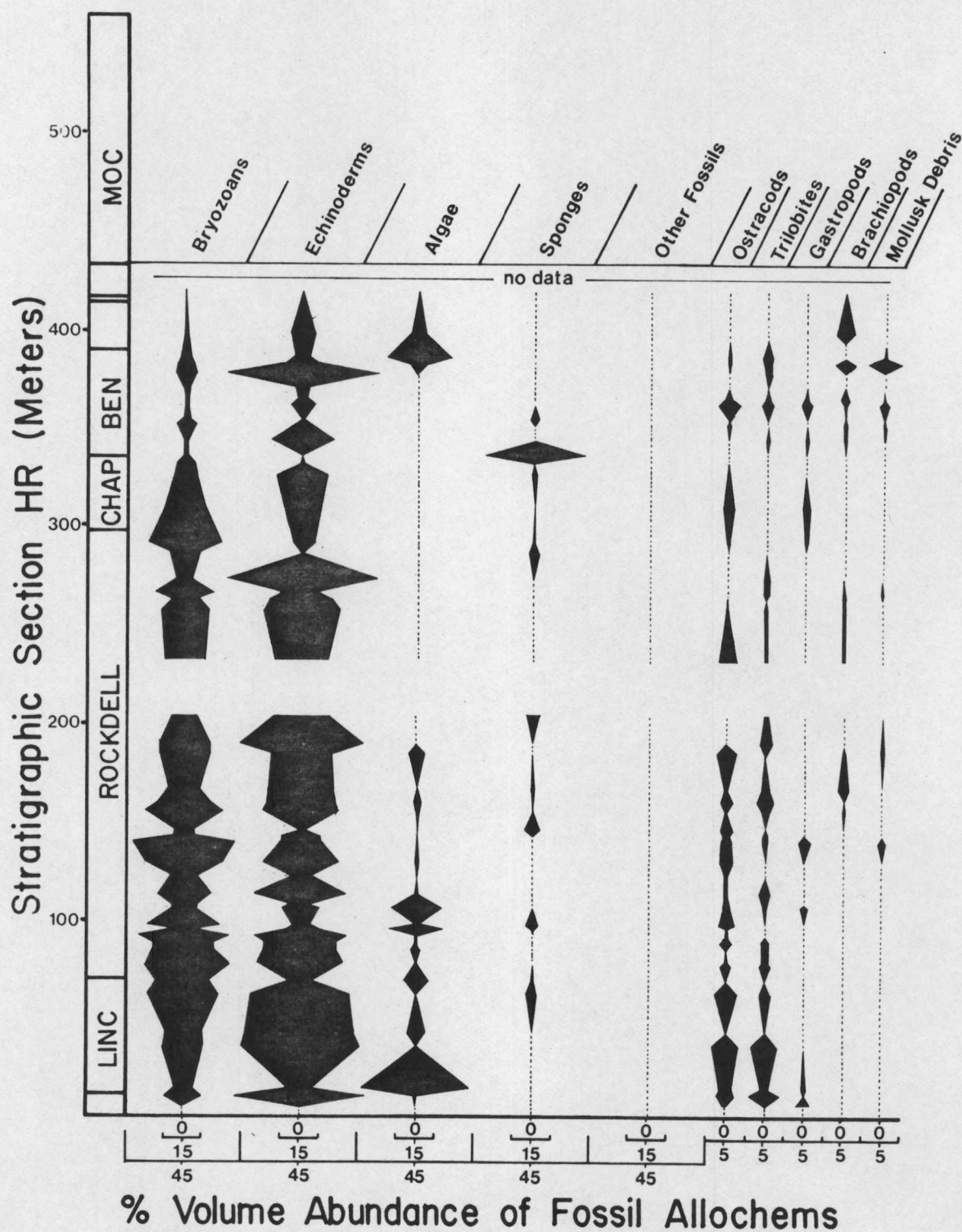
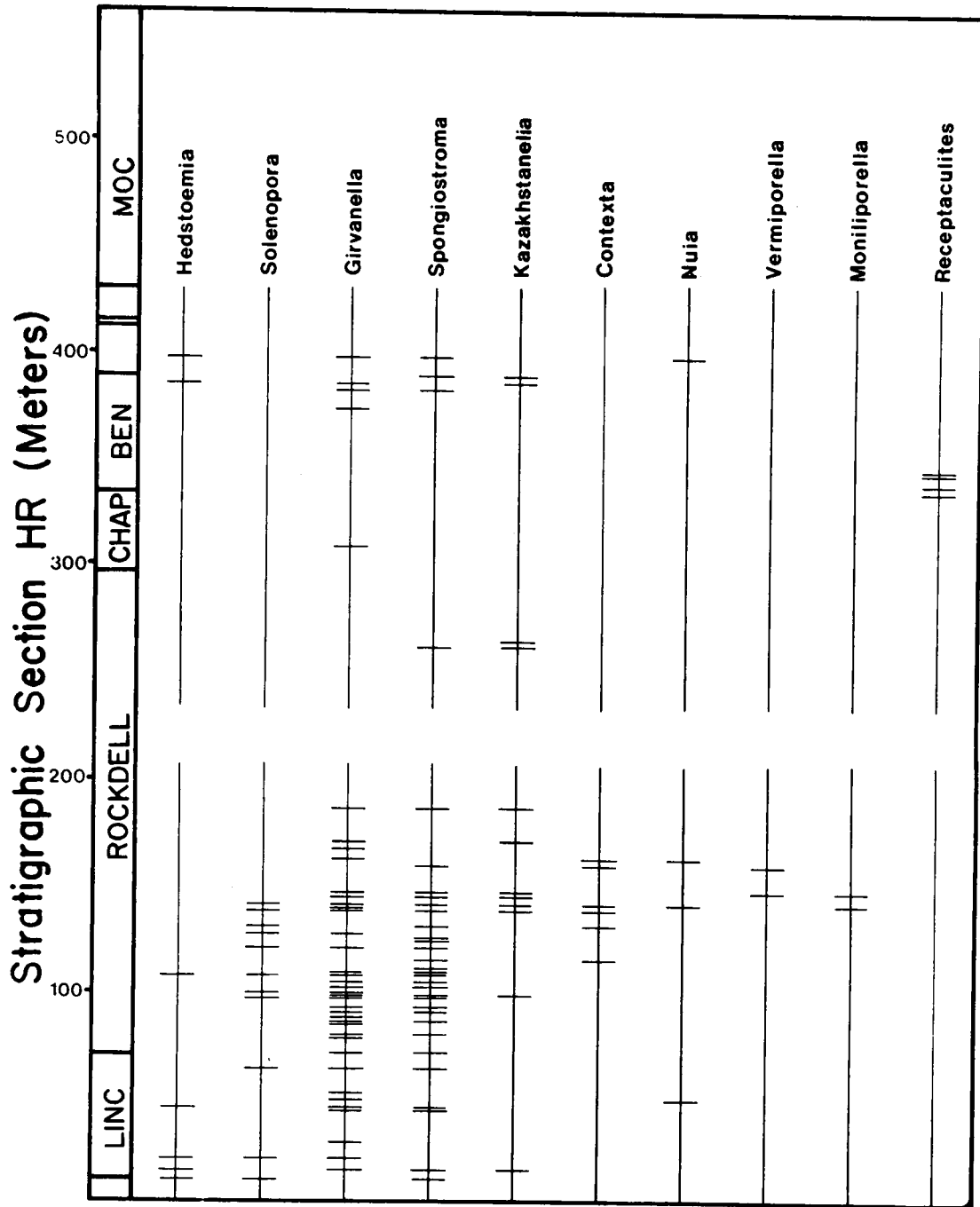


Figure 2.11. Stratigraphic distribution of fossil allochems in the measured section at Harbison, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).



Stratigraphic Occurrence of Algae

Figure 2.12. Stratigraphic occurrence of algae in the measured section at Harbison, Tennessee.

Each horizontal bar represents the occurrence of an alga at a particular stratigraphic interval as revealed by petrographic thin section examination. Vertical bars represent exposed portion of the measured section.

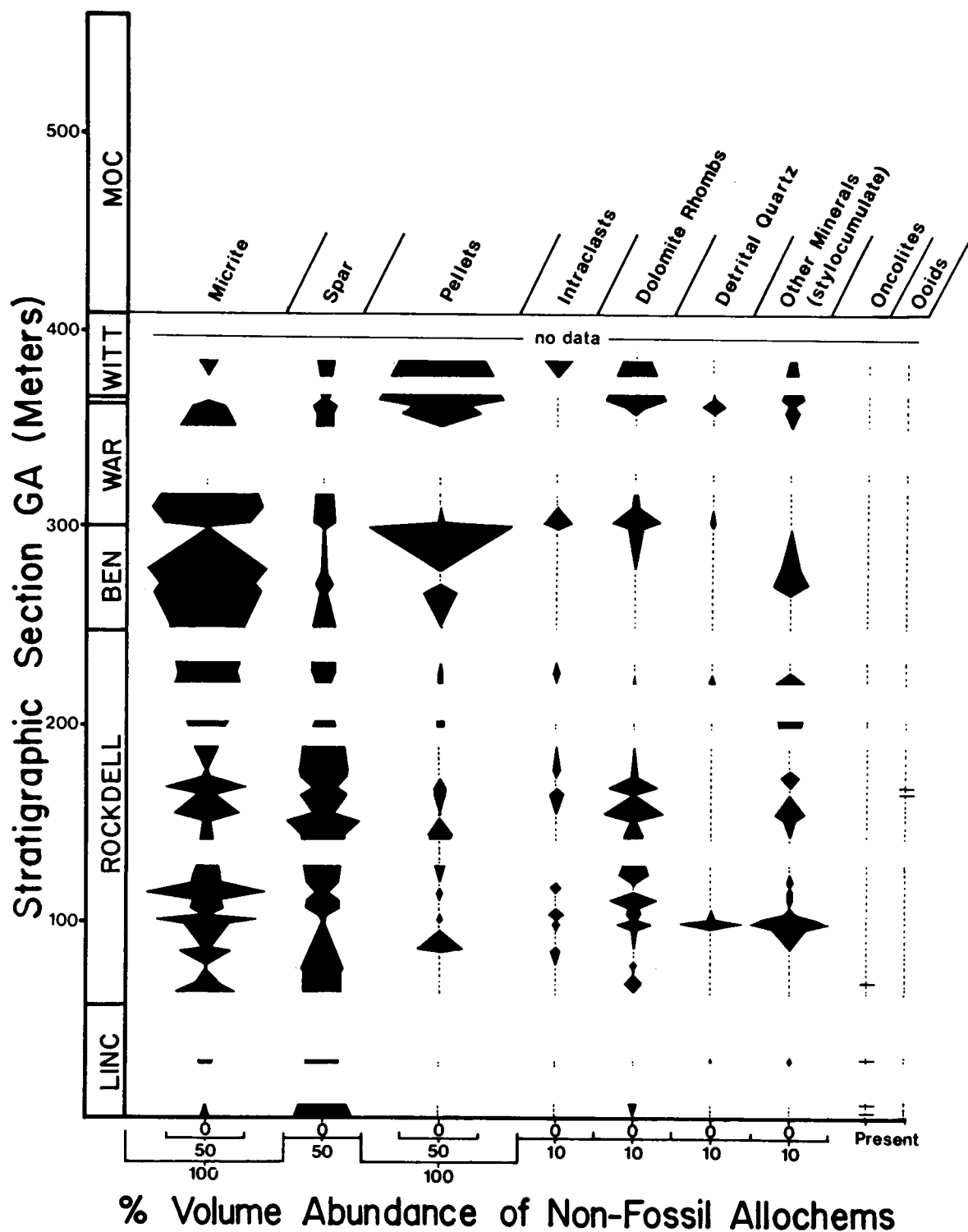


Figure 2.13. Stratigraphic distribution of nonfossil allochems in the measured section at Gravelston, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).

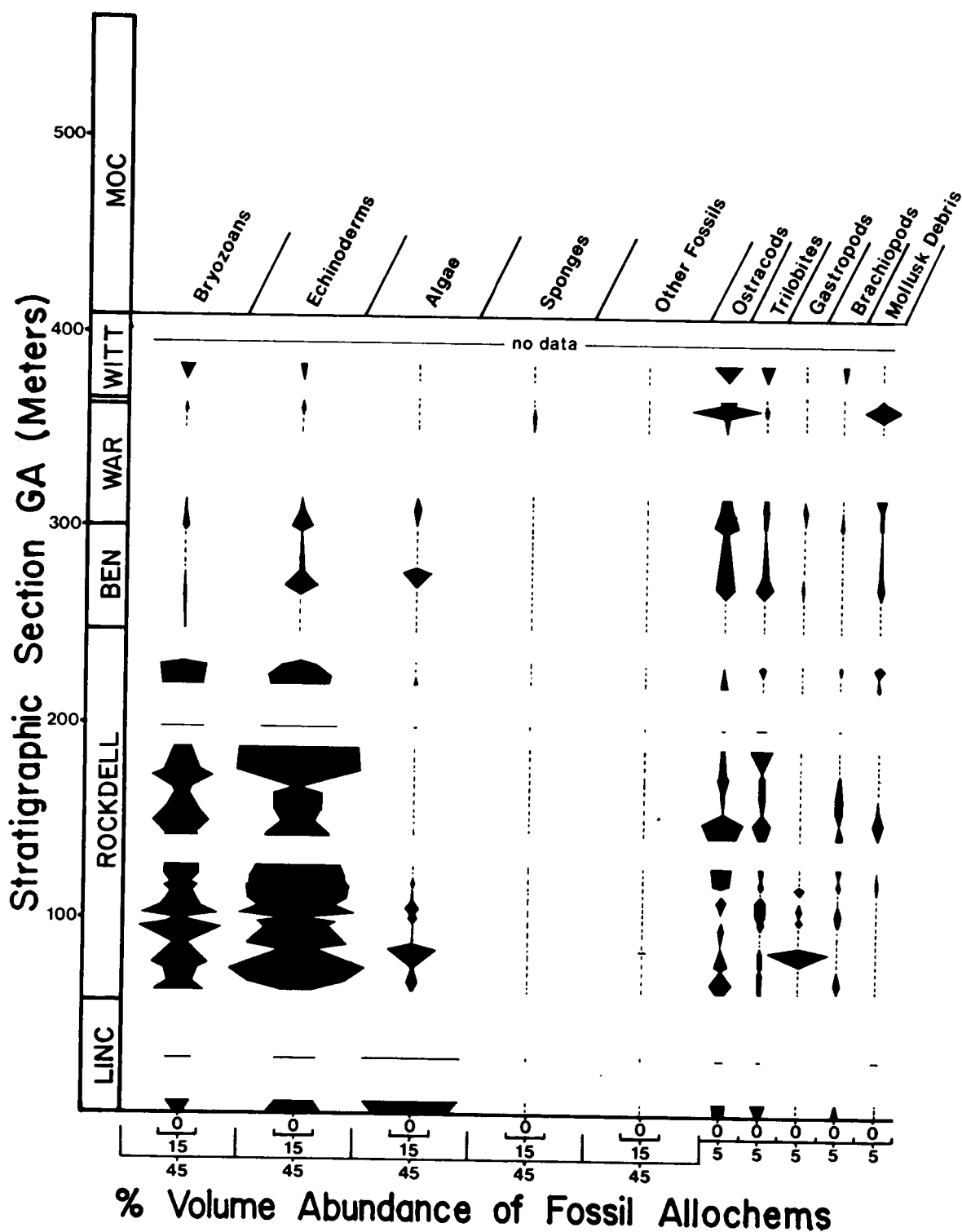
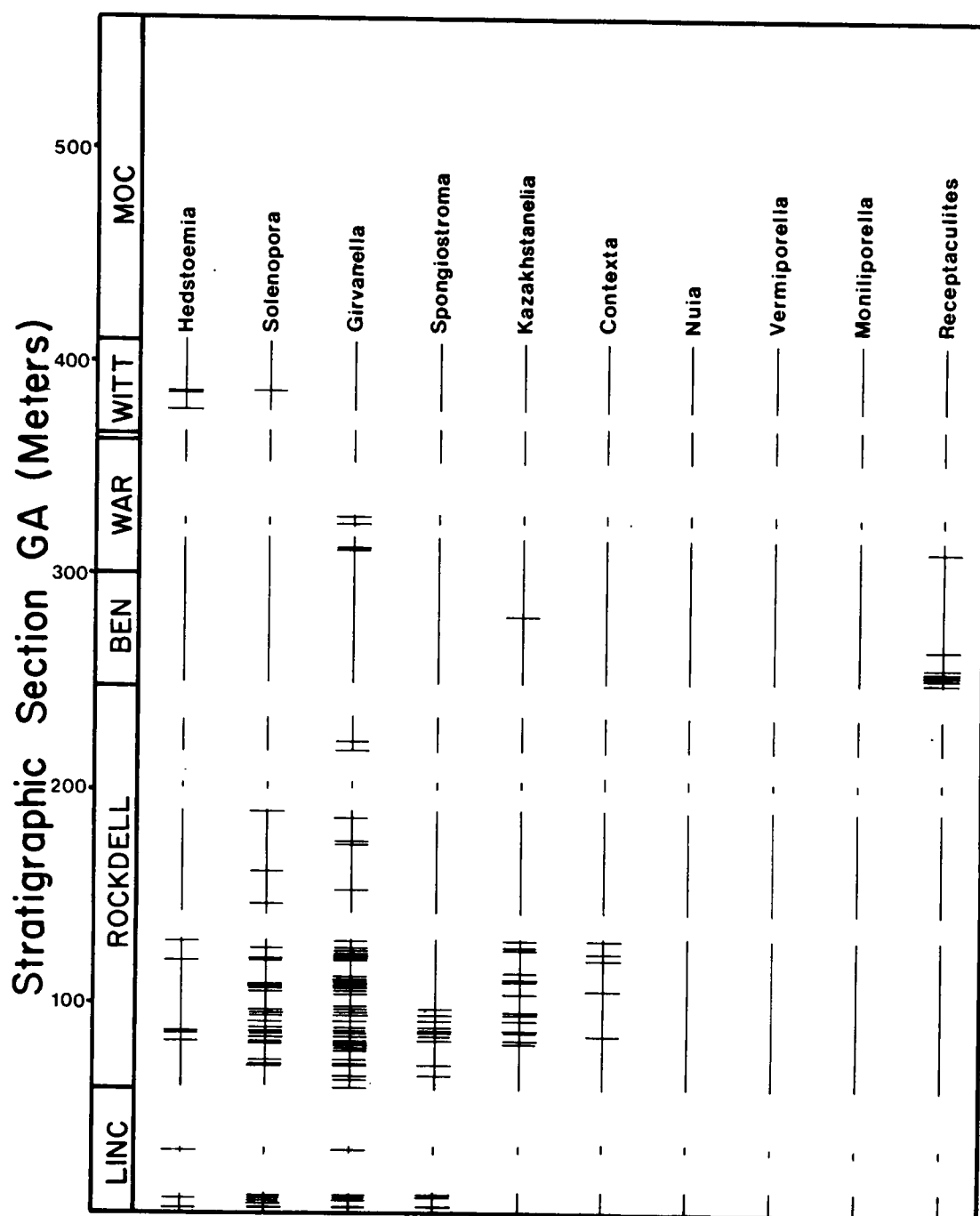


Figure 2.14. Stratigraphic distribution of fossil allochems in the measured section at Gravelston, Tennessee.

Volume percent was derived from point count data (see Appendix B for precise location of samples).



Stratigraphic Occurrence of Algae

Figure 2.15. Stratigraphic occurrence of algae in the measured section at Graveston, Tennessee.

Each horizontal bar represents the occurrence of an alga at a particular stratigraphic interval as revealed by petrographic thin section examination. Vertical bars represent exposed portion of the measured section.

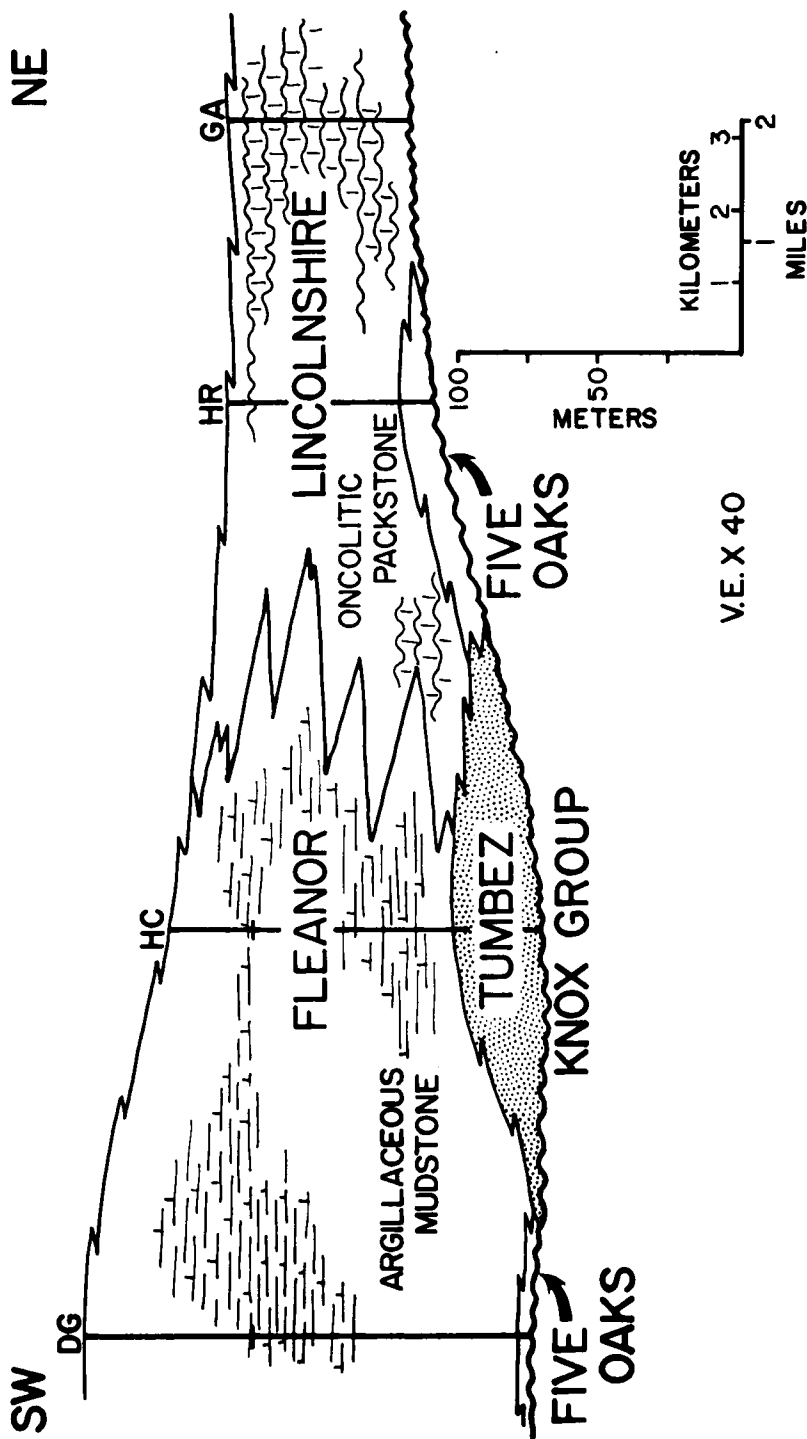


Figure 2.16. Lower stratigraphic package representing peritidal to shallow marine environments.

Note the inferred interfering relationships between the Fleanor and Lincolnshire Formations. Using this inferred interfering relationship, datum was determined by a line bisecting the Fleanor and Lincolnshire.

Figure 2.17. Petrographic features of the Five Oaks and Tumbez Formations.

- A. Upper Knox Group near the contact with the overlying Five Oaks Formation at the Dry Gap section. Note the large chert clasts (10.0 cm. in diameter). Scale in 10.0 cm. units.
- B. Photomicrograph of laminated pelletal packstone/grainstone of the Five Oaks Formation. Dry Gap section (DG1A). 25X.
- C. Polished slab of the Five Oaks Formation showing the mottled grey lime mudstone with areas of brownish dolomite. Dry Gap section (DG1A). 25X.
- D. Photomicrograph of an algal fragment, Hedstroemia sp., from the Five Oaks Formation. Dry Gap section (DG1A). 25X.
- E. Photomicrograph of a laminated zone of gastropods (Loxoplocus sp.) in a pelletal packstone/grainstone. From the Five Oaks Formation at the Harbison section (HR1A). 25X.
- F. The two lithofacies of the Tumbez Formation at Halls Crossroads. Top sample is a red bryozoan boundstone/wackestone (HC3C) and the lower sample is a coarse grained skeletal packstone/grainstone (HC3D).
- G. Photomicrograph of the bryozoan boundstone/wackestone facies of the Tumbez Formation. Halls Crossroads section (HC3E). 25X.
- H. Photomicrograph of the skeletal packstone/grainstone facies of the Tumbez Formation. Note the two types of Solenopora sp. and the single fragment of Spongiostroma sp. (at the top). Halls Crossroads section (HC1B). 25X.

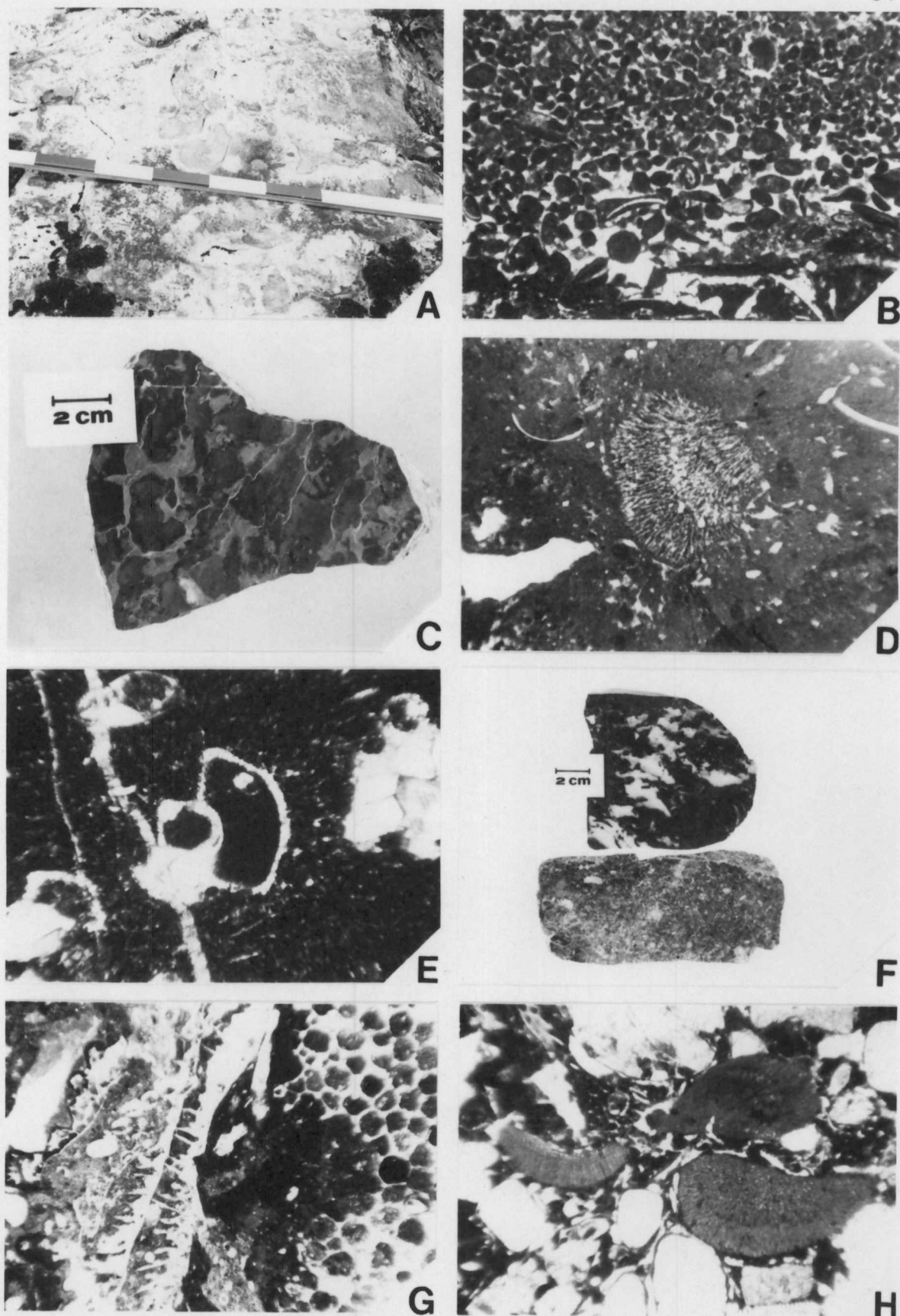


Figure 2.17.

Graveston (GA), although the contact was not exposed, weathering characteristics of the Knox dolomite and the overlying limestones were distinctive enough to allow delineation of the contact within a few meters.

Five Oaks Formation. Immediately overlying the unconformable contact with the Lower Ordovician Knox Group is the Five Oaks Formation which occurs at only two localities (Dry Gap and Harbison sections). The Five Oaks is composed of a dove grey, fine grained lime mudstone and a pelletal-intraclastic packstone/grainstone which commonly has a greenish internal coloration (Figure 2.17B). On polished slabs (Figure 2.17C), the mottled grey lime mudstone shows areas of light brownish dolomite and commonly contains tubular and poorly developed irregular fenestral fabric (terms from Grover and Read, 1978). The biotic components of the pelletal packstone/grainstone are generally restricted to a few fossil fragments. The biota is confined to randomly oriented, disarticulated and articulated ostracod valves, rare algal fragments (Hedstroemia sp., Figure 2.17D) and minor amounts of pelmatozoan debris (See Figures 2.4-2.6, pages 20-22, and Figures 2.10-2.12, pages 26-28). Occasionally associated with nonfossiliferous zones in the pelletal-intraclast packstone/grainstone are comparatively large gastropods (e.g., Loxoplocus sp., Figure 2.17E).

Logan (1974) reported that irregular fenestral fabric is formed by detachment of pustular algal mat-sediment layers. The general absence of cryptalgal structures in the Five Oaks suggests that algal mats may have played a lesser role than physical and diagenetic processes. Shinn (1968a) produced irregular fenestrae by desiccation of nonlaminated lime

mud. Grover and Read (1978) observed similar irregular fenestrae in the New Market Limestone which they attributed to alternate periods of wetting and drying.

Tubular fenestrae in the Five Oaks are similar to burrow and root structures reported by Shinn (1968b) and Logan et al. (1974) in recent intertidal sediments, however, the absence of Ordovician vascular plants precludes a plant root origin. Grover and Read (1978) reported an association of tubular fenestrae and gastropod bearing lime mudstone in the New Market Limestone which they said was suggestive of subtidal and infrequently exposed pond and nearshore marine sediment reported in the Bahamas by Ginsburg and Hardie (1975).

The restricted fauna of the Five Oaks, particularly the gastropods and ostracods, is suggestive of a high stress, perhaps hypersaline environment. Gastropods and ostracods are euryhaline animals capable of surviving in high stress conditions characteristic of peritidal environments. Although Moore (1977) observed that calcareous algae were noticeably absent in upper peritidal and tidal flat sediments, the presence of fragments of Hedstroemia sp. in the Five Oaks is evidence of a close proximity to a shallow subtidal environment.

The Five Oaks lithofacies is interpreted to be representative of deposition in a peritidal environment. Many modern analogues occur in peritidal environments in Florida (Multer, 1977), the Bahamas (Shinn et al., 1969), and Australia (Logan et al., 1970; Logan et al., 1974). Similar sediments in ancient environments have been reported by Laporte (1967; 1971), Walker (1973), Ruppel (1979) and Sickafoose (1979) but it is not always possible to subdivide an ancient peritidal environment into

constituent subenvironments because of complex depositional patterns and relationships. This is the case with the Five Oaks in the study area.

Tumbez Formation. Interfingering laterally with peritidal sediments of the Five Oaks Formation are the shallow subtidal (lagoonal) and channel deposits of the Tumbez Formation. The Tumbez overlies the Knox Group and is exposed at only one locality in the study area, the Halls Crossroads section. It is approximately 30.0 meters of poorly exposed red bryozoan boundstone/wackestone and medium to coarse grained skeletal packstone/grainstone (Figure 2.17F). Because of poor exposure, it is difficult to determine the exact relationship between the bryozoan boundstone/wackestone and the skeletal packstone/grainstone. At a few of the small exposures, the boundstone/wackestone is thin bedded but massive at others. Exposures of the skeletal packstone/grainstone are generally very massive. The biotic constituents of the boundstone/wackestone are dominated by encrusting bryozoans (Figure 2.17G). The skeletal packstone/grainstone is dominated by pelmatozoan debris and algal fragments such as Solenopora sp., (two ecophenotypes present), Spongiostroma sp., Girvanella sp. and Kazakhstanelia sp. (Figure 2.17H).

It is interesting to note that algae in the Tumbez appear to be associated only with skeletal sands implying that this particular algal assemblage has been transported into the depositional environment of the Tumbez from an adjacent subenvironment. Of particular interest is the appearance of an encrusting form of Solenopora sp. first described by Breland and Walker (1980) and interpreted to be indicative of on-shelf patch reef deposits. While the complete complement of algae listed by

Moore (1977) for patch reefs was not observed in the Tumbez, the assemblage that does exist (Figure 2.9, page 25) is not incompatible with that reported by Moore. Apparently, small patch reefs, perhaps developing on submerged, topographically high, areas on the Knox erosional surface existed at the same time as the depositional environment of the Tumbez.

From the nature of the lithofacies and the biota present, particularly the algae, the depositional environment of the Tumbez is inferred to be shallow subtidal lagoon (see Figures 2.7-2.9, pages 23-25). The delicate thin character of the encrusting bryozoans (Figure 2.17G) suggests weak to moderate current activity. Associated with the bryozoan "mudmounds" are medium to coarse grained, well washed sediments (channel deposits perhaps) derived from an adjacent but presently unexposed subenvironment (i.e., patch reef). These two lithofacies were intimately associated in an interfingering fashion and deposited upon the karst surface of the Knox.

Fleanor Formation. The Fleanor Formation is a poorly exposed, thin bedded, buff colored, calcareous shale and comprises a major covered interval in the study area approximately 150.0 meters in thickness (see Appendix A). This covered interval is inferred to be the Fleanor Formation from scattered, poorly exposed outcrops in the southwest portion of the study area (Figure 2.18A). Also, the Fleanor, which is generally very shaly except in a few isolated areas where a fairly diverse fauna including brachiopods, gastropods and bryozoans occurs, weathers deeply and consequently is very poorly exposed. A similar position in the sequence, above the Five Oaks/Tumbez and below the

Figure 2.18. Petrographic features of the Fleanor and Lincolnshire Formations.

- A. Upper Fleanor Formation approximately 1.0 mile north of the Halls Crossroads section on U. S. Highway 33. The upper Fleanor, near the contact with the Rockdell Formation, becomes more calcareous. Note thin bedded and shaly weathering. Scale divisions are 10.0 cm.
- B. Irregular bedding and nodular weathering typical of the Lincolnshire Formation. Harbison section. Scale divisions are 10.0 cm.
- C. Photomicrograph of the skeletal packstone/grainstone in the Lincolnshire Formation. Note the dark areas which are lumps of the alga Girvanella sp. Graveston section (GA2C). 25X.
- D. Oncolites which are characteristic of the lower Lincolnshire Formation. Graveston section. Scale divisions are 10.0 cm.
- E. Photomicrograph of one of the numerous fragments of Girvanella sp. in packstone/grainstone of the lower Lincolnshire Formation. Note the twisted tubules within the fragment. Graveston section (GA1A). 100X.
- F. Photomicrograph of the red alga Solenopora sp. (type P of Moore, 1977) from the Lincolnshire Formation. Note thin rim of Girvanella sp. encrusting fragment of Solenopora sp. Graveston section (GA1A). 25X.
- G. Photomicrograph of the green alga Hedstroemia sp. from a grainstone in the Lincolnshire Formation. Note dark fragments of common Girvanella sp. in the upper left corner. Graveston section (GA1A). 100X.
- H. Photomicrograph of the less common problematical alga Nuia sp. from the lower Lincolnshire Formation. Note development of a stylocumulate (term after Logan and Semeniuk, 1976) rich dark area traversing central portion of photo. Graveston section (GA1A). 100X.

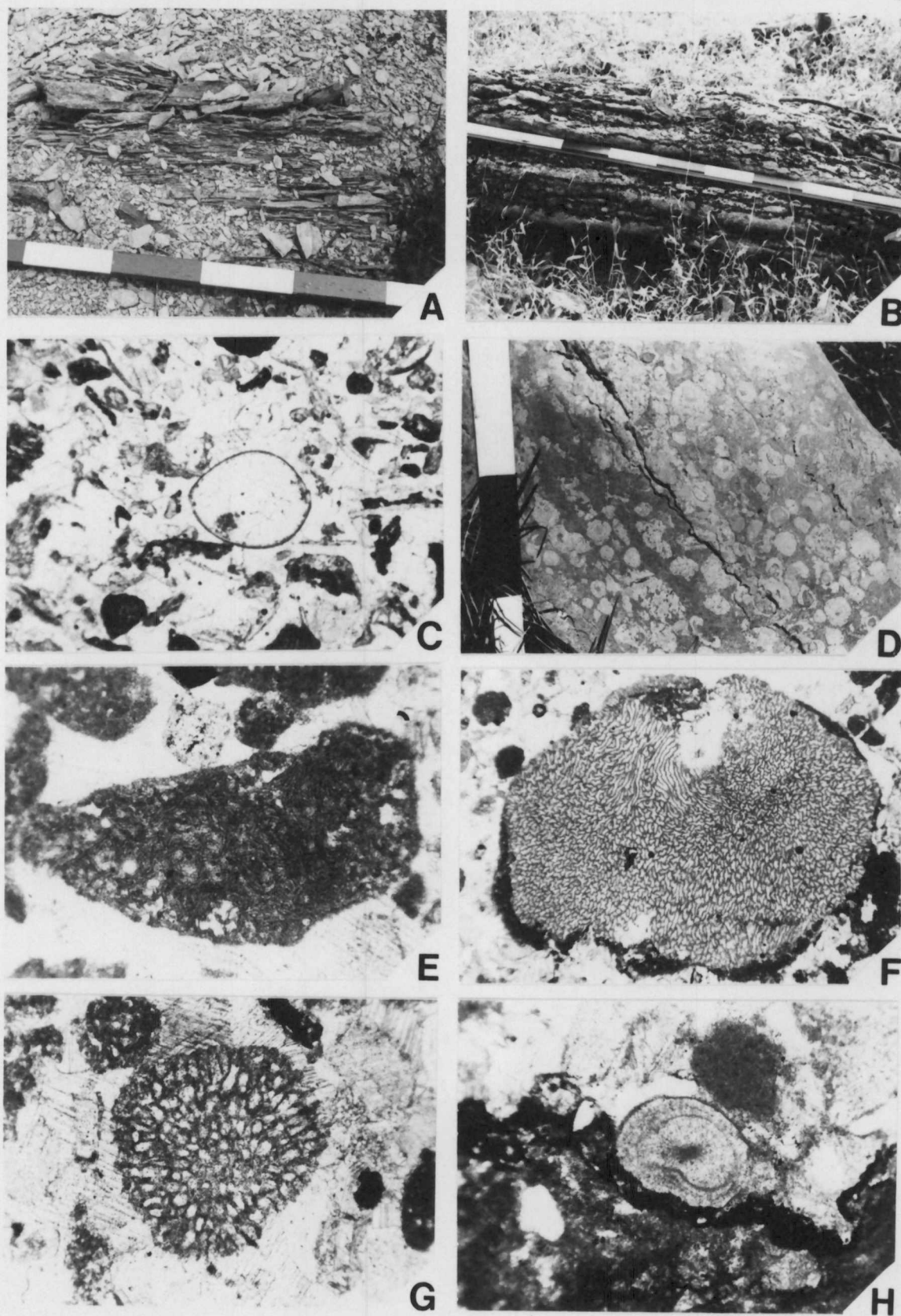


Figure 2.18.

Rockdell, in the type section of the Fleanor Formation near Heiskell, Tennessee (Cooper, 1956) is regarded as further evidence.

The Fleanor is thickest (159.0 meters) in the southwest at Dry Gap (DG) where it overlies the Five Oaks Formation and becomes thinner (129.0 meters) to the northeast at Halls Crossroads (HC) where it overlies the Tumbez Formation (see Figure 2.16, page 32). It is everywhere overlain by the Rockdell Formation and by inference interfingers with the coeval Lincolnshire Formation to the northeast between Halls Crossroads (HC) and Harbison (HR).

Environmental interpretation of the Fleanor is based primarily on its lithologic character (thin bedded calcareous shales) and on the interfingering relationship with the Lincolnshire. The shaly nature of the Fleanor and its relation and stratigraphic position with respect to the Lincolnshire implies a terrigenous source, in this case, to the southwest and northwest. The fine grained sediment and thin bedding suggest fairly quiet water conditions. The influx of terrigenous material apparently precluded the development of wide spread biotic communities as evidenced by the small number of fossils generally and the largely noncalcareous character of the Fleanor sediments.

Lincolnshire Formation. The Lincolnshire Formation crops out at Harbison (HR) where it overlies the Five Oaks Formation and at Graveston (GA) where it is in contact with the underlying Knox Group (see Figure 2.16, page 32). The Lincolnshire grades, by inference, laterally to the southwest into the Fleanor Formation and upward, at both localities, into the Rockdell Formation. The unit appears to thin toward the northeast, evidenced by the work of Ratliff (1974), who studied the Middle Ordovician

rocks exposed in the same strike belt as the present study but approximately 5 km. to the northeast at Luttrell, Tennessee (Figure 1.2, page 4). Ratliff (1974) reported thin (averaging 20 feet), localized occurrences of a lithotype similar to the Lincolnshire, which were not persistent along strike and graded laterally into a calcarenite similar to the Rockdell or Holston Formations which rest directly on the post-Knox unconformity in the vicinity of Luttrell, Tennessee.

The Lincolnshire Formation in the study area is light to medium grey, fine to coarse grained skeletal packstone/grainstone which in the field often shows a characteristic irregular bedding and nodular weathering (Figure 2.18B). Exposure of the Lincolnshire is variable and the unit may contain a higher proportion of carbonate mud-rich beds than samples extracted from outcrops reveal, particularly near the base of the formation. The primary constituents (see Figures 2.10-2.15, pages 26-31) of the skeletal packstone/grainstone are pelmatozoans and bryozoans with secondary ostracods, trilobites and algae (Figure 2.18C). The skeletal grains are generally well sorted and abraided and commonly show well developed syntaxial overgrowths, particularly on the pelmatozoan fragments.

Of the three common and two less frequently observed varieties of algae in these packstones, the most common is Girvanella sp. which is observed both as oncolites (Figure 2.18D) and as numerous small fragments containing twisted tubules (Figure 2.18E). Solenopora sp. (Type P of Moore, 1978) is an important constituent of these packstones and appears to be more persistent vertically in the stratigraphic sections than Girvanella sp. Ruppel (1979) reported Girvanella sp. and Solenopora sp.

in the lower part of the Lincolnshire, Solenopora sp. being more abundant than the Girvanella sp. which occurred mainly in oncolites. That particular relationship does not appear to hold for the Lincolnshire in the study area (Figure 2.18F). While Solenopora sp. does appear to increase in relative abundance upward in the sections with respect to Girvanella sp., the situation seems to be a function of the greater resistance of Solenopora sp. to destruction by transportation than the less calcified Girvanella sp. The algal form taxon Spongiostroma sp. is also an important constituent of these packstones. The green alga Hedstroemia sp. (Figure 2.18G) and the problematical alga Nuia sp. (Figure 2.18H) were also observed but are much less common.

Another common feature in the Lincolnshire is the development of stylocumulate (term after Logan and Semeniuk, 1976; see note on Figure 2.18H) along styolitic partings; styolites are one of the causes of the irregular bedding and nodular weathering of the formation. Sediment compaction is also important in producing irregular and nodular bedding.

In determining the environmental setting of the Lincolnshire Formation, a number of factors were considered. First, the abraided and fragmented nature of the skeletal grains and the relative paucity of carbonate mud implies moderate current transportation and winnowing of these grains. Secondly, the presence of abundant oncolites near the base of the formation suggests, by analogy with modern environments (Ginsburg, 1957, 1960; Logan et al., 1964), moderate current activity in comparatively shallow marine water (maximum depth of 6.0 to 10.0 meters). Finally, Moore (1977) interpreted the presence of Girvanella sp. oncolites, and Solenopora sp. (Type P) accompanied with a substrate of

skeletal sands and mud to be indicative of strong current activity in channels, perhaps associated with tidal and near shore current activity. The Lincolnshire Formation, therefore, is interpreted to be composed of near shore, shallow subtidal deposits which were subject to reworking and transportation by tidal and near shore currents.

Summary. The nature of the basal stratigraphic package is closely controlled by the karstic upper surface of the Knox group. The peritidal depositional environment of the Five Oaks Formation appears to be related to subaerially exposed Knox "islands" high on the Middle Ordovician carbonate shelf. The Tumbez Formation is stratigraphically equivalent and possibly coeval with the Five Oaks Formation and, by inference, the two formations interfinger laterally. The algal assemblage in the packstone/grainstone deposited in the shallow water, lagoonal environment of the Tumbez Formation indicates that these sediments were derived from on-shelf patch reef accumulations. These patch reefs may have developed on submerged topographically high areas on the Knox karst surface. The development of patch reefs was inhibited by introduction of terrigenous materials of the Fleanor Formation. On-shelf reef buildups are not observed again until higher in the sequence. The environment of deposition of the Fleanor Formation is interpreted to have been in a shallow, quiet water, somewhat restricted lagoon dominated by an influx of fine grained terrigenous sediments. The topography of the Knox erosional surface may have influenced sedimentation (by restricting the water movement) in much the same manner as the Pleistocene "keys" in South Florida restrict the movement of water in Florida Bay.

The Fleanor Formation, which is landward from the shelf margin, interfingers laterally and is doubtless coeval with the Lincolnshire Formation to the northeast. The Lincolnshire Formation is a near shore, shallow subtidal facies deposited under conditions of moderate to strong current activity. It grades upward into the Rockdell Formation in the study area and, from lithofacies data collected by Ratliff (1974), reinterpreted by the present author in terms of the stratigraphic nomenclature used in this paper, becomes thinner to the northeast in the vicinity of Luttrell where it also grades laterally into the Rockdell facies. It is interesting to note that the shelf-edge existed in the general area of Luttrell (Ratliff, 1974; see Figure 1.2, page 4) and the relatively high energy current conditions inferred for the Lincolnshire Formation might be better understood in terms of the lateral relationship to the Rockdell Formation and the environmental conditions under which the latter unit was deposited. This point will be discussed in greater detail in the next section.

Middle Stratigraphic Package—Near Shelf Margin and On-Shelf Patch Reef Environments

The reworked and transported sediments of the near shore, shallow subtidal depositional environment of the Lincolnshire Formation presage the transgression represented by massive grainstones and bryozoan "mudmounds" of the Rockdell Formation (see Figure 2.3, page 17). According to Ratliff (1974), the base of the Middle Ordovician section in the Luttrell belt is characterized by a thin and poorly developed Lincolnshire facies and is dominated by buildups of massive skeletal

grainstones and bryozoan boundstones similar to the lithofacies of the Holston Formation described by Walker and Ferrigno (1973).

Walker and Ferrigno (1973) interpreted the Holston Formation in the strike belt southeast of the Luttrell belt (and southeast of the present study area) to be a major Middle Ordovician reef tract which delineated the shelf margin. Recently, Walker (1977b) has elaborated on that interpretation to note that the Holston consists of a lower dominantly skeletal sand facies deposited in shallow water at the shelf-edge, and an upper boundstone plus skeletal sand facies deposited in deeper water down-slope from the shelf-edge.

Ratliff (1974) suggested the lithofacies in the Luttrell area represented a reef tract similar to the Holston but "less extensive and somewhat smaller" than that described by Walker and Ferrigno (1973). Ratliff (1974) postulated that this resulted in a less effective seaward barrier which in turn produced a higher wave and current energy gradient in the back reef sediments. The proximity of Luttrell to the measured stratigraphic sections of the subject area and their coincidence with the Middle Ordovician shelf margin can be seen in Figure 1.3 (page 6). The facies developed along this high energy gradient, near the shelf margin and on-shelf, are represented by the Rockdell Formation. Walker et al. (1980a), Breland and Walker (1980) and Ruppel (1979) have pointed out some of the distinguishing features of the shelf margin and down-slope sediments of the Holston Formation and the near shelf margin, on-shelf facies of the Rockdell Formation.

A thin unit of poorly developed oolite was used as a time-datum for the reconstruction of the middle stratigraphic package shown in

Figure 2.19. Sediments comprising this thin key bed are interpreted to have been spread across the shelf in a brief period of time, perhaps by a major storm (Figure 2.20A and 2.20B). Of the approximately 450 samples collected in the study area, ooids were confined to the Rockdell Formation and were observed in only four samples, one in each measured stratigraphic section. The stratigraphic position of the oolite samples in each section was as follows: Graveston, 164.0 m.; Harbison, 161.0 m.; Halls Crossroads, 205.0 m.; and Dry Gap, 165.0 m.

Rockdell Formation. The Rockdell in the study area is characterized by a complex assemblage of pelmatozoan-bryozoan packstone/grainstones, bryozoan wackestones and bryozoan-algal boundstones. These particular lithofacies are interpreted to represent sand bank/tidal channel, mud-mound and patch reef environments respectively (see Figure 2.19). The dominant facies of the Rockdell is the packstone/grainstone facies (Figure 2.20C) which, in the field, is usually well exposed and weathers to massive blocks that show a digitate weathering pattern (Figure 2.20D). At Graveston and Harbison the Rockdell overlies the poorly sorted pelmatozoan-bryozoan packstone/grainstones of the Lincolnshire Formation (Figure 2.3, page 17). Although many similarities exist between the lithofacies of the Rockdell and Lincolnshire, a major difference is the presence of abundant oncolites and fragments of Solenopora sp. found in the Lincolnshire. The abundance of algae markedly decreases upward in the sections at Graveston and Harbison (Figure 2.11, page 27, and Figure 2.14, page 30), but the base of the Rockdell at these sections has a well developed algal flora (see Figure 2.12, page 28, and Figure 2.15, page 31). Two algae generally not associated with the Lincolnshire,

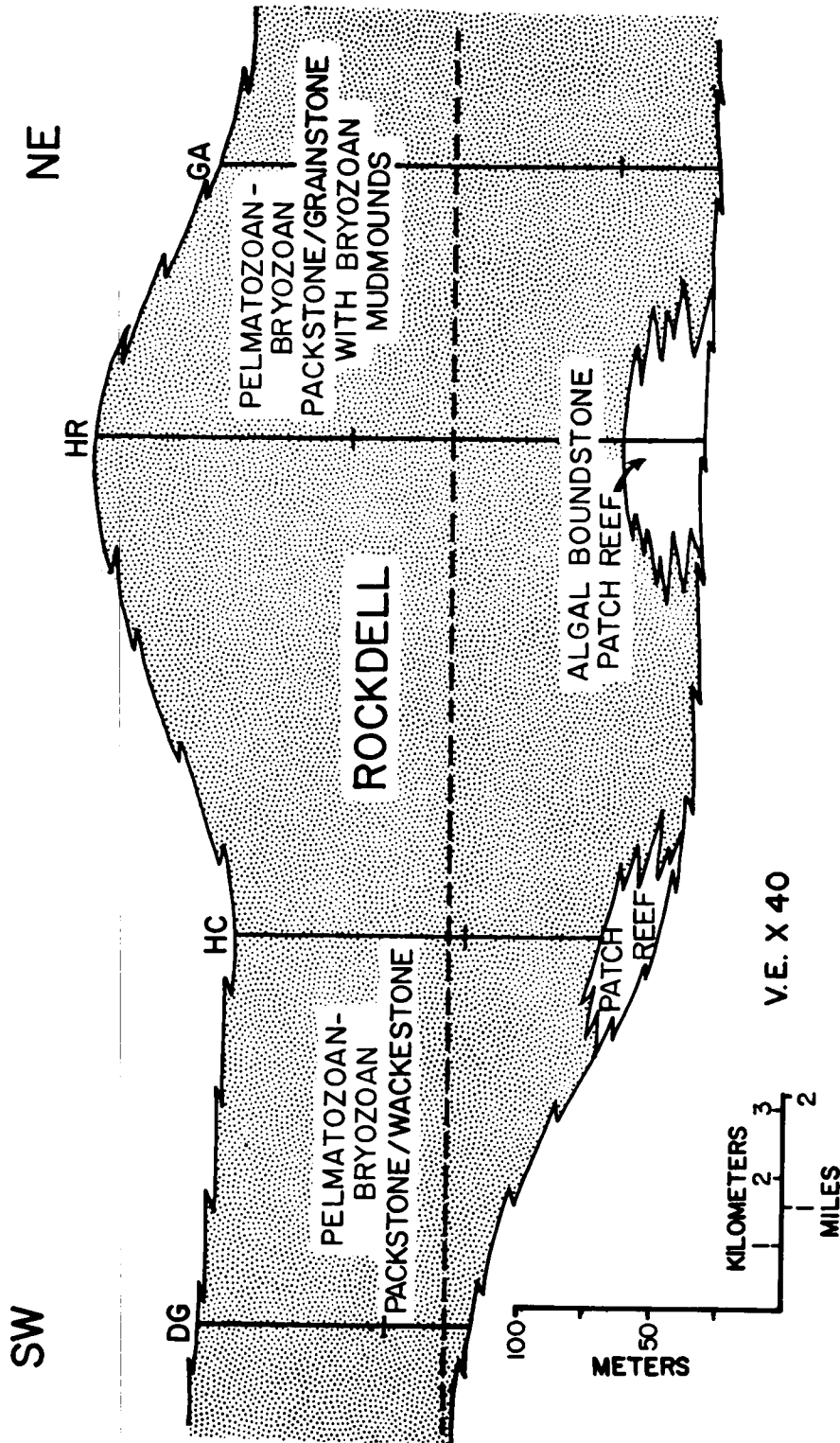


Figure 2.19. Middle stratigraphic package representing near shelf margin and on-shelf patch reef environments.

The stratigraphic datum (i.e., time line) used in this reconstruction (horizontal dashed line) is a thin unit of poorly developed oolite interpreted to have been deposited across the shelf in a brief period of time, perhaps by storm activity.

Figure 2.20. Petrographic features of the Rockdell Formation.

- A. Photomicrograph of ooids in an ooid-pelmatozoan grainstone. Note the development of thin micrite envelopes on some pelmatozoan fragments. Graveston section (GA19E). 25X.
- B. Photomicrograph of a single poorly developed ooid. Note the concentric layers of calcite around the central pelmatozoan fragment. Two to three layers are common. Dry Gap section (DG4A). 100X.
- C. Photomicrograph of a typical pelmatozoan-bryozoan grainstone. Note the bryozoan fragment in the central portion of the photo. Also note the development of syntaxial overgrowths on the abundant pelmatozoan fragments. Graveston section (GA7A). 25X.
- D. Digitate weathering common on many massive blocks of pelmatozoan grainstones. Graveston section. Scale divisions are 10.0 cm.
- E. Typical field exposure showing the lateral and vertical discontinuity of outcrop. Graveston section. Scale (in center of photo) is 2.0 m.
- F. Photograph showing abundant pelmatozoan holdfasts associated with many of the bryozoan "mudmounds." Graveston section. Scale is 10.0 cm.
- G. Typical bryozoan bound "mudmound." Note the encrusting bryozoans, a few isolated pelmatozoan holdfasts, styolitic surface and muddy nature of the exposure. Graveston section. Scale is 10.0 cm.
- H. Photomicrograph of typical Rockdell lithofacies found at Dry Gap. Note the presence of mollusk fragment (in center of photo), gastropods, trilobite, isolated sponge spicules and the problematical alga Nuia sp. Dry Gap section (DG5B). 25X.

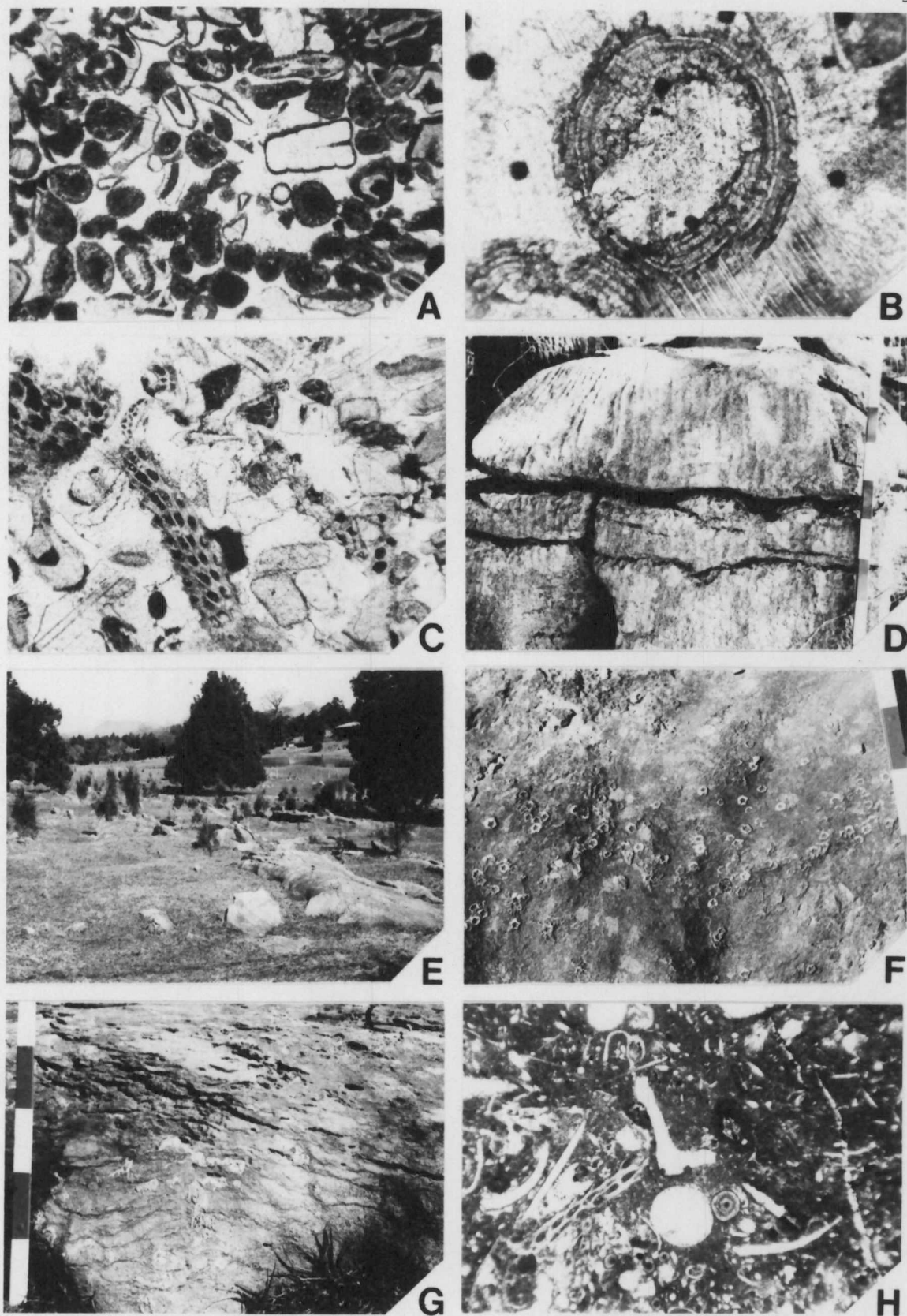


Figure 2.20.

Kazakhstanelia sp. and Contexa sp., occur at the base of the Rockdell (Figure 2.15, page 31). The algal flora at the base of the Rockdell, in part, represents the transition of the Lincolnshire to Rockdell environments but primarily these algae are associated with the development of patch reefs in the lower Rockdell (Figure 2.19).

The exposures of the Rockdell at Graveston and Harbison are characteristically discontinuous both vertically and laterally as illustrated in Figure 2.20E. The pelmatozoan-bryozoan packstone/grainstone facies interfingers both laterally and vertically in a patch-quilt fashion with the bryozoan wackestone "mudmound" facies. This "mudmound" facies consists primarily of encrusting and bifoliate bryozoans, relatively unabridged pelmatozoan debris and considerably more lime mud, usually red in color, in contrast to the more well washed and abridged sediments of the packstone/grainstone facies. Abundant pelmatozoan holdfasts (Figure 2.20F) observed on many of the "mudmounds" suggest that the pelmatozoans may have acted as a current baffle to trap fine grained carbonate sediments. The presence of abundant encrusting bryozoans, associated with pelmatozoan holdfasts (Figure 2.20G), implies that these organisms acted to bind carbonate mud to produce these "mudmounds." The mudmound lithofacies was not so massively encrusted with bryozoans that it could be classified as a boundstone or interpreted as reef core material (term from Walker and Ferrigno, 1973).

Bryozoans and echinoderms decrease in relative abundance near the top of the Rockdell, particularly in the Graveston section (Figure 2.11, page 27, and Figure 2.14, page 30), and the proportion of micrite to spar increases upward (Figure 2.10, page 26, and Figure 2.13, page 29).

To the southwest at Halls Crossroads and Dry Gap, the Rockdell Formation overlies the Fleanor Formation and is thinner (Figure 2.19). Carbonate mud (but not mudmounds) is more common (Figure 2.4, page 20, and Figure 2.7, page 23) than at Harbison and Graveston (Figure 2.10, page 26, and Figure 2.13, page 29). This increase in carbonate mud produces a gradual change in lithofacies laterally across the study area. Bryozoan "mudmounds" are almost nonexistent at Dry Gap and Halls Crossroads and the packstone/grainstone facies is not well developed. Also, algae are less abundant (Figure 2.6, page 22, and Figure 2.9, page 25) than in the northeast sections, particularly at Dry Gap, and the relative abundance of sponges increases (Figure 2.5, page 21, and Figure 2.8, page 24). Figure 2.20H is a representative example of the Rockdell lithofacies in the southwestern portion of the study area, particularly at Dry Gap.

One feature of the fauna observed in the upper Rockdell at Halls Crossroads and not seen at the other stratigraphic sections is stromatoporoids (designated other fossils in Figure 2.8, page 24). These stromatoporoids encrusted a muddy substrate (Figure 2.21A) in the Rockdell environment, but do not become an abundant faunal component until higher in the section at Halls Crossroads.

Another significant feature of the Rockdell Formation is the development of patch reefs at the base of the formation at Harbison and Halls Crossroads (see Figure 2.19). These limestone bodies are localized in area both vertically and laterally and are interpreted to be patch reefs primarily on the basis of diagnostic lithologic characteristics (e.g., core and flank deposits; terms from Walker and Ferrigno, 1973). The specimen in Figure 2.21B is interesting because it illustrates the

Figure 2.21. Petrographic features of the Rockdell and Chapman Ridge Formations.

- A. Encrusting stromatoporoid in the upper Rockdell at the Halls Crossroads section. Note the sharp contact between the overlying stromatoporoid and underlying mud substrate. Halls Crossroads section (HC8A).
- B. Specimen collected at the patch reef in the lower Rockdell at the Harbison section which shows the contact between pelmatozoan grainstone "flank" deposit at upper left and the bryozoan-algal boundstone "core" deposit at right. Note the layered nature of the flank material and the encrusting bryozoans (white) on red muds (dark) of the core material. Harbison section (HR6-2PR).
- C. Photonegative print of a petrographic thin section taken from the sample in Figure 2.21B at the contact of the flank and core material. Note the distinctive layering of the flank material. Harbison section (HRG-2PR). 1X.
- D. Typical exposure of the fine grained red bryozoan wackestone from the Chapman Ridge Formation. Note the thin bedded nature of the exposure. Halls Crossroads section. Scale in 10.0 cm. units.
- E. Sample from the Chapman Ridge showing small patches of encrusting bryozoans (white) and a comparatively large ramose bryozoan (top center). Halls Crossroads section (HC11C).
- F. Photomicrograph of a phylloporinid bryozoan, the dominant type of encrusting bryozoan observed in thin sections of the Chapman Ridge. Halls Crossroads section (HC13E). 25X.
- G. Photomicrograph of Pulchrilamina sp. This organism and lithistid demosponges are important sediment binders in the Chapman Ridge Formation. Halls Crossroads section (HC11C). 25X.
- H. Photomicrograph of the typical lithofacies of the Chapman Ridge in petrographic thin section. Note geopetal structure produced by internal sediment filled cavities. Harbison section (HR16B). 25X.

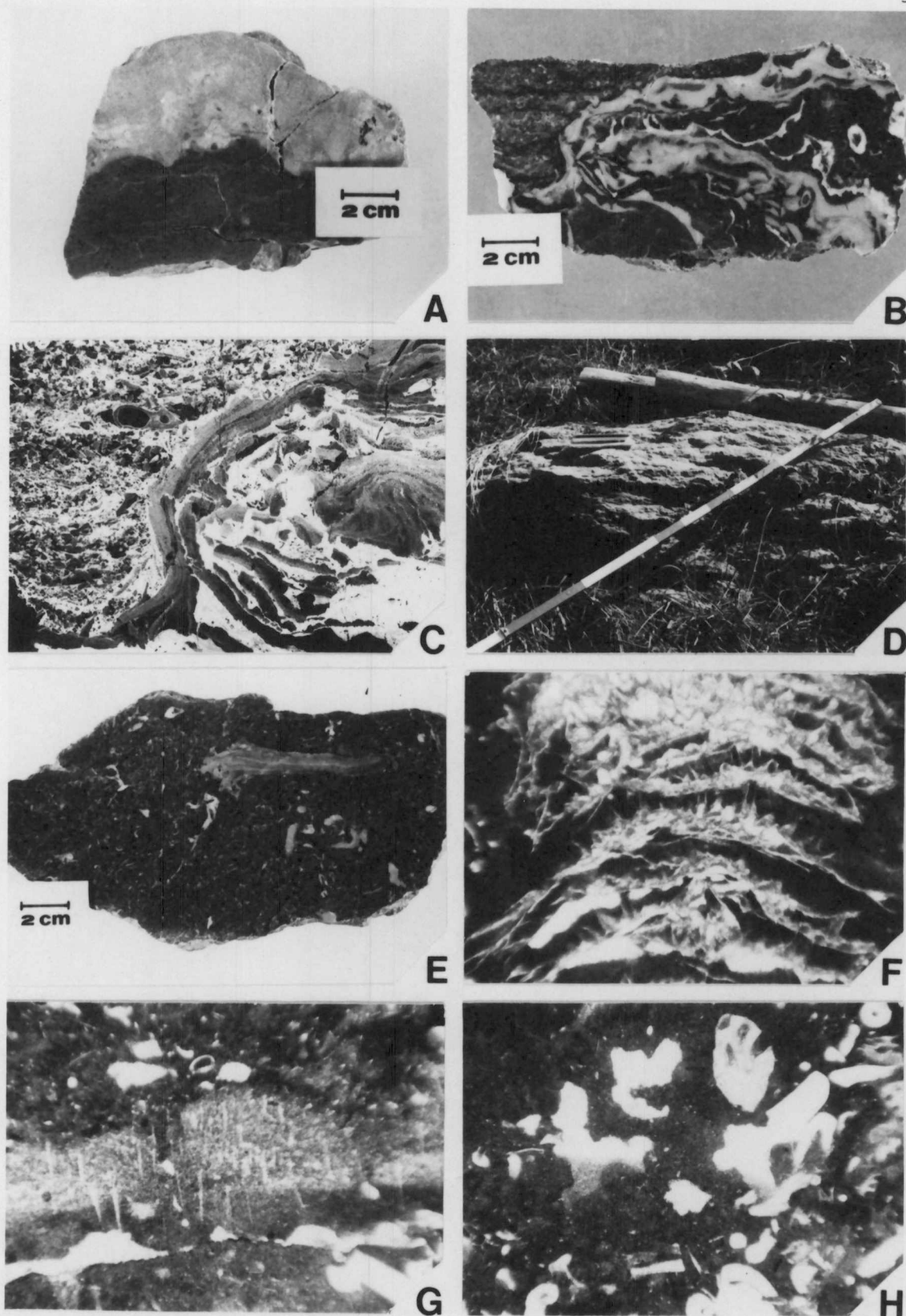


Figure 2.21.

character of both flank and core deposits. Figure 2.21C is a photonegative print of a petrographic thin section taken from the contact between the core and flank material on the hand specimen in Figure 2.21B. Figure 2.21C illustrates the bedded nature of the flank material (left) and the sharp contact between flank material and the encrusting bryozoan (right), in this case Batostoma sp. It is obvious from this specimen that the bryozoan formed a hard substrate at the surface of the boundstone. The flank material is most commonly a pelmatozoan-bryozoan packstone/grainstone facies which often contains eroded and transported fragments of the core complex such as encrusting bryozoans, algae and fragments of radial fibrous marine cement (Bathurst, 1975) which formed penecontemporaneously with the core material. One aspect of the patch reefs, particularly the one at Harbison, which has been reported recently (Breland and Walker, 1980) is the presence of the encrusting alga Solenopora sp., which acted as a sediment binder in the core material, a role taken exclusively by encrusting bryozoans in Holston boundstones. A more detailed examination of these patch reefs will be presented in the next chapter.

The Rockdell Formation in the vicinity of Graveston and Harbison, is interpreted to represent an inner shelf-shelf margin transition area. According to Multer (1977), transition areas are "stabilized or migrating channels, banks or belts between two distinctly different environmental areas and are subject to tidal action and are generally limited in areal extent." The major buildup of skeletal sands along strike to the northeast, reported by Ratliff (1974) and the thin, carbonate mud rich, poorly developed Rockdell to the southwest strongly suggest such a transitional area.

The paucity of carbonate mud, well sorted, well washed and abraided nature of the packstone/grainstone indicates moderate current activity. The bryozoan wackestone "mudmound" facies is intimately associated with the packstone/grainstone facies. The patchlike accumulation of carbonate mud on the skeletal sands and the formation of "mudmounds" is no doubt a response to local hydrodynamic conditions (tidal influences and topography) and the trapping and binding activity of pelmatozoans and algae. From personal observation of recent carbonate sedimentation in South Florida, it is not uncommon to find tidal channel deposits of coarse Halimeda sp. sands in sharp contact with adjacent areas of carbonate mud accumulation stabilized by the grass Thalassia testudinum. Stalked echinoderms commonly associated with many "mudmounds" apparently acted as a current baffle to trap fine grained sediment and the encrusting bryozoans and algae acted to stabilize and bind these sediments. Marine cement forming penecontemporaneously with deposition of the mudmounds was also important as a binding agent.

Wanless (1969) studied similar recent sediments in an analogous transition area in Biscayne Bay and reported the presence of nontidal and tidally influenced migrating mud and sand banks. He noted two distinct sediment types that produced patchlike accumulations: skeletal sands that were winnowed by wave and tidal current activity and lime mud deposits that were controlled primarily by hydrodynamic considerations and the grass Thalassia sp. Analogous modern environments in South Florida and the Bahamas have been reported by Turmel and Swanson (1964), Basan (1973), Enos (1974a, 1974b) and Multer (1977). Ruppel (1979) examined Middle Ordovician carbonates in the same strike belt as the

present study but further to the northeast and discussed similar lithologies which he interpreted to have been deposited in a shallow water skeletal sand bank environment. Ratliff (1974) looked at an almost identical facies in the same strike belt as the present study and interpreted the rocks to represent an outer shelf back reef skeletal sand bank environment.

To the southwest at Dry Gap and Halls Crossroads, a gradual lithofacies change occurs primarily due to an increase in the percentage of carbonate mud. Also, the Rockdell thins toward the southwest, the packstone/grainstone facies is not well developed and the bryozoan wackestone "mudmounds" are almost nonexistent. These facts, plus the increase in abundance of demosponges and stromatoporoids, the decrease in relative abundance of algae and the position of patch reefs in the study area suggest an inner shelf, shallow water shoal environment somewhat restricted and removed from the higher current energies encountered in the sand bank and tidal channel environments of the transition area to the northeast. The "restricted" nature of the environment is, in part, due to the development of the patch reefs to the northeast across the shelf. Multer (1977) has reported similar analogous modern environments in South Florida.

The growth of patch reefs in South Florida are a function of shelf topography (Enos, 1974a) and position on the shelf (Hoffmeister and Multer, 1968). The demise of on-shelf patch reefs at the base of the Rockdell can best be explained by the gradual transgression of the near shelf margin and transition area environments. The lithofacies of the upper Rockdell at Harbison are almost identical to those observed at Gravelston.

The greatest thickness of skeletal sands is located to the northeast at the Graveston and Harbison sections, particularly at Harbison (Figure 2.19, page 48). Apparently, the shelf margin migrated toward the southwest in the study area and stabilization of environmental conditions in the vicinity of Harbison resulted in the accumulation of skeletal sands and carbonate mud of the transition area environments. Sedimentation continued in the Rockdell until environmental conditions altered enough to allow the onset of deposition of the upper stratigraphic package.

Summary. The Rockdell Formation in the northeastern portion of the study area represents a transition area (term after Multer, 1977) between inner shelf deposits to the southwest and outer shelf-shelf margin deposits further to the northeast. Transition area environments consist of skeletal sand banks, tidal channels and mudmounds which were characterized by pelmatozoan-bryozoan packstone/grainstones and bryozoan wackestone/boundstones respectively. Southwestward along strike the Rockdell becomes a relatively thinner sequence of pelmatozoan-bryozoan packstone/grainstones with more abundant carbonate mud and representing a more restricted, shallow water, shoaling environment. Patch reefs flourished on the inner shelf between the relatively higher current energy environments to the northeast and the lower current energy environments to the southwest.

Upper Stratigraphic Package—Shallow Marine
(Restricted Lagoon) and Peritidal Environments

Southeast of the regional shelf-edge, the "Sevier" basin was slowly filling with fine mud during the deposition of the middle stratigraphic package (Walker, 1977a). However, as deposition continued, terrigenous sediments from the southeast filled the basin and spilled northwestward to kill the shelf-edge Holston reef complex (Walker, 1977a; see Figure 1.3, page 6, for location of shelf-edge). Deposition of the upper stratigraphic package in the study area is, in part, a direct response to the first time when the basin became sufficiently filled to allow sediment to be transported from the southeast onto the carbonate shelf.

The upper stratigraphic package consists of complexly interrelated lithofacies of the Chapman Ridge, Ottosee, Benbolt, Wardell, Bowen and Witten Formations and is reconstructed in Figure 2.22. One of the curious features of this package is the presence of the Chapman Ridge and Ottosee Formations which are generally not associated with the inner shelf deposits (Figure 2.1, page 11). The stratigraphic datum used in the reconstruction is the Bowen Formation. Use of the Bowen as a time datum has been discussed previously.

Chapman Ridge Formation. The Chapman Ridge is not widespread in the study area but is well exposed at the Halls Crossroads and Harbison sections (see Figure 2.22). There, the Chapman Ridge is predominantly a thin to medium bedded, maroon to red, fine to medium grained bryozoan wackestone/packstone (Figure 2.21D, page 53). Sedimentation was dominated by carbonate mud reflected in the high micrite to spar ratio

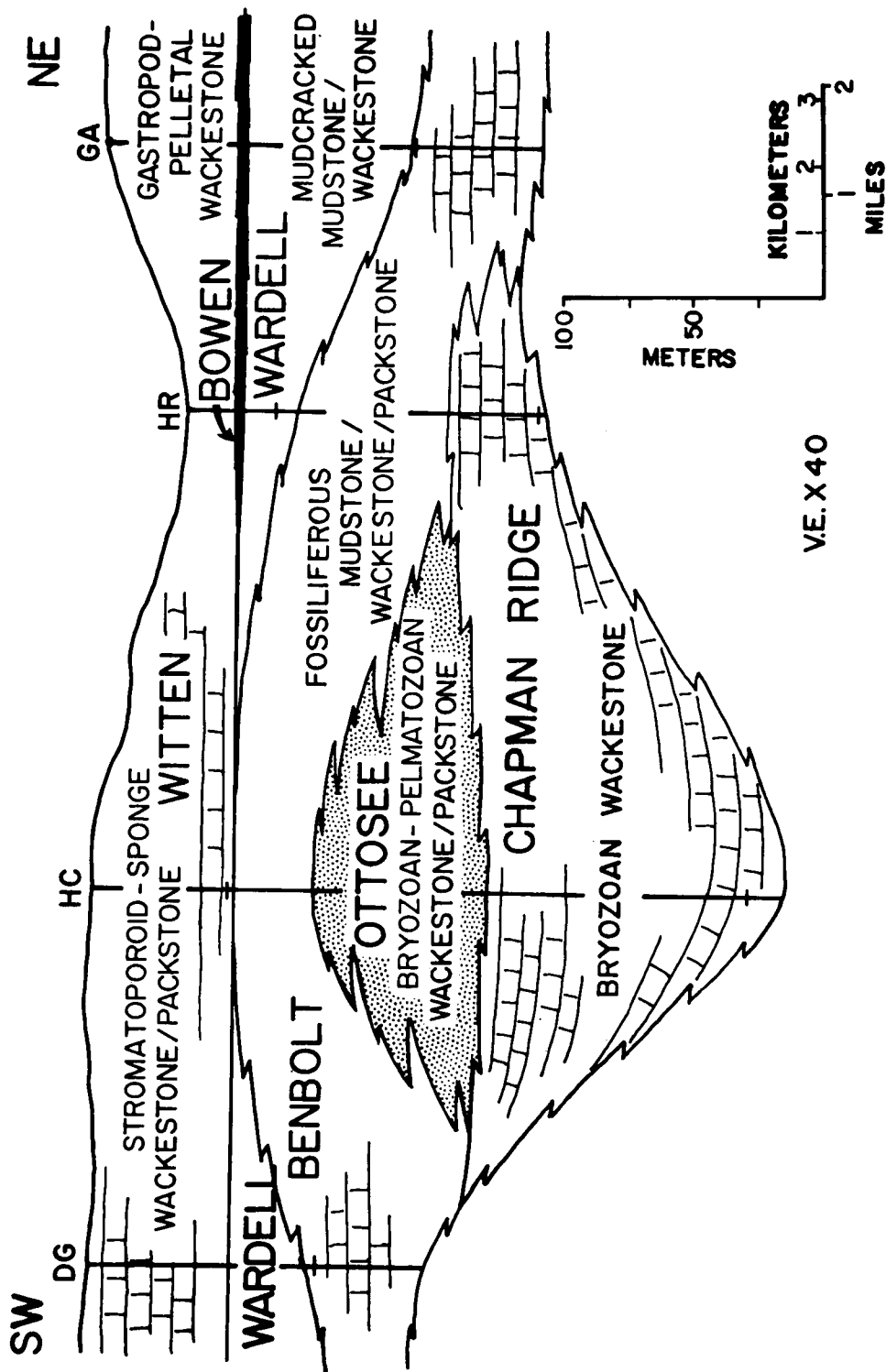


Figure 2.22. Upper stratigraphic package representing shallow marine (restricted lagoon) and peritidal environments.

Stratigraphic datum used in this reconstruction is the Bowen Formation. The Bowen is a thin unit (approx. 2.0 m.) representing a very brief period of progradational deposition, and therefore probably represents an approximate isochronous surface.

(Figure 2.7, page 23, and Figure 2.10, page 26). Major faunal components in the Chapman Ridge are ramose and encrusting bryozoans and secondary amounts of pelmatozoan debris (Figure 2.8, page 24, and Figure 2.11, page 27).

Large (2.0 cm. in diameter) ramose bryozoans commonly are encased in a matrix of red mud (Figure 2.21E, page 53), however, encrusting bryozoans (Figure 2.21F, page 53) are more abundant than the ramose bryozoans and more important as sediment binders. Phylloporinid bryozoans (Figure 2.21F, page 53) are the dominant type of encrusting bryozoan observed in thin section.

Subsidiary in relative abundance but also important as sediment binders are lithistid demosponges and the problematical sponge-like organism Pulchrilamina sp. (Figure 2.21G, page 53). Toomey and Ham (1967) first described Pulchrilamina sp. from the Lower Ordovician of Texas and Oklahoma as an important mound-building organism. Field and thin section observations do not suggest that Pulchrilamina sp. and the more abundant encrusting bryozoans were mound-builders but rather that these organisms, along with the ramose bryozoans, were stabilizers and binders of sediment deposited in a shallow, quiet water environment.

The Chapman Ridge in the Halls Crossroads section exhibits a diverse algal flora (Figure 2.9, page 25). Moore (1977) observed similar algal assemblages in what he interpreted to be restricted lagoon or mud-bank environments. This interpretation of restricted lagoon corresponds well with an expected environment for growth of the bryozoans and sponges as well as the sedimentological features of the deposit (i.e., thin bedding and high percentage of carbonate mud).

Figure 2.21H (page 53) shows the typical lithofacies of the Chapman Ridge encountered in the study area. The Chapman Ridge in the study area is somewhat atypical of the rocks in its type section. Usually it is characterized by pelmatozoan debris, bryozoan fragments, terrigenous quartz silt and an abundance of current-induced sedimentary structures (Walker, 1977b). McWilliams (1975) studied the Chapman Ridge Formation in East Tennessee and observed that it is common to find wackestones at the base of the Chapman Ridge. Walker (pers. comm., 1980) observed a similarity between the lithofacies described by McWilliams and the lithofacies in the present study area and suggested that the bryozoan wackestones at Halls Crossroads and Harbison represent fine grained sediment deposited onto the inner shelf but derived from the distal primary center of deposition of the Chapman Ridge near the shelf-edge to the southeast. Figure 2.1 (page 11) shows the relationship of the Chapman Ridge to the shelf-edge and the present study area (the line of sections is oriented perpendicular to strike; the present study area is located in the same strike belt as Fountain City (FC).

Recall that the shelf-edge is oriented southwest-northeast and only in the study area does the shelf-edge depart abruptly from that general trend (see Figure 1.3, page 6). Sedimentation appears to have been restricted topographically along strike as evidenced by the localized nature of the deposits (Figure 2.22). The Chapman Ridge and Ottosee Formations are interpreted to be influenced by and partially derived from a source to the southeast. Deposition in the study area was a function of the initial spilling over of these sediments onto the carbonate shelf as the basin to the southeast was finally filled. This interpretation

would explain the occurrence and stratigraphic position of these deposits in the area of study. It would also explain, in part, the restricted nature of the sedimentation because major accumulations of the Chapman Ridge and Ottosee sediments are associated with the basin and shelf margin to the southeast. Therefore, the Chapman Ridge and Ottosee in the study area represent a minor influx of sediments derived from the southeast which were superimposed onto carbonate shelf sediments accumulating along a southeast-northwest depositional strike.

Ottosee Formation. In the study area the Ottosee Formation was observed only at Halls Crossroads section and is poorly exposed, particularly at the base, where it is covered. The upper part of the Ottosee is a grey, medium to coarse grained bryozoan-pelmatozoan wackestone/packstone (Figure 2.23A) and weathers to small, massive blocks (Figure 2.23B). These wackestone/packstone units are interbedded and interfinger with a shaly facies that is poorly resistant to weathering. The Ottosee lithofacies is dominated by micrite with minor amounts of spar and well rounded intraclasts (Figure 2.7, page 23). Pelmatozoan debris and bryozoan fragments are the most important faunal components (Figure 2.8, page 24); except for minor amounts of transported fragments of Girvanella sp. and Spongiostroma sp. (Figure 2.9, page 25) algae are relatively rare.

Deposition of the Ottosee lithofacies appears to have been very localized in the area of study (see Figure 2.22) and is closely associated with the Chapman Ridge. As was mentioned above in the section on the Chapman Ridge, the sediments of the Ottosee probably influenced and perhaps partly derived from a southeastern source near the shelf-edge.

Figure 2.23. Petrographic features of the Ottosee and Benbolt Formations.

- A. Photomicrograph of a representative bryozoan-pelmatozoan packstone in the upper Ottosee. Halls Crossroads section (HC14C). 25X.
- B. Weathering characteristics and discontinuous nature of exposure of the upper Ottosee. Wackestone/grainstones are interbedded with a shaly facies to produce discontinuous exposures both horizontally and vertically. Halls Crossroads section. Scale is 2.0 m.
- C. Thin bedded limestone and shale of the Benbolt Formation. The shales weather to a distinctive yellowish to buff color. Graveston section. Scale in 10.0 cm.
- D. Photomicrograph of a typical fossiliferous wackestone in the Benbolt Formation. Note the two small cavities (lower center) partially filled with internal sediment. Dry Gap section (DG9D). 25X.
- E. Photonegative print of a thin section from the Benbolt Formation. Note the comparatively large lithistid sponge (center). The lithistid sponges encrusted muddy, soft substrates, and are recognized by the characteristic radiating ladder-like internal structure. Harbison section (HR17A). 1.5X.
- F. Photomicrograph of a hemispherical or irregularly lobate Girvanella sp. oncolite. Girvanella sp. oncolites are indicative of shallow water and their lobate shape implies low to moderate current activity. Dry Gap section (DG9B). 25X.
- G. Photomicrograph of lumpy and clotted appearance of the encrusting alga Girvanella sp. This growth form of Girvanella sp. is indicative of shallow, quiet water (protected) sublittoral zones. Dry Gap section (DG11A). 25X.
- H. Photomicrograph of an algal wackestone from the Benbolt Formation. The alga, Kazakhstanella sp., is preserved in probable life position. Graveston section (GA30B). 25X.

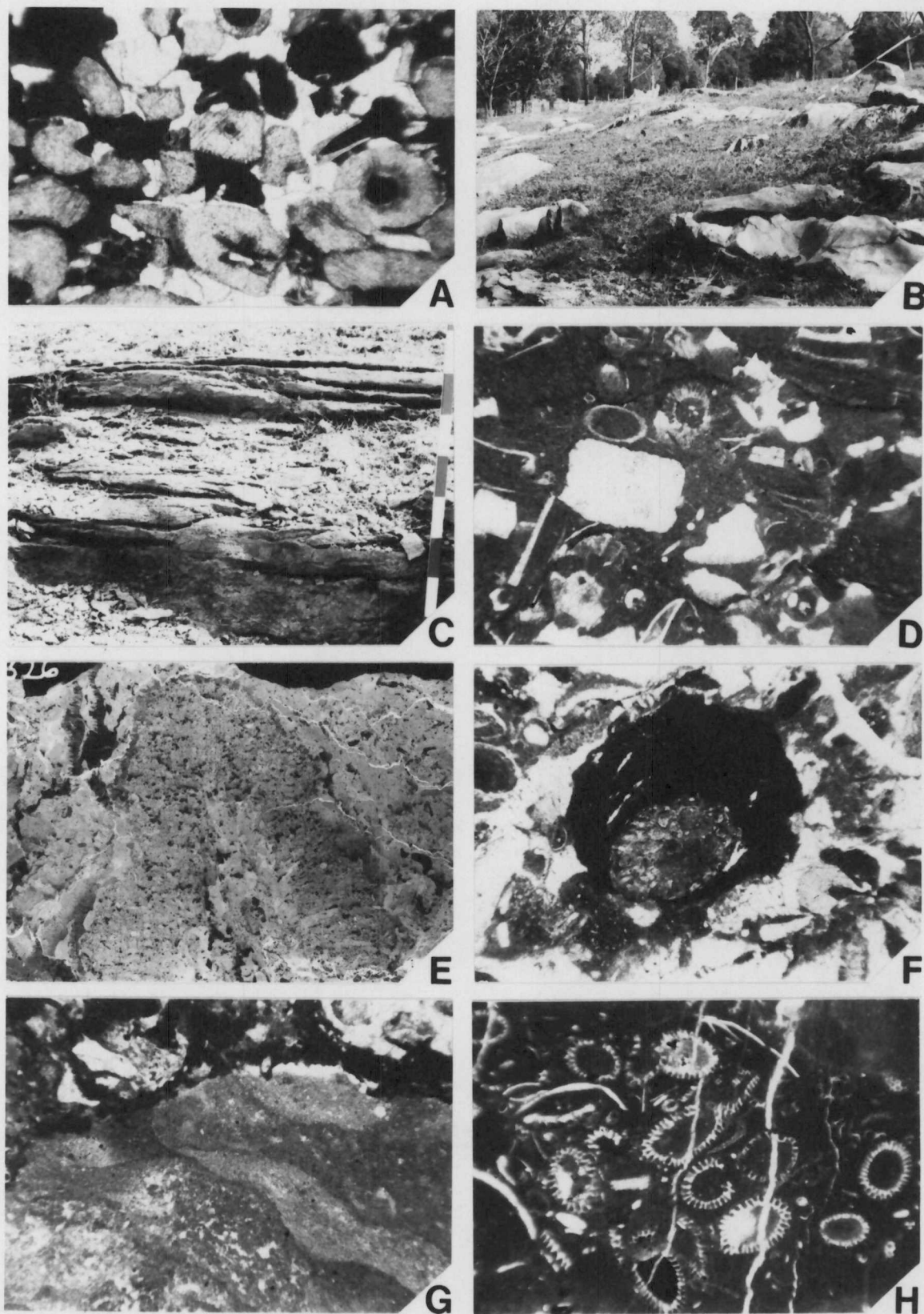


Figure 2.23.

In the study area, maroon bryozoan wackestones of the Chapman Ridge grade upward into a shaly nonresistant facies of the lower Ottosee. This shaly facies grades upward into coarser grained, more weather resistant carbonates of the upper Ottosee wackestone/packstone facies. The change in facies vertically in the section from mainly shale to interbedded shales and transported wackestone/packstones reveals an obvious change in environmental conditions. The shales of the lower Ottosee reflect quiet water conditions similar to the restricted lagoonal environment of the Chapman Ridge. These shales might also be interpreted to indicate availability of terrigenous material in the area. The coarser grained material of the upper Ottosee, although presumably somewhat restricted from the full influence of the shelf-edge and surrounding topography, reflects higher current energies, perhaps a shallow (1-6 ^M ~~cm~~) subtidal shoaling environment or simply less turbid water allowing more prolific growth of organisms and accumulation of skeletons. This depositional regime was, however, localized and short lived and soon gave way to the shallow, quiet water lagoonal environment of the Benbolt Formation.

Benbolt Formation. The Benbolt occurs at all localities in the study area and averages approximately 50.0 m. in thickness (Figure 2.22, page 60). The contact between the Benbolt and underlying Rockdell, Chapman Ridge and Ottosee Formations is generally distinctive because of the abundance of thin to nodular bedded shale in the Benbolt. The weathering of shaly facies (Figure 2.23C) of the Benbolt produces a characteristic yellowish brown coloration. The presence of the sponge Allosaccus sp. and the problematical alga Receptaculites sp. (considered

as lithologic constituents) were also used to delineate the base of the Benbolt. The boundary between the Benbolt and Wardell is less clear and will be discussed in more detail in the next section.

The Benbolt is generally a thin bedded, yellowish brown to grey, poorly exposed, burrowed, fossiliferous wackestone in the field. The wackestones are interbedded with the shaly facies and bedding is generally not laterally continuous. However, occasionally bedding can be followed laterally for tens of meters. Figure 2.23D shows the fossiliferous wackestone lithofacies. Chertification of bryozoans, brachiopods, and pelmatozoans is commonly observed in the facies.

The carbonate mud content of the Benbolt is illustrated by the high micrite to spar ratio at all localities (Figure 2.4, page 20; Figure 2.7, page 23; Figure 2.10, page 26; and Figure 2.13, page 29). Pellets form an important nonfossil component in some localities and a general trend can be seen as the volume percentage of pellets decreases southward across the study area from Graveston to Dry Gap (Figure 2.4, page 20; Figure 2.7, page 23; Figure 2.10, page 26; and Figure 2.14, page 30). The pellets are fairly uniform in size (approximately 0.2 mm. in diameter) and shape (circular to elliptical) and are probably fecal in origin.

The concentration of bryozoans and echinoderms at Graveston is small (Figure 2.14, page 30) compared to the relatively high concentration of pellets and carbonate mud. The volume percent of bryozoans and pelmatozoans increases slightly at the other localities (Figure 2.5, page 21; Figure 2.8, page 24; and Figure 2.11, page 27). Two encrusting bryozoans that are frequently observed in thin section are Constellaria sp. and

Hallopora sp. Bifoliate bryozoans are subordinate in volume percentage to the encrusting bryozoans. The excellent preservation of delicate features of fossil allochems suggests little or no transportation.

Sponges do not constitute an important part of the rocks at Graveston (Figure 2.14, page 30) and Dry Gap (Figure 2.5, page 21) but at Halls Crossroads and Harbison (Figure 2.8, page 24, and Figure 2.11, page 27) sponges are more abundant. The sponges are nearly always found in muddy lithofacies and apparently encrusted the mud substrate. Figure 2.23E shows a lithistid sponge encrusting a muddy, soft substrate.

Algae are not particularly abundant in the Benbolt in the study area (Figure 2.5, page 21; Figure 2.8, page 24; Figure 2.11, page 27; and Figure 2.14, page 30), but they exhibit some diversity (Figure 2.6, page 22; Figure 2.9, page 25; Figure 2.12, page 28; and Figure 2.15, page 31). Hemispherical or irregular Girvanella sp. oncolites (Figure 2.23F) have a limited occurrence at Dry Gap and Halls Crossroads. Girvanella sp. occurs in mottled lumps or matrix component (Moore, 1978) in wackestones at Harbison (Figure 2.23G). Occasionally the alga Kazakhstanelia sp. is found in probable life position (Figure 2.23H).

Ostracods, trilobites, gastropods, brachiopods and mollusks are sometimes quite noticeable in the field but are usually found in minor amounts in thin section and rarely contribute more than a few percent of the total volume of the rocks (see Figure 2.5, page 21; Figure 2.8, page 24; Figure 2.11, page 27; and Figure 2.14, page 30). Worms may have been present as evidenced by the numerous burrows observed in the field and thin section although other organisms were capable of burrowing also. In thin section, the burrows are commonly filled with microspar and

dolomite, and the boundary between the mud matrix and the burrow is always gradational indicating that the organism lived in a soft mud with a relatively high water content (Walker, 1974). The unabraded remains of trilobites, gastropods and other mollusks encased in mud suggest that these organisms were indigenous to the environment and lived on the organics in the mud. Brachiopods and sponges were also indigenous but the comparatively high suspended mud content in the environment would not have been ideal for filter feeding organisms and may have prevented these particular organisms from developing in significant numbers. Development of larvae in muddy substrate may also have been inhibitive.

According to Boardman (1960), bryozoans prefer muddy environments but must have moderate current movement. Echinoderms also require relatively clear water environments with active water circulation (Broadhead, pers. comm., 1980). The relatively low volume percent of pelmatozoans and bryozoans suggests that turbid environmental conditions were not suitable for these organisms to develop in large numbers.

The high concentration of shales in the Benbolt, particularly in the upper part, indicates a marked terrigenous influence and perhaps a slight increase in water depth. The minor presence of algae in this shelf environment suggests that the water may have been too turbid to allow development of abundant and diverse plant growth.

Ruppel (1977) interpreted the rarity or absence of algae in the upper Benbolt as a combination of a slight deepening of water and a reduction in light penetration due to turbidity caused by influx of terrigenous silt and clay. The preservation of algae in growth position (Figure 2.23H) argues for a very quiet water environment. Ahr (1971)

found that nonlaminated algal macrostructures, such as clotted fabric (Figure 2.23G, page 64) are indicative of quiet water, protected sublittoral environments. Ginsburg (1960) noted that hemispherical or irregular lobate oncolites (Figure 2.23F, page 64) are produced by low to moderate current activity. Irregular lobate oncolites are associated with minor deposits of bryozoan-pelmatozoan packstones. This packstone lithofacies, along with the oncolites, probably accumulated in response to tidal channeling activity and subject to low to moderate current conditions. The lower Benbolt in the study area can therefore be characterized as being a complex of tidal sand/mud flat deposits that interfingers with a quiet water, shallow (1-10 m.) subtidal lagoon environment. The upper Benbolt represents deposition in a slightly deeper water protected lagoonal environment. The environmental complex of the Benbolt was influenced by the influx of fine grained terrigenous sediments.

Wardell Formation. The contact between the Wardell and Benbolt Formations is very poorly exposed and appears to be gradational. Minor lithologic and stratigraphic differences exist in the Wardell across the study area (Figure 2.22, page 60). In the northeast the Wardell has a distinctive yellowish to buff color, caused by the predominance of shale, and shows mudcracks and burrows in the upper portion (Figure 2.24A). Lithofacies at Graveston and Harbison are dominated by pelletal mudstone/wackestones that interfinger with minor deposits of well washed, well sorted pelmatozoan-bryozoan packstone/grainstone. To the southwest, the Wardell pinches out at Halls Crossroads but occurs again at Dry Gap. The lithofacies at Dry Gap is dominated by mudstone/wackestones with very minor amounts of bryozoan-pelmatozoan wackestone/packstone.

Figure 2.24. Petrographic features of the Wardell and Bowen Formations.

- A. Burrowed and mudcracked surface of the pelletal wackestone lithofacies in the upper Wardell Formation. Graveston section. Scale in 1.0 cm. units.
- B. Photomicrograph of a lithofacies in the upper Wardell Formation interpreted to be a storm deposit. Note the inconsistency in particle size in the lower portion of the photo and the abrupt change in facies at the top. Graveston section (GA34D). 25X.
- C. Photomicrograph representative of the typical mudstone/wackestone lithofacies in the upper Wardell at Dry Gap. Note the unabraded nature of the bifoliate bryozoans. Dry Gap section (DG13E). 25X.
- D. Photomicrograph of dispersed sponge spicules which are prevalent in the mudstone/wackestone facies of the upper Wardell at Dry Gap. Whole sponge specimens are rare. Dry Gap (DG12C). 25X.
- E. Photomicrograph of a corallite from a Tetradium sp. colony in the upper Wardell. Corallites commonly are filled with spar and the interstitial space is occupied by micrite; however, this particular corallite is only partially filled with spar. Dry Gap section (DE13E). 25X.
- F. Photomicrograph of a thinly laminated hemispherical Girvanella sp. oncolite (center) observed in the upper Wardell which is surrounded by a very loosely laminated Girvanella sp. matrix component. Both forms of Girvanella sp. are characteristic of very quiet water environments. Dry Gap section (DG13F). 25X.
- G. Mudcracked surface in the Bowen Formation. The deep maroon to red color, mudcracks and burrows are distinctive features of the Bowen. Graveston section. Scale is in 10.0 cm. units.
- H. Typical sample of the Bowen Formation showing abundant vertical burrows. Graveston section (GA34C).

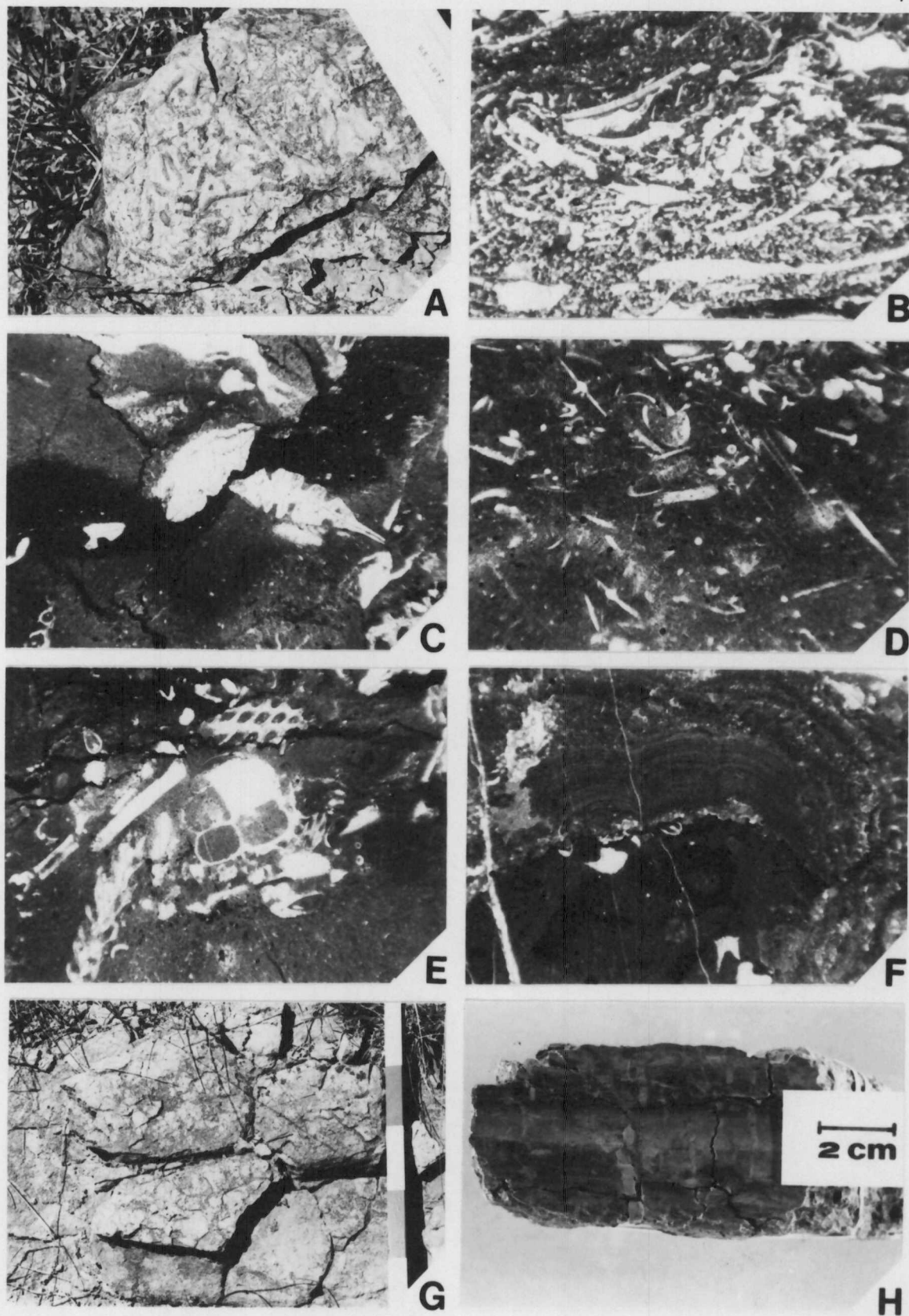


Figure 2.24.

The abundance of pellets in the northeastern portion of the study area (Figure 2.10, page 26, and Figure 2.13, page 29) follows a trend first observed in the Benbolt which continues upward in the northeast sections into the Witten Formation. The pelletal facies does not extend completely across the study area but is localized in the northeast (see Figure 2.4, page 20; Figure 2.7, page 23; Figure 2.10, page 26; and Figure 2.13, page 29) and grades laterally into a mud facies.

Except for the presence of ostracods, mollusks and minor amounts of bryozoans and pelmatozoans (Figure 2.14, page 30), the facies is almost completely dominated by pellets and carbonate mud at Graveston. Purdy (1963) observed a similar transition of pellets to mud in the Great Bahama Bank and attributed the change to a decrease in current velocity and a reduction in the formation of pellets.

Algae are limited to the lower portion of the formation and include primarily Girvanella sp. with minor amounts of Hedstroemia sp., Spongiostroma sp., the problematical alga Nuia sp. and rare Receptaculites sp. (Figure 2.12, page 28, and Figure 2.15, page 31). Girvanella sp. is in the form of irregular lobate and loosely laminated oncolites which, according to Ahr (1971), indicate low to moderate current activity. Matrix component Girvanella sp., indicate of low to moderate current activity (Moore, 1978), is also present. The assemblage of algae is similar to that which Moore (1978) recognized as being characteristic of shallow (1-3 m.) subtidal restricted lagoons (sand/mud flats) with variable but generally weak water agitation.

Irregular fenestrial fabric is sometimes associated with the pelletal facies and mudcracks of the upper Wardell at Graveston and

Harbison. Shinn (1968a) and Grover and Read (1978) reported that this type of fabric is indicative of high intertidal to supratidal environments. Ostracods and gastropods are commonly associated with this mudcracked and burrowed lithofacies, and are collectively euryhaline organisms capable of living under high stress conditions typical of peritidal environments. Abrupt changes in lithofacies (Figure 2.24B) suggest deposits washed onto the upper peritidal environment during storm activity. The mudstone/wackestone facies to the southeast is characterized by a dominance of carbonate mud with a negligible volume percent of pellets (Figure 2.4, page 20, and Figure 2.24C). Although sponges contribute only a small fraction to the total volume of rock (Figure 2.5, page 21), sponge spicules are an almost ubiquitous feature of the Wardell in this area (Figure 2.24D). The coral Tetradium sp. occurs as small, isolated and sparsely distributed colonies in the field and does not appear to constitute a major faunal element in the area until higher in the section in the Witten Formation. Rarely a single corallite of a Tetradium sp. colony is encountered in thin section (Figure 2.24E). Burrows seen in thin section are filled with microspar and dolomite and the burrow boundaries are diffuse, indicating soft mud with high water content. Algae at Dry Gap are confined to occurrences of Girvanella sp., Spongiostroma sp., Kazakhstanelia sp. and Receptaculites sp. (Figure 2.6, page 22). Bryozoans and pelmatozoans are not abundant (Figure 2.5, page 21) except in moderately well washed wackestone/packstones which contain moderately abraided and selectively pyritized bryozoans, ostracods, gastropods, pelmatozoans and algal fragments.

From the information presented above, the paleoenvironment for the lower Wardell in the northeastern portions of the study area is

interpreted to represent a shallow (1-3 m.) subtidal restricted lagoon. Minor amounts of pelmatozoans-bryozoan packstone/grainstone facies interbedded with the mudstone/wackestone facies are related to relatively higher current energies of a sand/mud flat environment associated with the shallow subtidal complex. The subtidal environment grades upward into a mudcracked and burrowed high intertidal to supratidal environment. The presence of a restricted fauna of ostracods and gastropods is suggestive of intertidal ponds.

To the southwest, the Wardell shows minor facies changes vertically. The lower Wardell at Dry Gap is interpreted to represent a shallow restricted lagoon (1-3 m.) mud flat environment. This interpretation is based primarily on the abundance of carbonate mud which generally indicates weak current conditions and the algal assemblage, particularly the presence of matrix component Girvanella sp., which is associated with shallow protected lagoons (Moore, 1977). The occurrence of the coral Tetradium sp. in the upper Wardell suggests moderate current activity. The upper Wardell at Dry Gap is interpreted to represent a shallow subtidal restricted lagoon environment with moderate current activity.

According to Shanmugan and Walker (1978), sedimentation in the basin to the southeast of the study area began to encroach upon the shelf to the northwest during the time of deposition of these formations in the upper stratigraphic package. The first influence of the southeastern source area is expressed by the deposition of the Chapman Ridge and Ottosee Formations in the study area. An influx of terrigenous shaly material is evidenced in the Benbolt. Accumulation of sediments in the

northeast along the shelf-edge culminated in the formation of peritidal environments in the upper Wardell, Bowen, Witten and Moccasin Formations. The formation of shallow water restricted lagoon environments to the southwest on the shelf is in direct response to sediment infilling to the southeast and northwest.

Bowen Formation. The Bowen Formation is a thin unit (approximately 2.0 m. thick) and observed only in the northeastern portion of the study area at Graveston and Harbison (Figure 2.22, page 60). The Bowen in the study area is characteristically maroon to red, fine grained mudstone overlying the Wardell. It commonly contains large polygonal mudcracks (Figure 2.24G) and abundant vertical burrows (Figure 2.24H). In thin section, the Bowen is a pelletal mudstone/wackestone and usually contains ostracod fragments. Irregular and laminar fenestral fabrics are also common. Petrographic features of the Bowen strongly suggest an intertidal to supratidal depositional environment.

As mentioned earlier, the Bowen is used as a time marker because it was interpreted to represent a pulse of sedimentation deposited over a geologically short period of time. Read (1978) interpreted the Bowen in Virginia to represent a prograding deltaic lobe emanating from some eastern source. Ruppel (1979), studying the Bowen in East Tennessee, supported Read's environmental interpretation. The Bowen in the study area, however, probably represents a brief period of regression in a generally transgressive sequence. The Bowen is not exposed to the southwest because the deeper water lagoonal environments present in the upper Wardell and later during Bowen time were not influenced by this short regression.

Witten Formation. The contact between the Bowen and Witten Formations (Figure 2.22, page 60) is not always clear, primarily due to poor exposure. The base of the Witten in the southwestern part of the area is also difficult to distinguish from the underlying Benbolt and Wardell Formations due to similarity in lithofacies and poor exposure. However, the contact with the overlying Moccasin Formation is fairly well defined because of the distinctive maroon to red coloration of the Moccasin. The Witten Formation is composed of two distinct lithofacies in the study area. To the northeast is a pelletal mudstone/wackestone which grades to the southwest into a stromatoporoid-sponge-coral mudstone/wackestone/packstone.

The pelletal mudstone/wackestone facies is not very fossiliferous (Figure 2.11, page 27, and Figure 2.14, page 30) and is dominated by pellets with minor amounts of micrite and spar (Figure 2.10, page 26, and Figure 2.13, page 29). In the field gastropods are quite evident but are not a distinguishing factor in petrographic thin section. Ostracods, trilobites and brachiopods are minor components and generally occur as fossil "hash," interpreted to represent storm deposits, interlaminated with pelletal muds (Figure 2.25A). Interlaminated layers of poorly sorted intraclasts (Figure 2.25B) are also a minor constituent, are generally associated with storm deposits, and are important indicators of deposition in the peritidal environment. Many of the fossil allochems, particularly the brachiopods, pelmatozoans and bryozoans, show replacement by silica. Except for minor occurrences of Hedstroemia sp. and Solenopora sp. (Figure 2.15, page 31), calcareous algae are almost nonexistent (Figure 2.11, page 27, and Figure 2.14, page 30).

Figure 2.25. Petrographic features of the Witten Formation.

- A. Photomicrograph of the pelletal mudstone/wackestone facies showing interlaminated mud and fossil "hash" interpreted to have been deposited by storm activity. Graveston section (GA35G). 25X.
- B. Photomicrograph of intraclasts which are indicative of intertidal environments. The intraclasts are often associated with storm deposits. Graveston section (GA35B). 25X.
- C. Photomicrograph of a probable primary desiccation feature. Desiccation cracks are common in the Witten and are often associated with cryptalgal lamination and fenestral fabrics. Graveston section (GA35D). 25X.
- D. Photomicrograph of laminar fenestral fabric common in the pelletal mudstone at Harbison. Laminar fenestral fabric are indicative of periodic desiccation. Harbison section (HR21D). 25X.
- E. Stromatoporoid from the upper Witten Formation at Halls Crossroads. The stromatoporoids are massive growths that encrusted a mud substrate in an anastomosing fashion. The stromatoporoids at Halls Crossroads are closely associated with large sponges (Figure 2.25G) and Tetradium sp. Halls Crossroads section.
- F. Photomicrograph of the stromatoporoid shown in Figure 2.25E. Harbison section (HR21B). 25X.
- G. Large sponge found in the upper Witten Formation at Halls Crossroads. It is not uncommon to find sponge heads 20.0 to 30.0 cm. in diameter. Halls Crossroads section. Scale is in cm.
- H. Photograph of numerous sponge spicules in a wackestone. Note the microspar filled burrow in the lower right corner. Dry Gap section (DG15B). 25X.

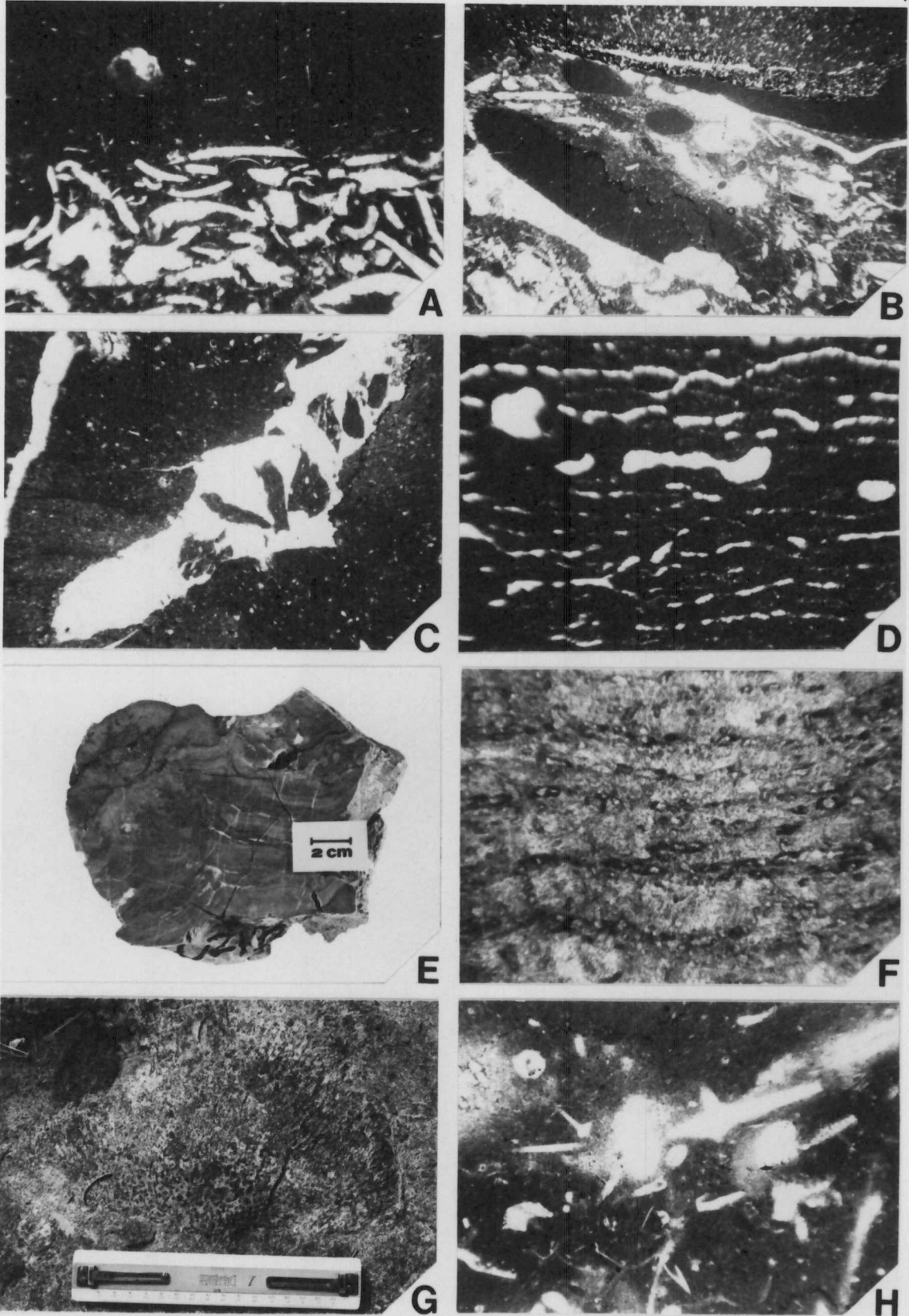


Figure 2.25.

The pelletal mudstone/wackestone facies is commonly burrowed. Burrows are filled with coarser material than the ground mass and are usually composed of dolomite rhombs or sometimes microspar or both. Burrow boundaries vary from gradational to comparatively sharp indicating variable amounts of interstitial water and sediment compaction. Vertical burrows commonly penetrate what are interpreted to be cryptalgal laminations. Aitken (1967) and others have reported that cryptalgalaminated sediments form today in protected intertidal carbonate mudflat and intertidal pond environments.

Although mudcracks were not observed in the Witten at Graveston they are a common feature of the rocks at Harbison. Desiccation features such as cracks (Figure 2.25C) are observed at both localities. Irregular and laminar fenestral fabrics are also prevalent in both localities, especially Harbison (Figure 2.25D). Grover and Read (1978) attributed irregular fenestral fabric to periodic tidal flat desiccation and laminar fenestral types to even more frequent emergence and desiccation.

The Witten in the northeast portion of the study area is therefore interpreted to represent a complex of protected intertidal to supratidal environments such as intertidal mudflats and tidal ponds. The very shallow water environments of the pelletal mudstone/wackestone facies are in marked contrast to the comparatively deeper water environment proposed for the stromatoporoid-sponge-coral facies to the southwest.

The Witten in the southwestern area is composed of a number of facies but is dominated at Halls Crossroads by a stromatoporoid-sponge-coral wackestone facies (Figure 2.22, page 60). Although the Witten is poorly exposed at Halls Crossroads, the upper portion contains a diverse

biota influenced primarily by large, laminated stromatoporoids (Figures 2.25E and 2.25F). The stromatoporoids are rarely thicker than 20.0 cm. and encrust the muddy substrate of the environment in a coalescing hummocky fashion. Interspersed among the stromatoporoids are sponges of variable size, some as large as 30.0 cm. in diameter (Figure 2.25G). Tetradium sp. colonies are generally small (5-10 cm. in diameter) but relatively abundant. Algae, although not particularly abundant, are diverse (Figure 2.9, page 25). Kazakhstanelia sp. and Moniliporella sp. were observed in thin section with unbroken branches and are interpreted to be preserved in life position.

The high volume percent of micrite (Figure 2.7, page 23), preservation of delicate fossil features, and the unabraded nature of fossil allochems all imply weak current activity. The presence of stromatoporoids, sponges and corals, however, suggests moderate current conditions. Perhaps the relatively large sponges and corals acted as a current baffle to trap fine grained sediments and protect the delicate structure of branching calcareous algae. The lithofacies of the Witten at Halls Crossroads is interpreted to represent shallow water (5-10 m.) lower subtidal restricted lagoon environment with low to moderate current activity.

The Dry Gap section is characterized by a poorly sorted sponge-algae wackestone in the lower part of the formation and a bryozoan-pelmatozoan wackestone/packstone in the upper part. Carbonate mud is predominant at the base of the Witten but decreases upward in the section to a higher percentage of pellets and spar (Figure 2.4, page 20).

In the lower Witten in this area gastropods, trilobites, brachiopods, algae and minor amounts of Tetradium sp. coral are relatively more abundant than in the upper Witten (Figure 2.5, page 21). Also in the lower Witten, sponge spicules are common in thin section (Figure 2.25H). However, sponges are rare in the field, a fact that belies the importance of these organisms in the environment. Algae show some diversity (Figure 2.6, page 22) and are dominated by Girvanella sp. The Girvanella sp. in the lower Witten form loosely bound oncolites and matrix component (term after Moore, 1978) whereas Girvanella sp. in the upper part of the formation form tightly bound, more rounded oncolites with no matrix component. Burrows are also more common in the lower part of the formation and imply soft mud with high water content. Bryozoans and especially pelmatozoans are more prominent (Figure 2.5, page 21) in the upper Witten and are associated with moderately well sorted, abraided packstone/grainstones.

It is obvious from the foregoing discussion that a lithofacies change takes place upward in the Witten at Dry Gap reflecting changes in current energy and water depth. The loosely bound oncolites, matrix component Girvanella sp., high mud content and relatively high percentage of algae and sponges in the lower Witten are interpreted to represent a shallow water (1-3 m.) restricted lagoon environment. The upper Witten at Dry Gap, by reason of the abraided and transported nature of the bryozoan-pelmatozoan packstone/grainstone facies, the rounded, tight Girvanella sp. oncolites and low mud content, is interpreted to represent slightly higher energy current conditions of a shallow water (1-10 m.) subtidal, near-shore lagoon environment.

Moccasin Formation. The base of the Moccasin Formation represents the top of the measured sections in the area, and the formation was not studied in any detail. The Moccasin in the study area is represented by a distinctive lithofacies consisting of a maroon to red, commonly mud-cracked and burrowed, lime mudstone/wackestone. In many respects, it is similar to the Bowen Formation except that it is much thicker. The Moccasin in the study area is in excess of 200 m. in thickness. The mudcracks, ripple marks and vertical burrows common to the Moccasin imply a peritidal depositional environment. This interpretation compares favorably with the conclusions of Milici and Walker (1973) who studied the Moccasin elsewhere in East Tennessee.

Summary. Paleoenvironments of the upper stratigraphic package consist primarily of shallow subtidal restricted lagoon and peritidal environments. Sedimentation in this package began with the deposition of the shallow water restricted lagoon environment of the Chapman Ridge bryozoan wackestone facies which was followed by the higher current energy shoaling environment of the bryozoan-pelmatozoan wackestone/pack-stone facies of the Ottosee. The stratigraphic relationship of these sediments to the surrounding shallow water inner shelf sediments suggests that the Chapman Ridge and Ottosee Formations were influenced by and distally derived from the primary deposition center of these formations near the shelf-edge to the southeast.

The Benbolt Formation represents a shallow subtidal complex of lagoon and sand/mud flat environments. Petrology of the Benbolt reflects similar environmental conditions throughout the study area, but lateral

facies changes become more evident above the Benbolt Formation. To the northeast in the study area the Wardell Formation grades upward from a shallow subtidal restricted lagoon facies to an intertidal-supratidal facies. Conditions of intertidal to supratidal environments continued through the deposition of the Bowen and Witten Formations in the northeast. Intertidal-supratidal environments of deposition of the upper Wardell, Bowen and Witten reflect the filling of the basin to the southeast and northwest and the encroachment of these sediments onto the inner shelf.

Shallow water protected lagoon environments characterize the deposition in the inner shelf to the southwest of the study area. The Wardell in this locality grades upward from a shallow subtidal mud flat environment to a shallow subtidal restricted lagoon environment. The shallow lagoon environment persisted upward in the southwest sections through the deposition of the Witten Formation. One of the characteristic features of this lagoonal environment is the development of a comparatively rich shallow water fauna of stromatoporoids, sponges and corals.

The distribution of pellets in the Benbolt, Wardell, Bowen and Witten Formations reflects increasing water depth and decrease in current energy across the study area from the northeast to the southwest. This interpretation is supported by the near-shore intertidal to supratidal environments which characterize the stratigraphic sequence in the northeast and the comparatively deeper water restricted lagoon environments proposed for the southwest portion of the study area.

Summary and Conclusions

Detailed field and laboratory investigations of four measured sections of the Middle Ordovician Chickamauga Group in East Tennessee have revealed a complex faunal and lithofacies relationships. The line of measured stratigraphic sections is oriented parallel to the regional southwest-northeast strike and represents a transect across a portion of the Middle Ordovician shelf from near the shelf-edge in the northeast to the inner shelf in the southwestern portion of the study area. The complex lithofacies relationships observed in the shelf sediments are best summarized as lower, middle and upper stratigraphic packages. The first or lower stratigraphic package is composed of the Five Oaks, Tumbez, Fleanor and Lincolnshire Formations and represents peritidal to shallow marine environments. This lower package is strongly influenced by the relief on the underlying post Knox unconformity. The middle stratigraphic package consists of the Rockdell Formation which is interpreted to represent a generally transgressive sequence of near shelf margin and on-shelf patch reef environments. The lithofacies and biofacies transitions which take place near the shelf-edge and shelfward in this particular line of sections in the study area are well exemplified by the lateral facies changes within the Rockdell Formation. This package shows the marked influence of the development and continuation of the shelf margin to the east and southeast. The upper stratigraphic package is dominated by sediments interpreted to represent shallow marine (restricted lagoon) and peritidal environments of the Chapman Ridge, Ottosee, Wardell, Benbolt, Bowen and Witten Formations.

CHAPTER III

RED ALGAL BOUND PATCH REEF IN THE ON-SHELF LOWER ROCKDELL FORMATION, EAST TENNESSEE: COMPARISON WITH THE DOWN-SLOPE SHELF-EDGE HOLSTON FORMATION REEF COMPLEX, CEMENT PARAGENESIS AND DIAGENETIC HISTORY

Introduction

Previous workers have studied the lithofacies relationships of Middle Ordovician rocks in the strike belts in the Ridge and Valley Province in East Tennessee, however, in most places, much valuable information is masked due to regional thrust faulting. One of the significant aspects of the present study lies in the position of the Middle Ordovician shelf-edge which is oriented perpendicular to the regional strike in the study area (Figure 1.3, page 6). Therefore, the area of study is unique in that it affords an excellent opportunity to examine the lithofacies and biofacies transitions which take place across the shelf-edge/shelf lagoon environments without having these lithofacies patterns dissected by regional thrust faulting. The exact location of the four measured sections in the study area is shown in Figure 1.2 (page 4). Each stratigraphic section is approximately 450 meters in thickness and the orientation of the sections represents a transect across the Middle Ordovician shelf environments at Dry Gap, Halls Crossroads and Harbison to the near shelf-edge/back reef environments at Graveston.

The major lithofacies exposed in the study area is the Rockdell Formation (Figure 2.3, page 17). The Rockdell is a complex assemblage of pelmatozoan-bryozoan packstone/grainstones, bryozoan wackestones and bryozoan-algal boundstones. The lithofacies of this complex are interpreted to represent deposits in a near shelf margin sand bank, tidal channel, mudmound and patch reef environmental complex. The bryozoan-algal boundstone patch reefs which occur in the lower Rockdell Formation are of particular interest and will be discussed in detail in this chapter.

The Rockdell and Holston Formations in East Tennessee represent, for the most part, coeval limestone deposits that are very similar in character but according to Ruppel (1979) can be distinguished on petrologic, sedimentologic and biologic grounds. The Holston Formation is composed primarily of skeletal sands (bryozoan-pelmatozoan packstone/grainstones) and bryozoan boundstones that Walker and Ferrigno (1973) interpreted to represent a major Middle Ordovician shelf margin reef complex. Walker has recently (1977b) refined the interpretation of the Holston and noted that it consists of a lower, up-slope to shelf margin skeletal sandbank part and an upper, down-slope bryozoan boundstone part. Comparison between the down-slope reef deposits of the Holston Formation and on-shelf patch reef deposits of the Rockdell Formation illustrate diagnostic features which prove helpful in distinguishing one reef type from the other (Breland and Walker, 1980; Walker, Ruppel and Breland, 1980).

The paragenetic sequence of cementation and diagenetic history of reefs in East Tennessee has received little attention. A few workers in the region, notably Ferrigno (1973b) and Moore and Walker (1974) have

made cursory investigations into the diagenetic aspects of the Holston reef complex. The present investigation has shown that a definite paragenetic sequence of cementation exists in the patch reef and associated sediments which sheds light upon the diagenetic history of the rocks. This information should add significantly to the present knowledge of diagenesis in reefs and associated lithofacies in East Tennessee.

Organic buildups in the Middle Ordovician have been reported by numerous workers (Alberstadt et al., 1974; Alberstadt and Walker, 1976; Copper, 1976; Pitcher, 1964; Toomey and Finks, 1969; and Walker and Ferrigno, 1973). These organic buildups have been referred to variously as mounds, reef-mounds and reefs. The paleoenvironmental settings and paleoecology of these buildups have indicated that a high degree of variability exists among them and further documentation of similarities and differences is warranted.

The purpose of this chapter is to present the results of a detailed examination of one of these organic buildups interpreted to be a patch reef in the lower Rockdell Formation situated on the ancient Middle Ordovician shelf in East Tennessee. Further, comparison will be made between the on-shelf patch reef of the Rockdell Formation and the shelf margin and down-slope reef complex of the Holston Formation. Finally, the cement paragenesis and diagenetic history of the patch reef will be discussed.

Red Algal Bound Patch Reef in the Lower

Rockdell Formation

One of the features of the Rockdell Formation is the development of patch reefs at the base of the formation in the Harbison and Halls Crossroads stratigraphic sections (Figure 2.19, page 48). The patch reef lithofacies is very localized in areal extent both vertically and horizontally and interpretation is based primarily on diagnostic lithologic characteristics (e.g., core and flank deposits; terms from Walker and Ferrigno, 1973). The patch reef at Harbison (Figure 3.1) is of particular interest because of the presence of red algal boundstones. Also, because the patch reef locality at Harbison was once a quarry site it is particularly well exposed and well illustrates the relationship between reef flank and core material.

The flank material is composed of well washed and well sorted pelmatozoan-bryozoan packstone/grainstones. Figures 3.2A and 3.2B show a typical packstone/grainstone encountered in the flank material of the patch reef which is also similar to flank material observed in the Holston reef complex. The bryozoans observed in thin section consist primarily of biofiates and fragments of encrusting forms. The bryozoans, along with the pelmatozoan fragments, are moderately abraided. The clean, well washed and abraided nature of the packstone/grainstones indicates that the sediments have been transported. Fragments of the algae Spongiostroma sp. and Solenopora sp. are often associated with the flank material, but their occurrence is relatively rare.

The pelmatozoan fragments in the flank material commonly show syntaxial overgrowths (Figure 3.2B). Another type of cement observed in

Figure 3.1. Photomosaic of the bryozoan-algal bound patch reef deposits in the lower Rockdell Formation at the Harbison section.

Note the interfingering relationship between the bryozoan-algal boundstone core material (left) and the pelmatozoan-bryozoan packstone/grainstone flank material (right). Apparent dip along the line of outcrop is about 20 degrees to the left (approximately eastward). Scale is 2.0 m.



Figure 3.1.

Figure 3.2. Petrographic features of the patch reef deposits in the lower Rockdell Formation.

- A. Polished slab of a pelmatozoan-bryozoan grainstone from the patch reef at the base of the Rockdell Formation. This specimen is identical to grainstones observed in the Holston Formation and termed "flank material" by Walker and Ferrigno (1973). Harbison section (HR6-5PR).
- B. Photomicrograph of typical flank material of the patch reefs reveals a composition of well washed pelmatozoan and bryozoan fragments. Syntaxial overgrowths, particularly on the pelmatozoans, are a common cementing agent in the flank deposits. Harbison section (HR6B). 25X.
- C. Photomicrograph of radial fibrous marine cement commonly observed in the flank deposits of the Rockdell and Holston reefs. Harbison section (HR6C). 25X.
- D. Photomicrograph showing the development of radial fibrous cement along the margins of a cavity. The obvious change in cement morphology from the initial radial fibrous cement to a blocky calcite cement represents a change in diagenetic conditions. Harbison section (HR6-6PR). 25X.
- E. Polished slab illustrating both the grainstone "flank" deposits (upper left of specimen) and boundstone "core" deposits in the patch reef at the base of Rockdell. Note the sharp contact between the overlying flank material and the underlying bryozoan encrusted red core material. Harbison section (HR6-2PR).
- F. Photomicrograph of the contact of the flank and core material from the sample in Figure 3.2E. The grainstone and the encrusting bryozoan, Batostoma sp. in this case, are in all respects identical to those seen in the Holston reefs except for the presence of the encrusting alga, Solenopora sp. (center of photograph at contact above the bryozoan). Harbison section (HR6-2PR). 25X.
- G. Polished slab of an algal boundstone from the patch reef in the Rockdell. Harbison section (HR6K).
- H. Photomicrograph of the encrusting alga Solenopora sp. observed in an algal boundstone in the core material of the patch reef in the lower Rockdell. Note the distinctive vertical arrangement of cells in this alga which is characteristic of Solenopora sp. Harbison section (HR6-12PR). 25X.

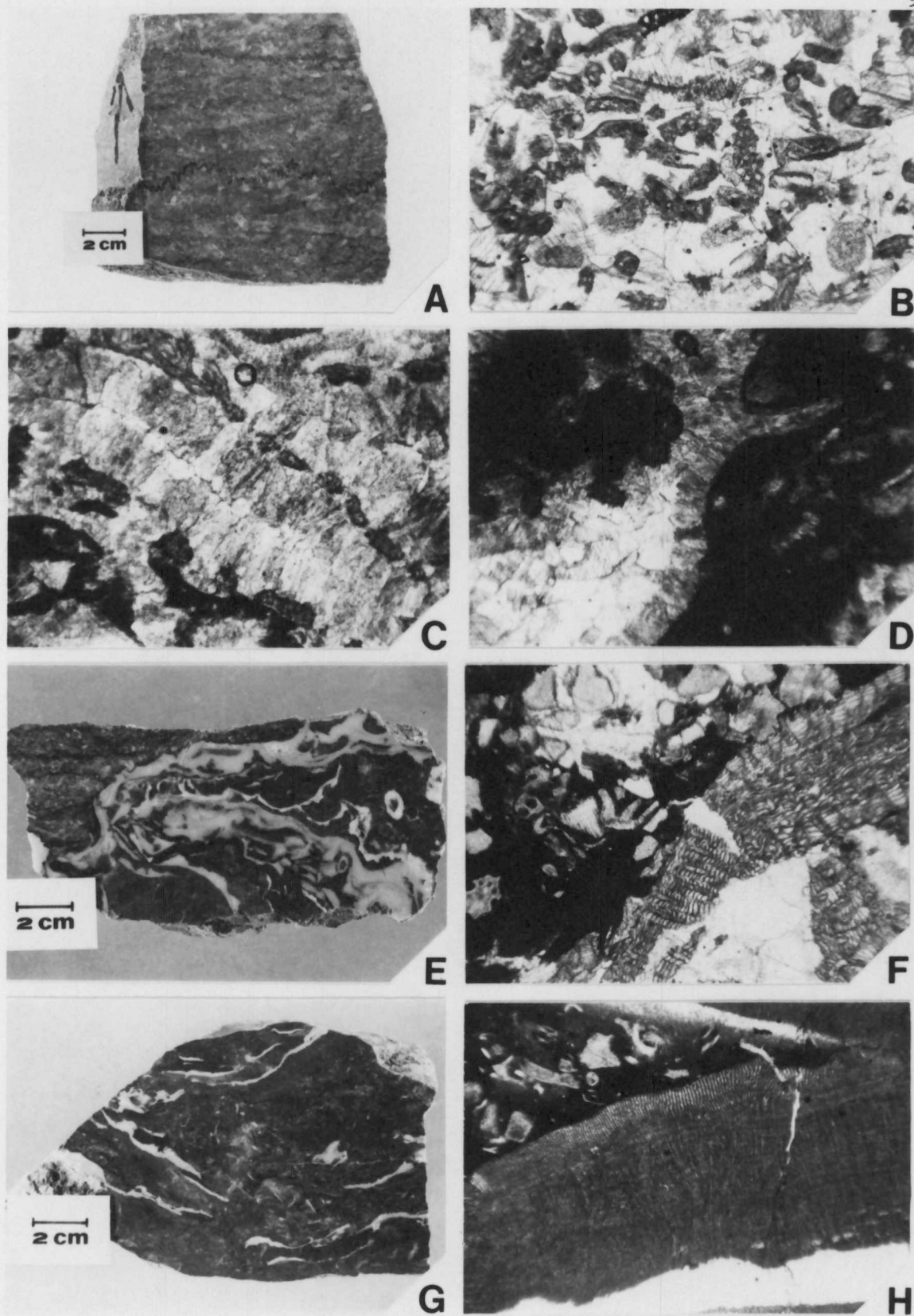


Figure 3.2.

petrographic thin section is radial fibrous cement (Figure 3.2D). The radial fibrous cement was precipitated in intraskeletal and growth cavities and rarely completely fills the cavity. Figure 3.2D shows the extent to which radial fibrous cement typically fills a cavity. The radial fibrous form is sometimes lost due to recrystallization which produces a cloudy blocky cement that rims the cavity or pore space and is everywhere approximately the same thickness. The cloudy cement is nearly always followed by a clear blocky calcite cement which fills the cavity. Occasionally, fragments of radial fibrous cement are observed incorporated into the sediments of the flank material indicating that the cement was forming penecontemporaneously with sedimentation. This cement morphotype (e.g., radial fibrous cement) forms in small primary voids penecontemporaneously with sedimentation and is interpreted to be marine in origin (James and Kobluk, 1978; Lindholm, 1974; Meyers, 1974; and Newell, 1955).

The core material from the patch reef is, in many respects, very similar to the core material from the Holston reef complex. The core consists of red mud bound by massive to thin laminate encrusting bryozoans. Figure 3.2E shows an example of core material from the patch reef. Examination of the growth position of the encrusting bryozoans in the core material in Figure 3.2E reveals that in some instances the bryozoans were growing downward, encrusting the roofs of cavities within the core. The sample in Figure 3.2E shows the two major lithofacies of the patch reef in sharp contact and illustrates graphically the relationship between the grainstone flank material and the boundstone core material. In the field, the two lithofacies, flank and core, interfinger with each other. It is obvious from the sharp contact on the hand sample in

Figure 3.2E that the surface of the core material produced a hard substrate potentially resistant to erosion. The contact between flank and core material is, however, not always sharp and can be quite gradational. The flank material in the sample shows some poorly developed bedding and in the field is sometimes crossbedded. The bedding may be a function of current activity or may be a simple debris-slope bedding.

A thin section taken from the contact of the flank and core material from the sample in Figure 3.2E shows pelmatozoan grainstone in sharp contact with the encrusting bryozoan Batostoma sp. and an encrusting form of the red alga Solenopora sp. (Figure 3.2F). This lithofacies relationship is in all respects identical to those seen in the Holston reef complex except for the presence of the encrusting alga.

In the field it is not easy to distinguish the encrusting alga from the encrusting bryozoans (compare Figure 3.2G with Figure 3.2E). However, from thin section study it is obvious that the binding mechanism for much of the core material in the patch reef was algal growth. The dominant encrusting alga is Solenopora sp. (Figure 3.2H) which, in longitudinal section, is characterized as having radiating cell threads separated by thin, straight walls of dark microcrystalline calcite (Moore, 1978). One of the interesting features of this encrusting alga is cavities which formed on the underside (Figure 3.2H). These cavities are usually floored with an internal sediment producing a geopetal structure. Another interesting feature of this form of Solenopora sp. is structures that suggest the presence of sporangia embedded in the tissue of the thallus (Figure 3.3A).

Solenopora sp. is a common encruster in Middle Ordovician sediments in East Tennessee, particularly in shallow lagoonal environments, but this

Figure 3.3. Petrographic features of the patch reefs and cements in the lower Rockdell Formation.

- A. Photomicrograph of the encrusting alga Solenopora sp. showing a longitudinal section of a possible sporangium. Harbison section (HR6K). 100X.
- B. Photomicrograph showing Solenopora sp. intimately associated with another subordinate encrusting alga interpreted to be Spongiostroma sp., a form taxon. Harbison section (HR6-12PR). 25X.
- C. Photomicrograph of flank material in the patch showing fragments of Solenopora sp. and Spongiostroma sp. illustrating that these two algae actually produced hard surfaces subject to the forces of erosion and incorporation into the flank material. Harbison section (HR6-12PR). 25X.
- D. Photomicrograph of a fractured encrusting sponge observed in the core material of the patch reef. Sponges were important as encrusters and binders of sediment but were subordinate to the algae and bryozoans. Sponge spicules contributed to sediment accumulation in the patch reefs of the Rockdell. Harbison section (HR6-15PR). 25X.
- E. Photomicrograph showing one of the many geopetal structures observed in the core material of the patch reefs. These cavities are usually floored with an internal sediment. Harbison section (HR6-12PR). 25X.
- F. Photomicrograph showing a fragment of Spongiostroma sp. roofing a cavity which is first floored by a pelletal internal silt, then followed by a radial fibrous marine cement and the remaining pore space is closed by later blocky calcite cement. Harbison section (HR6E). 25X.
- G. Photomicrograph of a mollusk illustrating the commonly observed paragenetic sequence of cementation in the patch reefs in the lower Rockdell. Harbison section (HR6-9PR). 25X.
- H. Photomicrograph showing the development of cement as revealed by a staining technique using potassium ferricyanide. The staining solution stains for iron, therefore, the dark areas of cement are relatively iron rich and the light areas of cement are relatively iron poor. Graveston section (GA4C). 50X.

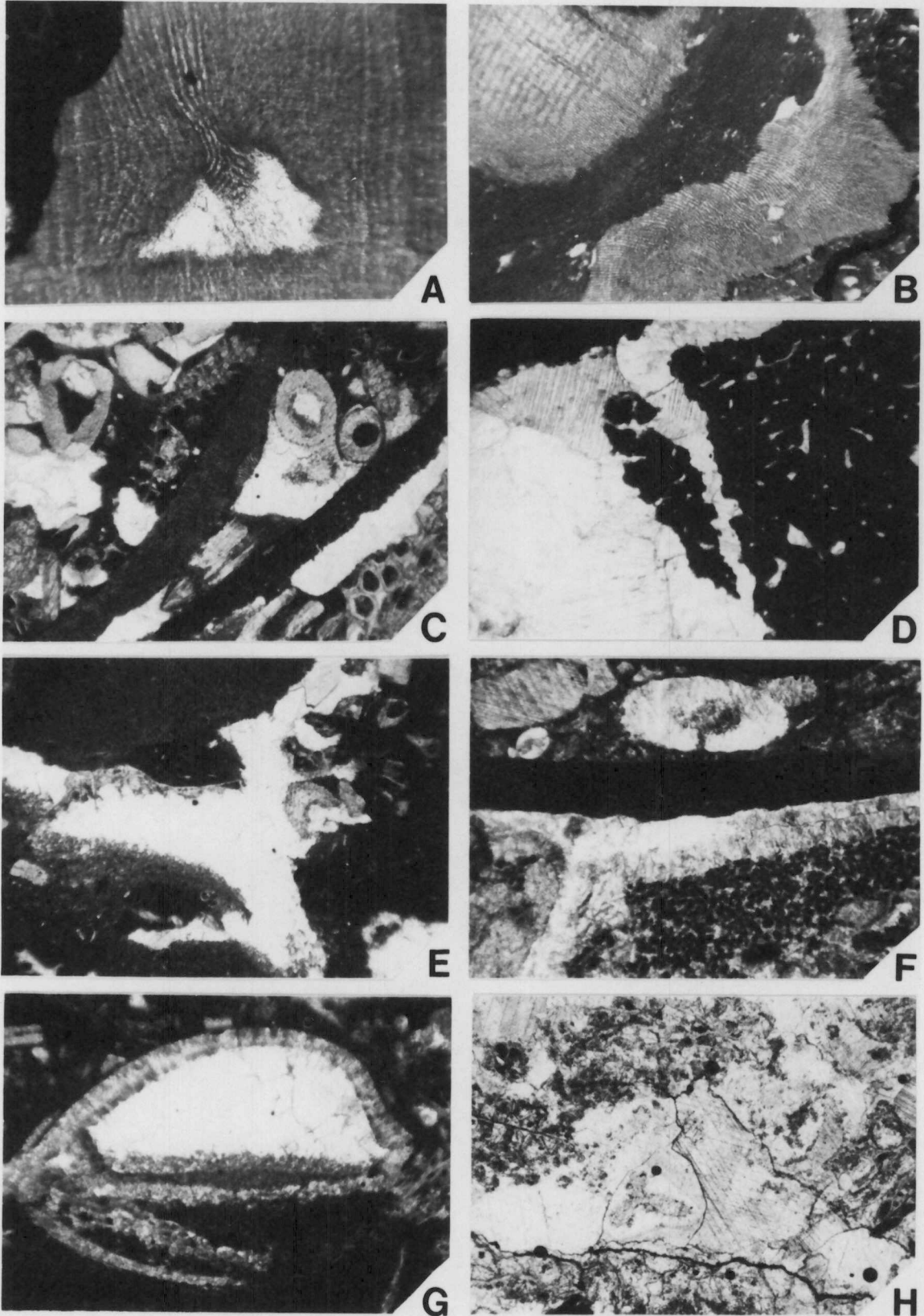


Figure 3.3.

particular ecophenotype of Solenopora sp. previously has not been reported in the role of a reef former (Breland and Walker, 1980). Moore (1978) did an intensive study of the paleoecology of the algae in Middle Ordovician sediments of East Tennessee and recognized two basic forms of Solenopora sp. (type R and type P) but the sediments he studied were, for the most part, confined to the shelf margin facies. In his study, Moore (pers. comm., 1979) observed a small quantity of abraided and transported fragments of the form of Solenopora sp. seen in the core material of the patch reef but because of the small number of samples, poor preservation, and transported nature of the specimens he was unable to place the alga in its proper ecological role. The fact that Moore (1978) studied mostly shelf margin sediments and did not encounter this form of Solenopora sp. in significant quantities, along with the localized nature of the deposits and the location of the patch reef deposits in the study area are the primary criteria for the on-shelf interpretation of these patch reefs.

This form of Solenopora sp. is often intimately associated with another subordinate encrusting alga interpreted to be Spongiostroma sp., a form taxon (Figure 3.3B). These two algae were important as encrusters and binders of sediment and were also significant sediment producers. Figure 3.3C shows two eroded and transported fragments of Solenopora sp. and Spongiostroma sp. illustrating that these two algae actually produced hard surfaces subject to abrasion and subsequent incorporation into the flank material. It may also be noted that the primary void space produced by the well washed coarse grained sediment is initially partially filled with an internal sediment and finally closed with blocky calcite cement.

Another important but subordinate group of encrusting and binding organisms in the patch reef at Harbison are encrusting sponges (Figure 3.3D). The sponges were probably passive binders of sediment and were probably more important as a current baffle trapping sediment. Sponges not only trap and bind sediment but also contribute to the total volume of sediment in the reef. Sponge spicules are a prevalent feature of the reef sediments. Encrusting sponges are common in the inner shelf patch reef but are generally not associated with the shelf margin reef buildups of the Holston Formation.

The sediments associated with the development of the patch reefs in the lower Rockdell reveal a high diversity of calcareous algae. According to Moore (1977) the diversity and abundance of algae in the patch reef subenvironment is unequalled in other shelf lagoon subenvironments. This statement certainly holds true for the patch reef at Harbison. Seven genera of algae are present other than Solenopora sp. and Spongiostroma sp.: sediment trappers and binders include the dasycladaceans (Vermiporella sp., Kazakhstanelia sp.), moniliporellaceans (Moniliporella sp., Contexta sp.), codiaceans (Hedstroemia sp.) and the problematical alga Nuia sp. Girvanella sp. occurred primarily as irregularly shaped masses and aided in the binding of sediment.

Comparison of On-Shelf Patch Reef of the Rockdell
Formation and the Shelf Margin Reef Complex
of the Holston Formation

The Rockdell and Holston Formations in East Tennessee represent, for the most part, coeval limestone deposits that are very similar in

character but can be distinguished on petrologic, sedimentologic and biologic grounds (Ruppel, 1979). Comparison between the shelf-edge reef tract of the Holston Formation and on-shelf patch reef deposits of the Rockdell Formation provides diagnostic features which prove helpful in distinguishing one reef type from the other (Breland and Walker, 1980; Walker, Ruppel and Breland, 1980).

The Rockdell in the study area is characterized by a complex assemblage of pelmatozoan-bryozoan packstone/grainstones, bryozoan wackestones and bryozoan-algal boundstones. These lithofacies represent deposition in a near shelf margin to on-shelf sand bank/tidal channel, mudmound and patch reef environments respectively. The patch reefs are very localized in areal extent both vertically and horizontally and their geometry is inferred from three dimensional exposure to be circular and small in size (30 m. x 50 m.). The deposits are interpreted to be patch reefs primarily on the presence of diagnostic lithologic characteristic (e.g., reef core and flank material; terms from Walker and Ferrigno, 1973) and the diverse assemblage of algae associated with the patch reefs. The reef core material consists of bryozoan-algal boundstone and the reef flank is typified by a pale grey, white or pinkish pelmatozoan-bryozoan packstone/grainstone.

The Holston Formation, characterized as deposits consisting primarily of skeletal sand (bryozoan-pelmatozoan packstone/grainstone) and bryozoan boundstone was interpreted by Walker and Ferrigno (1973) to be a major Middle Ordovician reef complex. The Holston is a large carbonate deposit which attained a linear dimension of more than 40 km. along the Middle Ordovician shelf-edge. The Holston Formation consists

of two facies: a lower, cross-bedded, echinoderm grainstone representing deposition in a shelf margin skeletal sandbank environment; and an upper reefoid facies consisting of bryozoan boundstone and associated flanking crossbedded echinoderm grainstone representing a down-slope reef complex (Walker, 1977c). The reef mass is divided into a reef core composed of anastomosing masses of bryozoan boundstone and reef flank material consisting of intervening pale grey, white or pinkish, crossbedded pelmatozoan-bryozoan grainstones.

Comparison of the lithofacies of the two types of reefs (Figures 3.4, 3.5, and Table C-1 in Appendix C) reveals similarities in reef flank material and diagnostic differences in reef core material. Reef flank material is dominated by pelmatozoan-bryozoan debris in both reef types. Reef flank samples collected near core material in the patch reef reveal slightly higher volume percentages of carbonate mud. The proportion of flank material is greater than core material in both reef types and is similar in proportion to debris and boundstone masses in modern reefs (Ladd, 1971). The reef core material in both kinds of volume in the patch reefs but generally much less abundant in the down-slope boundstones of the Holston. Encrusting bryozoans are important binders of the fine grained sediments in the reef core, especially in the Holston.

A major difference between the two reef types is the presence of algae, particularly the encrusting alga Solenopora sp., in the patch reefs and the total absence of algae in the Holston reef complex. Solenopora sp. and, to a lesser extent, Spongiostroma sp. were instrumental in binding fine grained sediments in the reef core and are

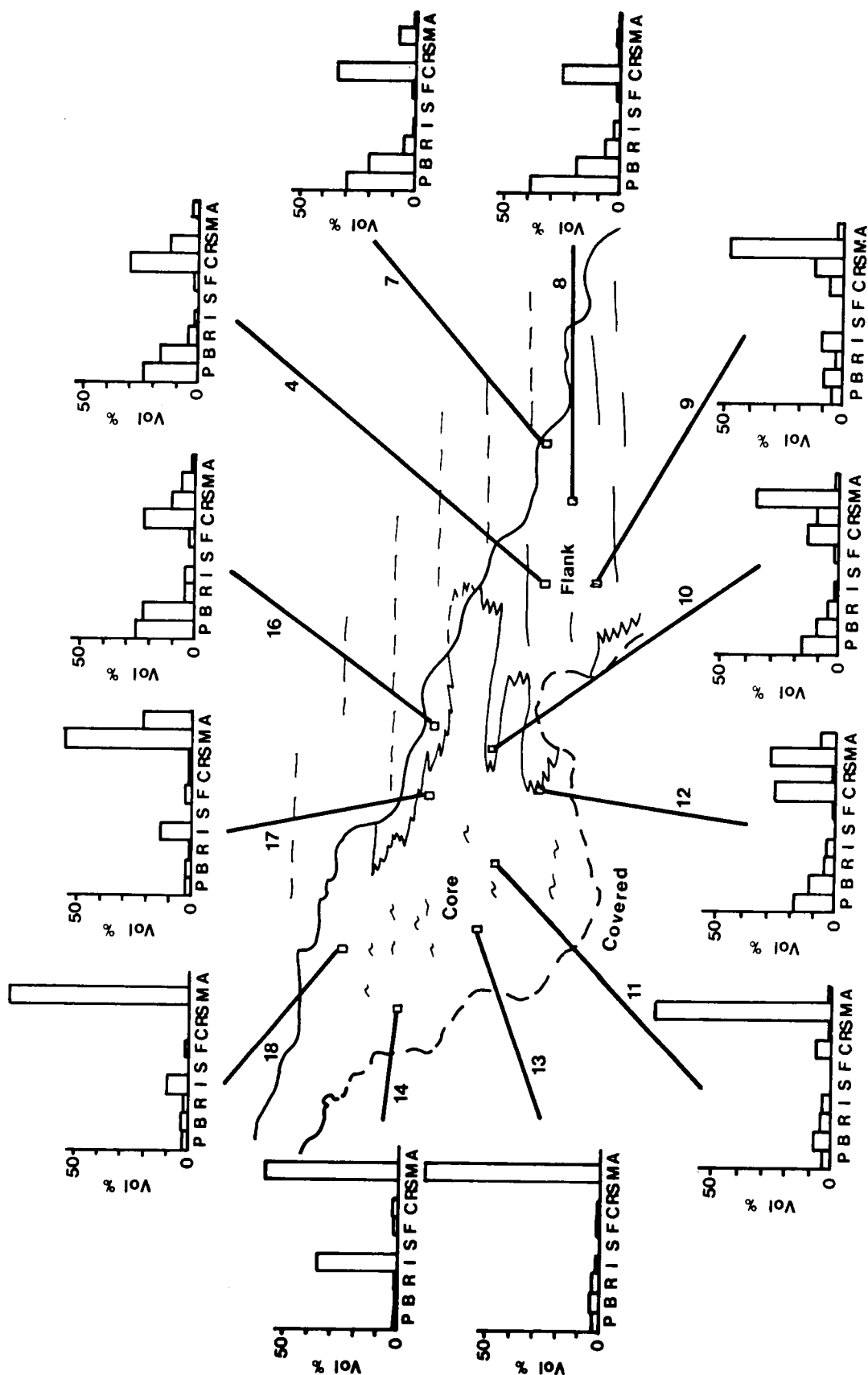


Figure 3.4. Sketch of the patch reef in the lower Rockdell at the Harbison section showing the location and composition of samples from the two reef facies.

Abbreviations of components are: P = pelmatozoan debris, B = bryozoan fragments, R = ramose bryozoa, I = encrusting bryozoa *in situ*, S = stromatolite structures, F = other fossils, C = sparry calcite mosaic cement, RS = radial fibrous marine cement, M = fine grained matrix, and A = algae.

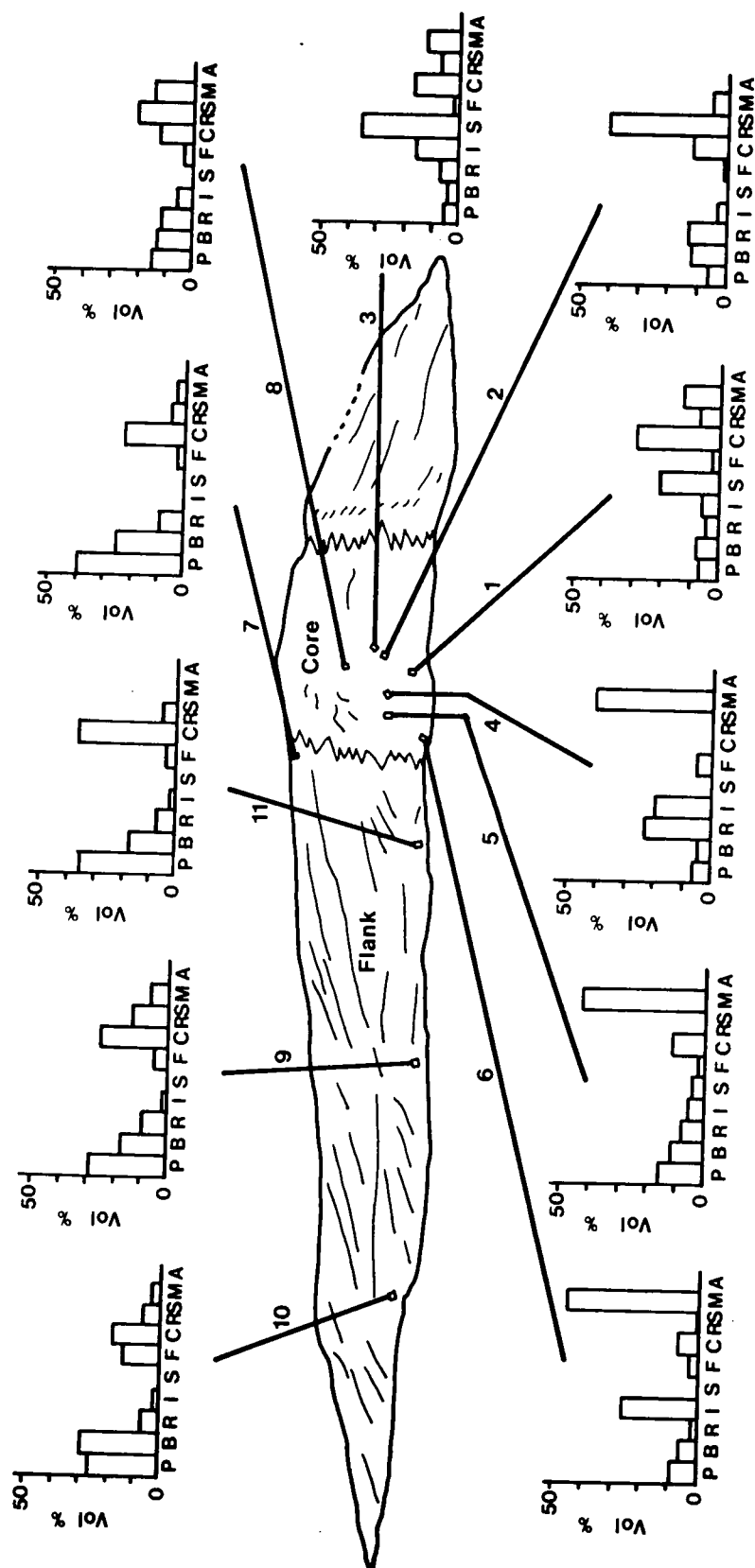


Figure 3.5. Sketch of small reef in the Holston along Alcoa Highway showing location and composition of samples from the two reef facies.

Abbreviations of components are: P = pelmatozoan debris, B = bryozoan fragments, R = ramose bryozoa, I = encrusting bryozoa *in situ*, S = stromatolitic structures, F = other fossils, C = sparry calcite mosaic cement, RS = radial fibrous marine cement, M = fine grained matrix, and A = algae. (Modified from Walker and Ferrigno, 1973.)

common components in the patch reef flank material. One of the distinguishing features of Middle Ordovician patch reef environments is the diversity and abundance of algae (Moore, 1977). Algae associated with the patch reef sediments include Vermiporella sp., Kazakhstanelia sp., Moniliporella sp., Contexta sp., Hedstroemia sp., Nuia sp. and Girvanella sp.

Stromatactis structures were not observed in the patch reefs. According to Ferrigno and Walker (1973) stromatactis structures are formed where encrusting bryozoan colonies are replaced by sparry calcite cement. Ruppel (1977) studied stromatactis structures in the Holston and noted three basic types: type I was developed through the precipitation of calcite cement in cavities; type II was characteristically associated with bryozoan remains; type III was produced from cavity infilling but, unlike type I, cementation took place in two distinct stages. Although encrusting bryozoans are abundant in the patch reefs, the absence of stromatactis structures suggests that either the species of bryozoan that was characteristically replaced in the Holston reef tract was not an important or abundant faunal component in the Rockdell patch reefs or that the diagenetic environment in which the stromatactis structures developed in the down-slope area did not exist in the on-shelf patch reef environment.

The volume percentage of cement in both reef types varies with the characteristic lithofacies (e.g., low volume percent in the reef core and high volume percent in the reef flank) and is therefore not a distinguishing diagnostic feature. Analysis of cement morphologies in the Rockdell patch reefs has established a definite paragenetic sequence

of cementation which corresponds with observations on cements in the Holston reef complex. Evidence does not suggest that one cement morphotype is confined to a particular reef type or reef lithofacies.

Cement morphotypes include radial fibrous cement (Bathurst, 1975) which forms in small primary voids penecontemporaneously with sedimentation and is interpreted to be marine in origin (Cullis, 1904; James and Kobluk, 1978; Lindholm, 1974; Meyers, 1974; and Newell, 1955). Sparry calcite mosaic cement (sometimes referred to as blocky calcite cement) which has an obvious interstitial growth position and features such as drusy growth fabric indicating development by void-filling (Bathurst, 1958). Spar cement developed as syntaxial overgrowths on pelmatozoan fragments is an almost ubiquitous feature of the grainstone in the reef flank of both reef types.

A summary of similarities and differences between the characteristics of the Rockdell patch reefs and the Holston reef complex is illustrated in Table 3.1. Major diagnostic differences exist in the size, geometry and binding and framework components of the reef core material. Similarities and therefore nondiagnostic features of the two reef types include basic lithofacies (e.g., flank and core material), general composition of reef flank (except if algae are present), and mode of cementation.

Cement Paragenesis and Diagenetic History

An investigation into the different types of cements in the patch reefs of the Rockdell Formation has revealed a definite paragenetic sequence of cementation and internal sedimentation from which the

Table 3.1. Summary of the characteristic properties of the Rockdell patch reefs and the Holston reef complex.

CHARACTERISTICS	SUMMARY	
	ROCKDELL PATCH REEFS	HOLSTON REEF COMPLEX
General Environ and Postion on Shelf	On Shelf	Shelf-Edge, Down-Slope from Shelf-Edge
Geometry	Localized, Circular	Linear (Parallel to Shelf-Edge
Size	Small (M x M)	Large (M x KM)
Lithofacies	Flank and Core Material	Flank and Core Material
Flank Material	Pelmatozoans and Bryozoans	Pelmatozoans and Bryozoans
Core Material (Bind and Frame)	Bryozoans, Algae	Bryozoans
Cementation	Radial Fibrous Marine Cement, Syntaxial Overgrowths, Blocky Calcite Cement	Radial Fibrous Marine Cement, Syntaxial Overgrowths, Blocky Calcite Cement

diagenetic history of the patch reefs can be interpreted. Determination of compositional zonation and carbonate cement morphology was ascertained by use of the petrographic microscope, artificial stains (Evamy, 1969), and cathodoluminescence (Sippel and Glover, 1965; see Appendix D).

Cavities of all types within the reef lithofacies were sites of cement precipitation (Figures 3.3E, 3.3F and 3.3G, page 96). These cavities, along with skeletal components, were affected by carbonate dissolution and later reprecipitation of carbonate cement. Precipitation of cement in the reef lithofacies commonly occurs penecontemporaneously with sedimentation of the reef facies (Cullis, 1904; Land and Goreau, 1970; MacIntyre et al., 1968; Meyers, 1974; Newell, 1955; and others).

Two types of cement are observed in the first stage of cementation in the pelmatozoan-bryozoan packstone/grainstone of the reef flank. The first type of cementation is a clear scalenohedral calcite associated with reef flank material somewhat removed from the reef core. Syntaxial overgrowths on abundant echinoderm debris account for much of this kind of cement (Figure 3.6A and 3.6B). Staining techniques using potassium ferricyanide (Lindholm and Finkleman, 1972) revealed an early nonferroan stage of cement followed by a late stage ferroan cement (Figure 3.3H, page 96). Under cathodoluminescence compositional zonation of the syntaxial overgrowths is evident (Figure 3.6A and 3.6B). The first stage nonferroan calcite shows numerous zones produced by variation in the Mn^{+2}/Fe^{+2} . The compositional zones show no strong correlation between thickness of zones and number of zones (e.g., cement stratigraphy) from sample to sample. The presence of a late ferroan stage of cementation is common in ancient rocks and may be the norm (Bathurst, 1975). This stage may represent a deep burial diagenetic environment (Walker, pers. comm., 1980).

Figure 3.6. Petrographic features observed in selected thin sections from the patch reef deposits in the lower Rockdell Formation as revealed under plane light and cathodoluminescence.

- A. Photomicrograph of pelmatozoan fragments with syntaxial overgrowths. Harbison section (HR6-12PR). 70X. Plane light.
- B. Photomicrograph of pelmatozoan fragments in Figure 3.6A under cathodoluminescence showing different "generations" of cement in syntaxial overgrowths. Harbison section (HR6-12PR). 70X.
- C. Photomicrograph of flank material showing a recrystallized radial fibrous marine cement (dark cement) followed by a blocky calcite cement (light cement). Harbison section (HR6-6PR). 70X. Plane light.
- D. Photomicrograph of flank material in Figure 3.6C under cathodoluminescence showing two distinct generations of cement. The dark cement represents the initial phase of cementation (radial fibrous cement) followed by a second generation of cementation (lighter colored cement). Harbison section (HR6-6PR). 70X.
- E. Photomicrograph of a cavity roofed by the encrusting alga Solenopora sp. and floored with an internal silt. Harbison section (HR6-15PR). 70X. Plane light.
- F. Photomicrograph of the cavity in Figure 3.6E under cathodoluminescence showing the development of a gravity (pendant) cement on the underside of the encrusting alga. These gravity cements always reveal the same zonation sequence from dark to light. Harbison section (HR6-15PR). 70X.
- G. Photomicrograph of a sediment floored cavity that shows remnant initial cementation (dark cement) followed by clear blocky calcite cement. Harbison section (HR6-15PR). 70X. Plane light.
- H. Photomicrograph of the cavity in Figure 3.6G under cathodoluminescence showing that the internal silt and initial phase of cementation is dark. Gravity cements develop on the roof of the cavity and exhibit a striking zonation from dark to light. The cavity is finally closed with blocky calcite cement (grey). Harbison section (HR6-15PR). 70X.

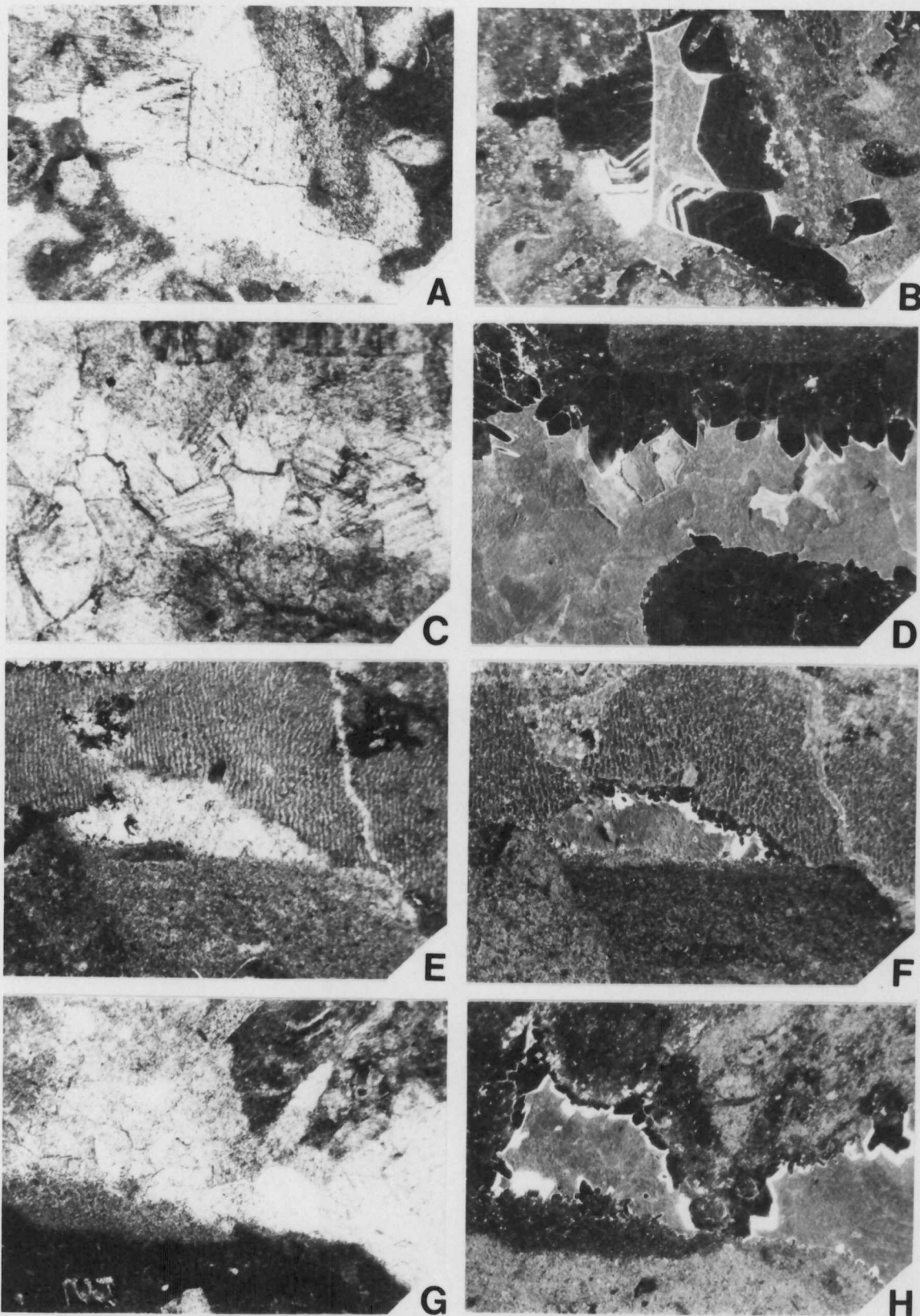


Figure 3.6.

The second type of first stage cement is a radial fibrous cement (Bathurst, 1975; Figures 3.2C and 3.2D, page 92, and Figure 3.3F, page 96). It is usually associated with, but not confined to, reef flank material located near or adjacent to reef core material. Sometimes the radial fibrous cement is relatively clear and completely fills the pore space or cavity as in Figure 3.2C (page 92) but more commonly is a cloudy, thin rim of cement which is followed by a clear, blocky calcite cement as in Figures 3.2D (page 92) and 3.3F (page 96). The first stage radial fibrous cement is low in iron content, but the last stage blocky calcite cement in most pore and cavity fillings is slightly iron rich (Figures 3.6C and 3.6F). Fragments of radial fibrous cement have been observed as detrital components in the reef flank material suggesting that the cement was forming penecontemporaneously with reef sedimentation. This form of cement is commonly observed in modern and ancient reefs and is interpreted to be marine in origin (Cullis, 1904; James and Kobluk, 1978; Lindholm, 1974; Meyers, 1974; Newell, 1955).

Internal marine sediments, such as the pelleted micrite in Figure 3.3F (page 96), are also a common cementing agent. Land and Goreau (1970) reported similar types of cementation, both radial fibrous marine cement and pelleted micrite, in shallow water (1 m. or less) in Jamaican reefs. Much of the high Mg calcite cement in modern reefs takes a pseudopelletal form.

The first stage radial fibrous cement is not ubiquitous but is random in occurrence and is best developed in the lithofacies in close proximity to the reef core material. James et al. (1976) noted that early subsea cement was sporadic, cemented sediments were restricted to very

shallow marginal facies of the Belize reefs, and that internal sediment was critical to the precipitation of rock-making cement. MacIntyre (1977) observed that cements were absent or generally poorly developed in the deeper fore-reef talus or in protected reef flat rubble and back-reef sediments in a modern Caribbean reef. Inability to correlate thickness and number of compositional zones from sample to sample may be a function of the sporadic nature of formation of the first stage cements.

Pores and cavities not initially completely filled by the first stage radial fibrous cement were finally filled with a clear scalenohedral (blocky or drusy) calcite cement which is nearly always relatively iron-rich (Figure 3.2D, page 92; Figure 3.3F, page 96; Figures 3.6C and 3.6D). The second stage cement is composed of elongate to obtuse, dentate calcite crystals. The crystals protrude into the pore space or cavity and crystal growth proceeds inward at the expense of smaller adjacent crystals until the pore space or cavity is closed by a single large crystal.

According to Dickson (1966) ferroan calcite can be secondary in origin and is usually associated with replacement minerals. Berner (1966) suggests that the transition of high-Mg calcite to low-Mg calcite can take place in sediments by interaction with fresh water. Richter and Füchtbaur (1978) reported that the occurrence of most ferroan calcite cement is associated with a meteoric-phreatic origin. Meyers (1974), using many lines of evidence, interpreted clear scalenohedral calcite cement to have been precipitated in a fresh water phreatic zone.

Internal fine silt is a common feature in both reef flank and core material (Figures 3.3C, 3.3E and 3.3G, page 96). This fine silt always occurs in a definite sequential position: after the radial fibrous cement

and before the blocky calcite cement. This internal sediment commonly floors cavities in the reef core material (Figure 3.6E and 3.6G). Cavities filled with clear blocky calcite cement seen in plane light reveal, under cathodoluminescence, cavities roofed with crystals interpreted to be pendant or gravity cements (Figure 3.6F and 3.6H) which are associated with cementation in the vadose diagenetic environment (Dunham, 1971). The sequence of occurrence of the internal sediment and the association with the pendant cements strongly suggests that the fine grained sediment is a vadose silt (Dunham, 1969).

From the general paragenetic sequence of cementation and internal sedimentation, the diagenetic history of the patch reef can be determined. Initial partial cementation took place in the shallow marine environment penecontemporaneously with sedimentation of the patch reef. The first stages of cementation may have been sporadic and were generally associated with very shallow deposition in close proximity to reef core material. The patch reef sediments were subsequently subaerially exposed for a period of time. During this time dissolution, reprecipitation and internal sedimentation took place in the vadose diagenetic environment as evidenced by vadose silt and pendant cements. Following the period of subaerial exposure the remaining primary porosity and the secondary porosity produced in the vadose diagenetic environment were sealed with clear ferroan blocky calcite cements precipitated in the fresh water phreatic diagenetic environment. Figure 3.7 summarizes the sequence of the stages of sedimentation, cementation and diagenetic alteration in the patch reef sediments.

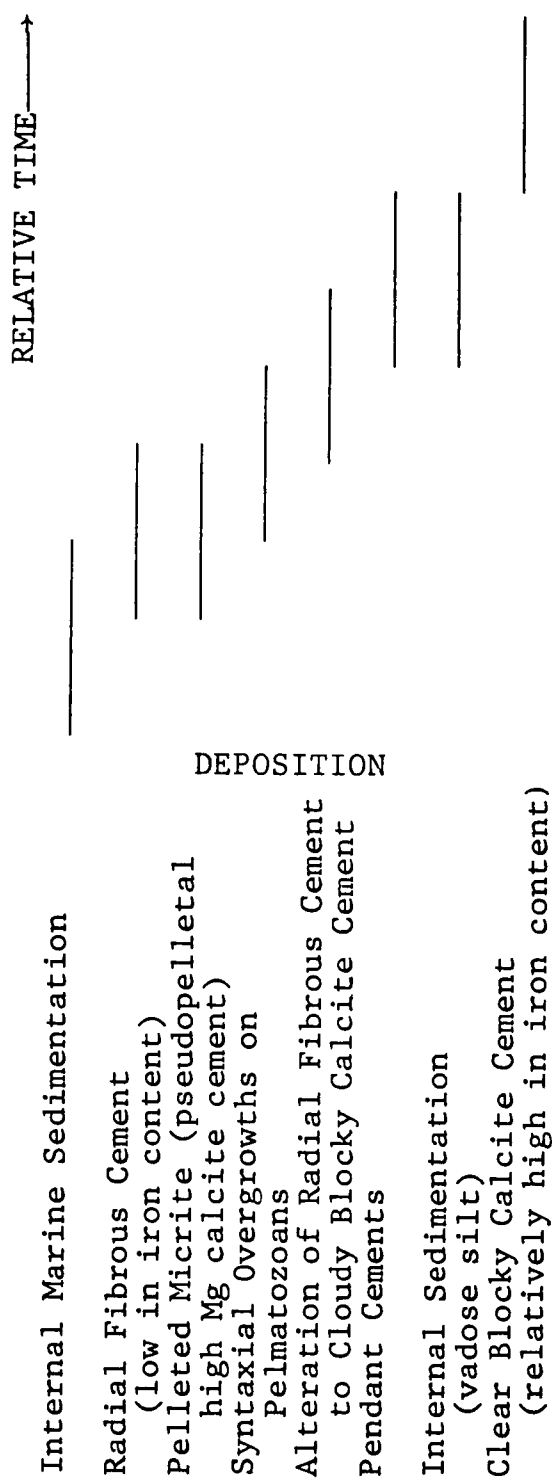


Figure 3.7. Sequence of the stages of sedimentation, cementation and diagenetic alteration in the patch reef sediments.

Summary

Petrographic analysis of the bryozoan-red algal bound patch reefs observed in the lower Rockdell Formation in the study area proves to be helpful in recognizing and distinguishing on-shelf from down-slope reef buildups. The encrusting red alga, Solenopora sp., associated with these patch reefs assumed a morphology and a role in the buildup process not previously observed in East Tennessee. It formed extensive thin (0.5 cm.), sinuous layers which bound muds of the reef core. Previously, Solenopora sp. was known to be associated with shallow water lagoonal facies in the Middle Ordovician sequence.

Comparison of a bryozoan-red algal bound patch reef in the on-shelf Rockdell Formation with the reef complex of the down-slope part of the Holston Formation revealed characteristic similarities in the diagnostic reef flank and core lithofacies. Reef flank material, composed primarily of pelmatozoan and bryozoan fragments is almost identical in both reef types. Cement morphotypes and paragenesis (that is, radial fibrous marine cement, syntaxial overgrowths and blocky calcite cement) also show marked similarities. Distinct differences are present in the size and geometry of the reefs. The Rockdell patch reef is small in area and circular whereas the Holston reef complex is large in area and assumes a linear geometry coincident with the shelf-edge. Binding and framework components of the patch reef are characterized by encrusting bryozoans and red algae in contrast to the bryozoans of the shelf-edge reef complex.

Investigation into the different types of cements in the Rockdell patch reef has revealed a definite paragenetic sequence of cementation

and internal sedimentation from which the diagenetic history of the patch reef could be determined. The paragenetic sequence of cementation and internal sedimentation consists of an initial stage of low-iron content radial fibrous marine cement which formed penecontemporaneously with the sedimentation of the patch reef. The radial fibrous cement rim is commonly followed by vadose silts which floor cavities and pore spaces and pendant cements which often roof cavities. Primary and secondary porosity is finally sealed in the sequence by a relatively high-iron content scalenohedral calcite cement.

The diagenetic history of the patch reefs is believed to have begun with the partial cementation of reef sediments by radial fibrous cements in the marine environment. The reef sediments were then subjected to subaerial exposure in the vadose diagenetic environment. This stage of diagenesis is evidenced by pendant cements and vadose silts. The final stage in the diagenetic history of the patch reefs consists of sealing the remaining primary porosity and the secondary porosity (produced by the dissolution and reprecipitation in the vadose diagenetic environment) by a high-iron content scalenohedral calcite cement precipitated in the fresh water phreatic diagenetic environment.

CHAPTER IV

OCCURRENCE AND STRATIGRAPHIC DISTRIBUTION OF
ECHINODERMS IN MIDDLE ORDOVICIAN INNER
SHELF TO NEAR SHELF-EDGE ENVIRONMENTS
IN EAST TENNESSEE

Introduction

This investigation into the occurrence and stratigraphic distribution of echinoderms is part of a larger project designed to develop an operable stratigraphic and paleoenvironmental framework for a portion of the Middle Ordovician shelf in East Tennessee. The significance of the project lies primarily in the unique structural setting of the study area. In the study area, the Middle Ordovician shelf-edge deviates abruptly from its general northeast-southwest trend (Figure 1.3, page 6). In this area, this important environmental boundary is oriented normal to the regional thrust faulting rather than parallel to it as it is in other parts of the region. A detailed study of the sedimentary petrology and environmental stratigraphy in this fortuitous setting has elucidated the pattern of shifting environments developed by the transition between shelf-edge and restricted on-shelf facies without having the lithofacies patterns developed by these environments dissected by regional thrust faulting. The echinoderm study is an attempt to document, in detail, the stratigraphic occurrence and distribution of identifiable echinoderm remains and to interpret their occurrence in the context of the environmental stratigraphic study. Such

an evaluation is long overdue for the abundant and diverse echinoderm fauna of the Middle Ordovician in East Tennessee.

The Middle Ordovician was a time of great morphologic elaboration and diversification in many groups of organisms and particularly in the echinoderms. Numerous classes of echinoderms developed and flourished during this time (e.g., Crinoidea, Rhombifera, Edrioastroidea, Edrioblastoidea, Eocrinoidea, Paracrinoidea and Parablastoidea). The crinoids appear to have stimulated the most interest among early workers. Work on the crinoid fauna in the Middle Ordovician in Eastern Tennessee historically has been confined to the "Benbolt and allied formations" (Brower and Veinus, 1978). Early workers have described many of the forms first noted by Troost (1850) (e.g., Miller and Gurley, 1894 and 1895; Wachsmuth and Springer, 1897; White, 1880; and Wood, 1909). More recently Brower and Veinus (1978) have described almost all of the known "Benbolt" crinoids. Information on the occurrence and descriptions of the other classes of echinoderms in the Middle Ordovician of Eastern Tennessee are, with a few exceptions (Bassler, 1950; Broadhead, 1980; Broadhead and Breland, 1980; and Sprinkle, 1973) almost completely lacking. Also, nearly all described species from the region are referred, not necessarily correctly, to the Benbolt Formation or to formations believed by some workers to be coeval with the Benbolt (e.g., Heiskell and Ottosee Formations). The object of this study is to report on the occurrence of all identifiable echinoderms in the study area and determine their stratigraphic distribution.

Stratigraphic Framework

Before the echinoderm study could proceed, it was necessary to develop an operable stratigraphic framework for the study area. This goal was accomplished by measuring, in detail, four stratigraphic sections along strike: Dry Gap (DG), Halls Crossroads (HC), Harbison (HR), and Graveston (GA) (Figure 1.2, page 4). Petrographic and lithostratigraphic information was then correlated to produce Figure 2.3 (page 17). The lithofacies of the lower and middle Chickamauga Group (Middle Ordovician) were subdivided into 11 formations (Figure 2.3, page 17): Five Oaks, Tumbez, Fleanor, Lincolnshire, Rockdell, Chapman Ridge, Ottosee, Benbolt, Wardell, Bowen and Witten. These units are listed in stratigraphically ascending order although there are many complex lateral interfingering relationships. Using several lines of evidence lateral lithofacies relationships in the subject area have been interpreted to represent a transect from inner shelf sediments at Dry Gap (DG) to near shelf-edge deposits in the northeast at Graveston (GA).

Vertical changes in lithofacies and biofacies suggest an obvious differentiation of sedimentation into three stratigraphic packages. The first or lower stratigraphic package consists of peritidal to shallow marine sediments of the Five Oaks, Tumbez, Fleanor and Lincolnshire Formations. The middle stratigraphic package is characterized by the near shelf margin and on-shelf patch reef sediments of the Rockdell Formation. The upper stratigraphic package is dominated by sediments interpreted to represent shallow marine (restricted lagoon) and peritidal environments of the Chapman Ridge, Benbolt, Wardell, Bowen and Witten Formations. Unfortunately, no biostratigraphic work has been attempted

in this area and determination of the physical stratigraphy of the units is based primarily on environmental considerations, interfingering relationships and progradational cycles.

Occurrence and Stratigraphic Distribution
of Echinoderms

Table 4.1 shows the occurrence and stratigraphic distribution of identifiable echinoderms collected and observed in the field area. The collection of identifiable echinoderm remains was attempted for each formation and was variably successful. The major limitation to the study centered around the poorly exposed and weathered nature of the lithofacies examined. Certain formations (i.e., Five Oaks, Bowen and, to a lesser extent, the Witten) by reason of their depositional environments (i.e., high peritidal) did not produce or produced very limited numbers of specimens. Other formations (i.e., Tumbez, Fleanor and Lincolnshire) were poorly exposed. Fortunately some units, notably the Rockdell Formation, were comparatively well exposed and yielded a fairly diverse assemblage of echinoderms. However, determination of the lateral distribution of these organisms proved to be difficult either because of poor exposure or because of the nature of weathering of the rocks. For example, the Rockdell Formation (pelmatozoan-bryozoan pack-stone/grainstone) is fairly well exposed in the field but does not generally produce collectable specimens because of the nature of its weathering. The relatively good collection of echinoderms from the Rockdell at Halls Crossroads resulted from a fortuitous excavation at that locality which exposed echinoderms weathered in relief from which comparatively complete and well preserved specimens could be extracted.

Table 4.1. Occurrence and stratigraphic distribution of echinoderms at the Dry Gap (DG), Halls Crossroads (HC), Harbison (HR) and Graveston (GA) localities.

FORMATION	LOCATION			
	DG	HC	HR	GA
Five Oaks (Basal Unit)				
none				
Tumbez				
Crinoidea				
unidentifiable camerates		0		
Fleanor				
Crinoidea				
unidentifiable camerates		X		
<u>Hybrocrinus</u> sp.		X		
Lincolnshire				
Crinoidea				
unidentifiable camerates			0	0
Paracrinoidea				
<u>Ulrichocystis eximia</u>			0	
Rockdell				
Crinoidea				
unidentifiable camerates	X	X	X	0
<u>Diabolocrinus vesperalis</u>	X	X		
<u>Cleiocrinus</u> sp.	X	X	0	
<u>Carabocrinus</u> sp.	0	X	X	
<u>Carabocrinus micropunctatus</u>		X		
<u>Carabocrinus stellifer</u>		X		
<u>Hybocrinus</u> sp.		X		
<u>Hybocrinus punctatus</u>		X		
<u>Palaeocrinus</u> sp.		X	0	
<u>Palaeocrinus planobasalis</u>		X		
<u>Palaeocrinus avondalensis</u>		X		
Rhombifera				
<u>Coronocystis angulatus</u>		X		
<u>Regulaecystis pyriformis</u>		X		
Paracrinoidea				
<u>Ulrichocystis eximia</u>		X	0	
<u>Platycystites</u> sp.		X		
<u>Canadocystis</u> sp.		0		
<u>Springerocystis</u> sp.		X		
undescribed genus		X		
Edrioasteroidea				
<u>Cyathocystis</u> sp.		X	X	

Table 4.1 (continued)

FORMATION	LOCATION			
	DG	HC	HR	GA
Edrioblastoidea				
<u>Astrocystites</u> sp.		X		
Eocrinoidea				
<u>Batherocystis appressa</u>		X	X	
Chapman Ridge				
Crinoidea				
unidentifiable camerates		X	0	
<u>Carabocrinus stellifer</u>		X		
Paracrinoidea				
unidentifiable paracronoid		X		
<u>Ulrichocystis eximia</u>		X		
Parablastoidea				
<u>Meristoschisma hudsoni</u>			0	
Edrioasteroidea				
<u>Cyathocystis</u> sp.		X	0	
Ottosee				
Crinoidea				
unidentifiable camerates		0		
Benbolt				
Crinoidea				
unidentifiable camerates	X	0	0	X
<u>Archaeocrinus peculiaris</u>				X
<u>Cleioocrinus</u> sp.			X	0
<u>Diabolocrinus vesperalis</u>	X			X
<u>Carabocrinus</u> sp.	X			X
<u>Carabocrinus</u> sp. cf. <u>micropunctatus</u>	X			
<u>Carabocrinus stellifer</u>	X		X	X
<u>Hybocrinus</u> sp.	X			X
<u>Hybocrinus punctatus</u>				X
<u>Palaeocrinus</u> sp.	X			
<u>Palaeocrinus planobasalis</u>				X
<u>Palaeocrinus avondalensis</u>	X			
<u>Ristnacrinus</u> sp. cf. <u>altobasalis</u>				
Rhombifera				
unidentifiable rhombiferan	X			
Paracrinoidea				
unidentifiable paracrinoid	X		X	X
<u>Ulrichocystis eximia</u>	0			X
<u>Springerocystis</u> sp.			X	
Parablastoidea				
<u>Meristoschisma hudsoni</u>	X		X	X
Edrioasteroidea				
<u>Cyathocystis</u> sp.	X		X	X

Table 4.1 (continued)

FORMATION	LOCATION			
	DG	HC	HR	GA
Wardell				
Crinoidea				
unidentifiable camerates	0			
<u>Archaeocrinus peculiaris</u>	X			
<u>Carabocrinus</u> sp.	0			
<u>Carabocrinus stellifer</u>	X			
<u>Hybocrinus punctatus</u>	X			
<u>Palaeocrinus planobasalis</u>	X			
Rhombifera				
<u>Regulaecystis</u> sp.	X			
Parablastoidea				
<u>Meristoschisma hudsoni</u>	X			
Eocrinoidea				
<u>Batherocystis</u> sp.	X			
Bowen				
none				
Witten (Uppermost Unit Studied)				
Crinoidea				
unidentifiable camerates		0		
<u>Cleioocrinus</u> sp.		X		
<u>Palaeocrinus avondalensis</u>		X		
Edrioasteroidea				
<u>Cyathocystis</u> sp.		0		

Note: "X" indicates material collected in the field and "0" indicates specimens observed in the field but not collected.

Five Oaks Formation

The Five Oaks lies immediately above the Knox unconformity and is very poorly exposed in the two localities in which it occurs. It is composed of a dove grey, fine grained lime mudstone and a pelletal-intraclastic packstone/grainstone. It is commonly mottled with areas of light brownish dolomite and often contains tubular and poorly developed irregular fenestral fabric. The lithofacies of the Five Oaks is interpreted to represent deposition in the high peritidal environment. It has a very restricted fauna of ostracods and gastropods and no echinoderms were collected or observed (Table 4.1).

Tumbez Formation

The Tumbez is limited to one poorly exposed unit, approximately 30.0 meters thick at Halls Crossroads. It lies immediately above the Knox unconformity at this locality and consists of thin bedded, red bryozoan boundstone/wackestone and a massive skeletal packstone/grainstone facies. The depositional environment of the Tumbez is inferred to be a shallow water lagoon. The pelmatozoans which dominate the skeletal material in the packstone/grainstone facies, upon close inspection in the field, consist of unidentifiable camerate crinoid debris (Table 4.1).

Fleanor Formation

The Fleanor is a very poorly exposed, thin bedded, buff colored, shaly limestone and shale and comprises a major covered interval in the study area. The shaly nature of the Fleanor and the interfingering relationship with the Lincolnshire Formation to the northwest (refer to Figure 2.3, page 17) imply a terrigenous source to the southwest. The

fine grained texture and thin bedding suggest quiet water conditions, perhaps a restricted lagoon environment. However, the influx of terrigenous material apparently precluded the development of diverse faunal communities as evidenced by the small number of fossils in general and the largely noncalcareous nature of the Fleanor sediments. The top of the Fleanor near the Halls Crossroads section is somewhat calcareous and several unassignable camerate plates and one Hybocrinus sp. specimen were collected (Table 4.1).

Lincolnshire Formation

The Lincolnshire is a poorly exposed, light to medium grey, fine to coarse grained skeletal packstone/grainstone facies interbedded with carbonate mudstone. In the field, the Lincolnshire is characterized by irregular bedding and nodular weathering. Large (2.0 cm. in diameter) Girvanella sp. oncolites are commonly associated with the packstone/grainstone facies. The Lincolnshire is interpreted to represent near shore, shallow subtidal deposits subject to tidal and near shore current reworking. The primary constituents of the skeletal packstone/grainstone are pelmatozoans and bryozoans with secondary ostracods, trilobites and algae. Although echinoderms were present in the Lincolnshire environment, few specimens could be recovered because of limited and poor exposure. Unidentifiable camerates were observed at Harbison and Graveston along with the paracrinoid, Ulrichocystis eximia.

Rockdell Formation

The Rockdell is well exposed in the study area and is characterized by a complex assemblage of pelmatozoan-bryozoan packstone/

grainstones interbedded with bryozoan wackestone and bryozoan-algal boundstones. These particular lithofacies represent sand bank/tidal channel, mudmound and patch reef environments, respectively. The Rockdell represents a generally transgressive sequence of near shelf margin skeletal sands and mudmounds in the northeast portion of the study area which migrated over inner shelf patch reefs and associated lagoonal sediments to the southwest (Figure 2.3, page 17).

In the Rockdell environments, echinoderms, particularly the pelmatozoans, played an important role as a major sediment producer. The volume of pelmatozoan fragments in the packstone/grainstones of the Rockdell is ample testimony of the importance of these organisms as sediment producers. Upon death, echinoderms disarticulate rapidly into numerous calcitic skeletal fragments. An appropriate modern mechanical analogue is the green alga Halimeda sp. which is composed of articulated calcified segments of aragonite. Upon death, the plant disarticulates into individual segments which are deposited as whole or are broken down, mainly by organic activity, to sand and silt sized particles.

Relatively large stalked echinoderms in groups or "gardens," by nature of their stalks or stems, were capable of affecting local hydrodynamic conditions. They were instrumental in trapping sediment thereby altering local topography which further influenced local hydrodynamic conditions. The pelmatozoan-bryozoan packstone/grainstone facies inter-fingers both laterally and vertically in a patch-quilt fashion with the patchlike accumulation of the bryozoan wackestone "mudmound" facies of the Rockdell. This "mudmound" facies consists primarily of encrusting and bifoliate bryozoans, relatively unabraded pelmatozoan debris, and

considerably more lime mud, usually red in color, than is observed in the more well washed and transported sediments of the packstone/grainstone facies. The presence of abundant pelmatozoan holdfasts observed on many of the "mudmounds" suggest that the pelmatozoans acted as a current baffle to trap fine grained carbonate sediments and the pelmatozoans, encrusting bryozoans, and algae acted to stabilize and bind these sediments. It is not uncommon to find holdfasts with extensive "root" networks actually binding coarse grained sediments interpreted to represent channel deposits (Plate E-5, figures 7 and 8, Appendix E).

Similar lithofacies relationships between skeletal sands and patch-like accumulations of carbonate mud have been reported by workers in South Florida (Basan, 1973; Enos, 1974a and 1974b; Multer, 1977; and Turmel and Swanson, 1964). Skeletal sands are winnowed by wave and tidal current activity and lime mud deposits are controlled primarily by hydrodynamic considerations and the grass Thalassia. This sea-grass is an excellent modern analogue to the pelmatozoans because the blades of the grass act as a current baffle to trap carbonate sediments and the intricate root system binds the sediment. These Thalassia mudmounds often exist in close proximity to strong current conditions of tidal channels and can develop topographic relief sufficient to affect water movement.

Although the Rockdell Formation is relatively well exposed in the study area, the nature of weathering of the unit makes specimen collecting extremely difficult. However, as previously noted, recent excavation at the Halls Crossroads locality has yielded a representative collection of echinoderms. The collection was supplemented by specimens from Dry Gap and Harbison (Table 4.1, page 120).

The Rockdell contains a diverse group of echinoderms including representatives of the classes Crinoidea (camerates and inadunates), Rhombifera, Paracrinoidea, Edrioasteroidea, Edrioblastoidea and Eocrinoidea. Unidentifiable camerates (Plate E-1, figure 4, Appendix E) were collected or observed in the Rockdell at all localities. Important camerates are Diabolocrinus vesperalis (Plate E-1, figures 1 and 2, Appendix E) and Cleiocrinus sp. (Plate E-3, figure 1, Appendix E). A strong association appears to exist between Cleiocrinus sp. and a transversely ribbed, externally pentagonal columnal with a large lumen and pentagonally shaped axial canal (Plate E-5, figure 1, Appendix E). A similar relationship exists between camerates and a round columnal with alternating meridional bands of short spines (Plate E-5, figure 2, Appendix E). Inadunate crinoids consist of Carabocrinus sp., Carabocrinus micropunctatus (Plate E-2, figure 1, Appendix E), Carabocrinus stellifer (Plate E-2, figures 5 and 8, Appendix E), Hybocrinus sp., Hybocrinus punctatus (Plate E-2, figure 6, Appendix E), Palaeocrinus sp. (Plate E-2, figure 12, Appendix E), Palaeocrinus planobasalis (Plate E-2, figures 11 and 13, Appendix E) and Palaeocrinus avondalensis (Plate E-2, figures 4 and 9, Appendix E). Rhombiferans are represented by Coronocystis angulatus (Plate E-3, figures 6 and 7, Appendix E) and Regulaecystis pyriformis (Plate E-3, figure 4, Appendix E). Paracrinoids include Ulrichocystis eximia (Plate E-4, figures 8 and 9, Appendix E), Platycystites sp. (Plate E-4, figure 10, Appendix E), Canadocystis sp., Springerocystis sp. (Plate E-4, figures 1-3, Appendix E) and one undescribed paracrinoid (Plate E-4, figure 4, Appendix E). The edrioasteroid Cyathocystis sp. (Plate E-3, figure 10, Appendix E) is

fairly common in the Rockdell and appears to be associated with fine grained sediment substrates where it is often found attached in life position. Astrocystites sp. (Plate E-3, figure 11, Appendix E) is the only representative of the class Edrioblastoidea found in the Rockdell. Finally, marginal plates of the eocrinoid Batherocystis appressa (Plate E-3, figure 12, Appendix E) were found at Halls Crossroads and Harbison.

Apparently, the shallow water, relatively high current activity of the near shelf margin sand bank and inner shelf lagoon environments of the Rockdell were conducive to the development of diverse communities of echinoderms. The environment was probably dominated by the larger camerates (e.g., Diabolocrinus vesperalis, Archaeocrinus peculiaris and Cleioocrinus sp.), if not in biovolume certainly in size. As mentioned above, the large camerates may have been capable of altering hydrodynamic conditions sufficiently to produce suitable microenvironments for many of the moderately sized (e.g., inadunates) and small short-stalked, small echinoderms (i.e., rhombiferans and paracrinoids) in much the same way the modern grass Thalassia produces habitable microenvironments for many marine organisms. According to Parsley and Mintz (1975) some of the low suspension feeders such as Canadocystis sp. and Platycystites sp. may have lived partially buried. This adaption may have allowed these organisms to take advantage of the less congested but mobile sand bank areas surrounding the "mudmounds."

Chapman Ridge Formation

The Chapman Ridge is not widespread in the study area but is relatively well exposed at the Halls Crossroads and Harbison sections

(see Figure 2.3, page 17). The Chapman Ridge is best described as a thin to medium bedded, maroon to red, fine to medium grained bryozoan wackestone/packstone. Deposition of carbonate mud was dominant and the major faunal components were ramose and encrusting bryozoans with subordinate pelmatozoan debris. The Chapman Ridge and Ottosee deposits represent a minor influx of sediment derived from the southeast which were superimposed onto the carbonate shelf sediments accumulating along a southeast-northwest depositional strike. It should be recalled that the general trend of the shelf-edge is southwest-northeast and only in the study area does the shelf edge depart abruptly from that general trend (see Figure 1.3, page 6). The depositional environment of the Chapman Ridge is interpreted to represent a shallow water, restricted lagoon.

Echinoderms do not appear to be particularly abundant in the muddy sediments of the Chapman Ridge. Perhaps turbid conditions prevailed during deposition of the Chapman Ridge which prevented the development of a diverse echinoderm community. However, representatives of several classes of echinoderms were collected or observed: Crinoidea, Paracrinoidea, Parablastoidea and Edrioasteroidea (Table 4.1, page 120). The crinoids consist primarily of unidentifiable camerate remains and Carabocrinus stellifer. The paracrinoids include unidentifiable paracrinoids and Ulrichocystis eximia (Plate E-4, figure 7, Appendix E). An isolated deltoid plate of the parablastoid Meristoschisma hudsoni was observed at Harbison. The edrioasteroid Cyathocystis sp. was relatively common in the Chapman Ridge and again appears to be associated with muddy substrates.

Ottosee Formation

The Ottosee is confined to the Halls Crossroads section and is poorly exposed, particularly at the base where it is covered. The upper portion of the unit is a grey, medium to coarse grained bryozoan-pelmatozoan wackestone/packstone and is interbedded with a shaly facies (about 50 percent of the outcrop). The depositional environment of the lower Ottosee reflects quiet water conditions similar to the restricted lagoonal environment of the Chapman Ridge. The interbedded shales in the upper Ottosee could be interpreted to indicate an availability of terrigenous material in the area or could represent periods of quiet water lagoonal sedimentation intermittent between periods of deposition of wackestone/packstones in slightly stronger current conditions, perhaps in a shoaling environment presumably somewhat removed from the full influence of currents associated with the shelf edge to the southeast.

Pelmatozoan debris and bryozoan fragments are the most abundant faunal components in the Ottosee lithofacies. Unfortunately, due to poor exposure and the nature of weathering of the lithofacies, field observations disclosed only unidentifiable camerate remains (Table 4.1, page 120).

Benbolt Formation

The Benbolt occurs at all four localities in the study area and is generally a thin bedded, yellowish to grey, poorly exposed, burrowed, fossiliferous wackestone/packstone in the field. The relatively diverse faunal assemblage of brachiopods, bryozoans, pelmatozoans, sponges and algae, the yellowish to buff color (imparted by a high shale content) and

the thin, nodular bedding are characteristic features of the Benbolt. The lithofacies and biofacies vary laterally from one locality to another in fossil diversity and abundance. The Benbolt in the study area can be characterized as a complex of tidal sand/mud flat deposits that interfinger with a quiet, shallow water, subtidal lagoon environment. The environmental complex was influenced by the influx of terrigenous material (shales).

Much of the information about Middle Ordovician echinoderms, particularly the crinoids, in Eastern Tennessee has been derived from specimens collected from the Benbolt and allied formations (Brower and Veinus, 1974). The Benbolt in the study area yielded a fairly representative sampling of "Benbolt" crinoids, particularly at the Dry Gap and Graveston sections (Table 4.1, page 120). The echinoderms collected in the study area represented five classes: Crinoidea, Rhombifera, Paracrinoidea, Parablastoidea and Edrioasteroidea. The crinoids comprise unidentifiable camerates and the camerates Archaeocrinus peculiaris, Cleioocrinus sp. (Plate E-3, figure 3, Appendix E) and Diabolocrinus vesperalis (Plate E-1, figures 4-8, Appendix E). Inadunate crinoids consist of Carabocrinus sp., Carabocrinus sp. cf. micropunctatus, Carabocrinus stellifer, Hybocrinus sp. (Plate E-2, figure 10, Appendix E), Hybocrinus punctatus, Palaeocrinus sp., Palaeocrinus planobasalis, Palaeocrinus avondalensis and Ristnocrinus sp. cf. altobasalis (Plate E-2, figure 3, Appendix E). The Rhombifera are represented by one unidentifiable rhombiferan and Regulaecystis sp. (Plate E-3, figure 6, Appendix E). Paracrinoidea were found in all localities except Halls Crossroads and consist of unidentifiable paracrinoidea, Ulrichocystis eximia (Plate E-4, figure 6, Appendix E) and Springerocystis sp. (Plate

E-4, figure 1, Appendix E). Also prevalent in nearly all localities in the study area was the parablattoid Meristoschisma hudsoni (Plate E-4, figures 11-14, Appendix E) along with the edrioasteroid Cyathocystis sp. (Plate E-3, figure 9, Appendix E)..

Echinoderms are not found in significant numbers except as pelmatozoan debris in packstones at the base of the Benbolt at Gravelston and Dry Gap. The low volume percent of pelmatozoans and bryozoans suggests that turbid environmental conditions caused by the influx of terrigenous material and weak current activity were not suitable for these organisms to develop in large numbers.

It is interesting to note that Meristoschisma hudsoni is not encountered in sediments older than the Benbolt and Chapman Ridge Formations which are probably coeval in the study area. Sprinkle (1973) first described Meristoschisma from the Benbolt and its equivalents (Ottosee Group) in Eastern Tennessee. Although Meristoschisma hudsoni is found in younger units (Wardell Formation), evidence from this study suggests the lower range for Meristoschisma hudsoni in this area is the base of the Benbolt and equivalent rocks.

Wardell Formation

Some minor lithofacies and stratigraphic differences exist in the Wardell across the study area (Figure 2.13, page 29). In the northeast the Wardell is a distinctive yellowish to buff (caused by the predominance of shale), poorly exposed, pelletal mudstone/wackestone which interfingers with minor deposits of well washed, well sorted pelmatozoan-bryozoan packstone/grainstones. Mudcracks and burrows occur in the upper

portion of the formation. To the southwest it pinches out or inter-fingers with the Benbolt at Halls Crossroads but is exposed again at Dry Gap where it is dominated by yellowish to buff and grey, poorly exposed, thin bedded mudstone/wackestones with minor amounts of bryozoan-pelmatozoan wackestone/packstones. The lower Wardell in the northeastern portion of the study area is interpreted to represent a shallow subtidal restricted lagoon that was influenced by the relatively higher current energies of a sand/mud tidal flat environment. The subtidal environment grades upward into a mudcracked and burrowed high intertidal to supratidal environment. To the southwest the lower Wardell is interpreted to represent a shallow restricted lagoon mud flat environment and the upper Wardell represents a shallow subtidal restricted lagoon with moderate current activity and perhaps slightly deeper water than that in which the lower Wardell was deposited.

The Wardell at Harbison and Graveston is dominated by upper peritidal sedimentation and consequently echinoderms were, for the most part, nonexistent in that environment. However, some echinoderms were found in the subtidal environment at Dry Gap, particularly the lower Wardell (Table 4.1, page 120). This echinoderm assemblage included numerous plates of unidentifiable camerates, Archaeocrinus peculiaris (Plate E-1, figures 9-11, Appendix E), Carabocrinus sp. (Plate E-2, figure 2, Appendix E), Carabocrinus stellifer, Hybocrinus punctatus and Palaeocrinus planobasalis (Plate E-2, figure 7, Appendix E). Also included in the assemblage were the rhombiferan Regulaecystis sp. (Plate E-3, figure 5, Appendix E), the paracrinoid Meristoschisma hudsoni (Plate E-4, figure 15, Appendix E) and the eocrinoid Batherocystis sp.

Bowen Formation

The Bowen is confined to the northwest portion of the study area (see Figure 2.13, page 29) and is characteristically a thin, maroon to red, burrowed and mudcracked, fine grained mudstone. The petrographic features of the Bowen strongly suggest an intertidal to supratidal deposition environment. No echinoderm remains were collected or observed in the Bowen (Table 4.1, page 120).

Witten Formation

The Witten is composed of two distinct lithofacies in the study area (Figure 2.13, page 29). To the northeast it is a mudcracked, fine grained pelletal mudstone/wackestone which grades to the southwest into a poorly exposed stromatoporoid-sponge-coral mudstone/wackestone/packstone. The lithofacies of the Witten in the northeast is interpreted to represent a complex of protected intertidal to supratidal environments such as intertidal mudflats and tidal ponds. The peritidal environments of the pelletal mudstone/wackestones lithofacies are in marked contrast to the comparatively deeper water subtidal, near shore lagoon environment proposed for the stromatoporoid-sponge-coral-lithofacies.

The Witten Formation yielded very little information about echinoderms as expected for the upper peritidal environments represented at Graveston and Harbison which would not be conducive to the development of echinoderm communities and because the Witten at Halls Crossroads and Dry Gap is poorly exposed. Echinoderms found in the Witten are comprised of unidentifiable camerates, numerous partial calyces and stems of Cleiocrinus sp. (Plate E-3, figure 2, Appendix E) and Palaeocrinus avondalensis. The edrioasteroid Cyathocystis sp. was frequently observed

and was associated with fine grained sediment. Figure 4.1 summarizes the occurrence and distribution of echinoderms in relation to the environmental and stratigraphic framework of the study area.

Summary

Documentation of the occurrence and stratigraphic distribution of echinoderms in the paleoenvironments of the study area has shown that echinoderms are abundant and relatively diverse (i.e., Crinoidea, Rhombifera, Paracrinoidea, Parablastoidea, Edrioasteroidea, Edrioblastoidea and Eocrinoidea). Echinoderms were found in all eleven formations except the Five Oaks and Bowen and were particularly abundant in the sand bank/tidal channel and mudmound environments of the Rockdell Formation. Large and diverse collections were taken from the Rockdell and Benbolt Formations.

The examination of echinoderms showed that they played a significant sedimentological role in the shelf environments of the study area. First, they were important as sediment producers. The multi-segmented skeleton of these organisms produced, upon death, abundant whole segments as well as sand and silt sized particles. Secondly, the larger pelmatozoans were capable of affecting local hydrodynamic conditions by acting as a current baffle and were instrumental in trapping sediment in mudmounds in the Rockdell. These mudmounds probably affected local water movement in much the same way as the Thalassia grass mounds in South Florida influence local relief and hydrodynamic conditions. The large pelmatozoans initially stabilized the sediments of the mudmounds which were bound by their "root" systems

and encrusting bryozoans to produce a stable substrate which could be populated by other smaller organisms thereby developing a more diverse community.

Most of the information to date on Middle Ordovician echinoderms from Eastern Tennessee has centered around the crinoids and has been derived from collections from the Benbolt Formation and secondarily from the Hogskin Member of the Lincolnshire Formation. Also, no previous effort has been made to associate paleodepositional environments with the occurrence of echinoderms. This investigation documents the stratigraphic occurrence of members of seven classes of echinoderms in the Middle Ordovician of East Tennessee (although all had previously been reported from the region): Crinoidea, Rhombifera, Paracrinoidea, Parablastoidea, Edrioasteroidea, Edrioblastoidea and Eocrinoidea. The occurrence and stratigraphic distribution of echinoderms were associated with specific sedimentary environments interpreted for the study area. The diverse assemblage of echinoderms in the Rockdell Formation contributes significantly to the informational gap between the Lincolnshire and Benbolt Formations and suggests that formational names (e.g., Benbolt) assigned to many echinoderm specimens by earlier workers in the complex Middle Ordovician lithofacies in the region may be in error. This study indicates that the lower range boundary in the study area for the parablastoid Meristoschisma hudsoni Sprinkle is the lower Benbolt and coeval units.

CHAPTER V

SUMMARY AND CONCLUSIONS

1. The Middle Ordovician Chickamauga Group sequences in the study area (Dry Gap, Halls Crossroads, Harbison and Graveston) in East Tennessee are composed of the following formations: Five Oaks, Tumbez, Fleanor, Lincolnshire, Rockdell, Chapman Ridge, Ottosee, Benbolt, Wardell, Bowen, Witten and Moccasin.

2. Detailed field and laboratory examination of a line of measured stratigraphic sections oriented parallel to the regional southwest-northeast strike are interpreted to represent a transect across a portion of the Middle Ordovician shelf from near the shelf-edge in the northeast at Graveston to the inner shelf in the southwestern portion of the study area at Dry Gap, Halls Crossroads and Harbison. The complex lithofacies relationships observed in the shelf sediments are best summarized as lower, middle and upper stratigraphic packages. The first or lower stratigraphic package is composed of the Five Oaks, Tumbez, Fleanor and Lincolnshire Formations and is interpreted to represent peritidal to shallow marine environments. The middle stratigraphic package consists of the Rockdell Formation which represents deposition in a generally transgressive sequence of near shelf margin and on-shelf patch reef environments. The lithofacies and biofacies transitions which take place near the shelf-edge and shelfward in this particular line of sections in the study area are well exemplified by the lateral facies changes within the Rockdell Formation. The upper stratigraphic package

is dominated by the shallow marine (restricted lagoon) and peritidal environments of the Chapman Ridge, Ottosee, Wardell, Benbolt, Bowen and Witten Formations.

3. Petrographic study of the bryozoan-red algal boundstone patch reefs observed in the study area proved to be helpful in recognizing and distinguishing on-shelf from shelf-edge reef buildups. The encrusting red alga, Solenopora sp., associated with these patch reefs assumed a morphology and a role in the buildup process that had previously not been observed in East Tennessee. It formed extensive thin (0.5 cm.), sinuous layers which bound muds of the reef core. Previously, Solenopora sp. was only known to be associated with shallow water lagoonal facies in the Middle Ordovician sequence.

4. Comparison of a bryozoan-red algal bound patch reef in the on-shelf Rockdell Formation with the reef complex of the down-slope part of the shelf margin Holston Formation revealed characteristic similarities in the diagnostic reef flank and core material lithofacies. Reef flank material, composed primarily of pelmatozoan and bryozoan fragments, is almost identical in both reef types. Cement morphotypes and paragenesis (that is, radial fibrous marine cement, syntaxial overgrowths and blocky calcite cement) also show marked similarities. Distinct differences are present in the size and geometry of the reefs. The Rockdell patch reef is small in area and circular whereas the Holston reef complex is large in area and assumes a linear geometry coincident with the shelf-edge. Binding and framework components of the patch reef are characterized by encrusting bryozoans and red algae in contrast to the bryozoans of the shelf-edge reef complex.

5. Investigation into the different types of cements in the Rockdell patch reef has revealed a definite paragenetic sequence of cementation and internal sedimentation from which the diagenetic history of the patch reef could be determined. Sequence of cementation consist of an initial stage, low-iron content, radial fibrous marine cement which was generally followed by vadose silt and pendant cement. Primary and secondary pore space and cavities were finally filled with a late stage, high-iron content, blocky calcite cement. Initial partial cementation of sediments took place in the marine environment penecontemporaneously with sedimentation of the patch reef. The patch reef sediments were subsequently subaerially exposed for a period of time during which dissolution, reprecipitation and internal sedimentation took place in the vadose diagenetic environment. Following the period of subaerial exposure the remaining primary porosity and the secondary porosity produced in the vadose diagenetic environment were sealed by cementation in the fresh water phreatic diagenetic environment.

6. Documentation of the occurrence and stratigraphic distribution of echinoderms in the paleoenvironments of the study area has shown that echinoderms are abundant and relatively diverse (i.e., Crinoidea, Rhombifera, Paracrinoidea, Parablastoidea, Edrioastroidea, Edrioblastoidea and Eocrinoidea). Echinoderms were found in all formations except the Five Oaks and Bowen and were particularly abundant in the sand bank/tidal channel and mudmound environments of the Rockdell Formation. Large and diverse collections were taken from the Rockdell and Benbolt Formations.

7. Examination of echinoderms showed that they played a significant sedimentological role in the shelf environments of the study

area. First, they were important as sediment producers. The multi-segmented skeleton of these organisms produced, upon death, abundant whole segments as well as sand and silt sized particles. Secondly, the larger pelmatozoans were capable of affecting local hydrodynamic conditions by acting as a current baffle and were instrumental in trapping sediments in mudmounds in the Rockdell. These mudmounds probably affected local water movement in much the same way as the Thalassia sp. grass mounds in South Florida influence local relief and hydrodynamics conditions. The larger pelmatozoans initially stabilized the sediments of the mudmounds which were bound by their "root" systems and encrusting bryozoans to produce a stable substrate which could be populated by other smaller organisms thereby developing a more diverse community.

8. Most of the information to date on Middle Ordovician echinoderms from Eastern Tennessee has centered around crinoids and has been derived from collections from the Benbolt Formation and secondarily from the Hogskin Member of the Lincolnshire Formation. Also, no previous effort has been made to associate paleodepositional environments with the occurrence of echinoderms. The areal and stratigraphic occurrence of the echinoderms were coupled with the sedimentary environments identified in the study area. Collection and identification of a diverse assemblage of echinoderms in the Rockdell Formation contributes significantly to the informational gap concerning these organisms between the Lincolnshire and Benbolt Formations and suggests that formational names (e.g., Benbolt) assigned to many echinoderm specimens by earlier workers in the complex Middle Ordovician lithofacies in the region may be in error.

9. This study indicates that the lower range boundary in the study area for the parablasteroid Meristoschisma hudsoni Sprinkle is the lower Benbolt and coeval units.

LITERATURE CITED

LITERATURE CITED

- Alberstadt, L. P., Walker, K. R., and Zurawski, R. P., 1974, Patch reefs in the Carters Limestone (Middle Ordovician) in Tennessee and vertical zonation in Ordovician reefs; *Geol. Soc. Amer. Bull.*, v. 85, pp. 1171-1182.
- _____, and Walker, K. R., 1976, A receptaculid-echinoderm pioneer community in a Middle Ordovician reef; *Lethaia*, v. 9, pp. 261-272.
- Ahr, W. M., 1971, Paleoenvironment, algae structures, and fossil algae in the Upper Cambrian of central Texas; *Jour. Sed. Pet.*, v. 41, no. 1, pp. 205-216.
- Aitken, J. D., 1967, Classification and environmental significance of cryptalgal limestone and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta; *Jour. Sed. Pet.*, v. 37, pp. 1163-1178.
- Basan, P. B., 1973, Aspects of sedimentation and development of a carbonate bank in Barracuda Keys, south Florida; *Jour. Sed. Pet.*, v. 43, pp. 42-53.
- Bassler, R. S., 1950, New genera of Middle Ordovician "Cystoidea"; *Jour. Washington Acad. Sci.*, v. 40, pp. 273-277.
- Bathurst, R. G. C., 1958, Diagenetic fabrics in some Dinantian limestones; *Liverpool and Manchester Geol. Jour.*, v. 2, pp. 11-36.
- _____, 1975, Carbonate Sediments and Their Diagenesis: Developments in Sedimentology 12, Second Edition, Elsevier, New York, 658 p.
- Berner, R. A., 1966, Chemical diagenesis of some modern carbonate sediments; *Am. Jour. Sci.*, v. 264, pp. 1-36.
- Boardman, R. S., 1960, Trepostomatous Bryozoa of the Hamilton County of New York State. U.S. Geol. Surv. Prof. Paper 340, 87 p.
- Breland, F. C., and Walker, K. R., 1980, Red algal boundstone in shallow water up-slope reef in Middle Ordovician of East Tennessee (abstr.), *Geol. Soc. Am., Southeast Ann. Meeting, (Abstr. with Programs)*, v. 12, no. 4, p. 172.
- Broadhead, T. W., 1980, Range extension—Middle Ordovician blastoids (Echinodermata) from the Southern Appalachians (abstr.), *Geol. Soc. Am., Southeast Ann. Meeting, (Abstr. with Programs)*, v. 12, no. 4, p. 172.
- _____, and Breland, F. C., 1980, Palaeocystitida—Middle Ordovician echinoderms with eocrinoid and paracrinoid affinities (abstr.), *Geol. Soc. Am., Southeast Ann. Meeting, (Abstr. with Programs)*, v. 12, no. 4, p. 172.

- Brower, J. C., and Veinus, J., 1974, Middle Ordovician crinoids from southwestern Virginia and eastern Tennessee; *Bull. Amer. Paleont.*, v. 66, no. 283, 125 p.
- Butts, C., 1940, Geology of the Appalachian Valley in Virginia; *Virginia Geological Society, Bull.* 52, pt. 1, 568 p.
- Campbell, M. R., 1894, Paleozoic overlaps in Montgomery and Pulaski Counties, Virginia; *Geol. Soc. Amer. Bull.*, v. 5, pp. 171-190.
- Cattermole, J. M., 1958, Geologic map of the Knoxville Quadrangle, Tennessee; U.S.G.S. Map CQ-147 NW.
- ✓ Chayes, F., 1954, The theory of thin-section analysis; *Jour. Geol.*, v. 62, pp. 92-101.
- Cooper, B. N., 1956, Chazy and related brachiopods; *Smithsonian Inst. Misc. Coll.*, pts. 1 and 2, 1245 p.
- _____, and Prouty, C. E., 1943, Stratigraphy of the Lower Middle Ordovician of Tazewell County, Virginia; *Bull. Geo. Soc. Amer.*, v. 54, pp. 819-886.
- Copper, P., 1976, The cyanophyte *Wetherdella* in Ordovician reefs and off-reef sediments; *Lethaia*, v. 9, pp. 273-281.
- Cullis, C. G., 1904, The mineralogical changes observed in the cores of the Funafuti borings, *in* The atoll of Funafuti, *Royal Soc., Coral Reef Comm. Rept.*, pp. 392-420.
- Dickson, J. A. D., 1966, Carbonate identification and genesis as revealed by staining; *Jour. Sed. Pet.*, v. 36, pp. 491-505.
- Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture, *in* Hamm, W. E., ed., *Classification of Carbonate Rocks*, *Amer. Assoc. Petroleum Geol., Mem.* 1, pp. 108-121.
- _____, 1969, Early vadose silt in Townsend mound (reef), New Mexico, *in* Friedman, G. M., ed., *Depositional Environment in Carbonate Rocks*; *Soc. Econ. Paleontologists and Mineralogists Spec. Pub.* 14, pp. 139-181.
- _____, 1971, Meniscus cement, *in* Bricker, O. P., ed., *Carbonate Cements*, John Hopkins Press, Baltimore, Md., pp. 297-350.
- ✓ Enos, P., 1974a, A carbonate shelf-margin, the third dimension (abstr.), *Geol. Soc. Amer., Ann. Meeting, (Programs with Abstr.)*, v. 6, no. 7, p. 723.
- ✓ _____, 1974b, Carbonate sedimentation patterns of South Florida shelf margins (abstr.), *Amer. Assoc. Petrol. Geol. Abstract*, v. 1, p. 31.

- Evamy, B. D., 1969, The precipitational environment and correlation of some calcite cements deduced from artificial staining; *Jour. Sed. Pet.*, v. 39, pp. 787-821.
- Ferrigno, K. R., 1973a, Paleoeecology of the reefs of the Holston Limestone; unpub. Ph.D. dissertation, The University of Tennessee, Knoxville, 142 p.
- _____, 1973b, The use of cathodoluminescence in the interpretation of the diagenetic history of the Holston Limestone (M. Ordovician) (abstr.), *Geol. Soc. Amer., Southeast Ann. Meeting, (Programs with abstr.)*, v. 5, no. 5, p. 395.
- _____, and Walker, K. R., 1973, Holston and Chapman Ridge Formations. *Tenn. Fiv. Geol. Bull.*, v. 70, pp. 117-121.
- Friedman, G. M., 1959, Identification of carbonate minerals by staining methods; *Jour. Sed. Pet.*, v. 29, pp. 87-92.
- Ginsburg, R. N., 1957, Early Diagenesis and Lithification of Shallow-Water Carbonate Sediments in South Florida, in La Blanc, R. J. and Breeding, J. G., eds., *Regional Aspects of Carbonate Deposition*; Soc. Econ. Paleontologists Mineralogists Spec. Pub. 5, Tulsa, Oklahoma, pp. 80-99.
- _____, 1960, Ancient analogues of recent stromatolites; XXI *International Geol. Cong.*, pt. 22, pp. 26-35.
- _____, and Hardie, L. A., 1975, Tidal and Storm Deposits, North-western Andros Island, Bahamas, in Ginsburg, R. N., ed., *Tidal Deposits, a Casebook of Recent and Fossil Counterparts*; New York, Springer-Verlag, pp. 201-208.
- Grover, G., and Read, J. R., 1978, Fenestral and associated vadose diagenetic fabrics of tidal flat carbonates, Middle Ordovician New Market Limestone, southwestern Virginia; *Jour. Sed. Pet.*, v. 48, pp. 453-473.
- Hayes, C. W., 1891, The overthrust faults of the Southern Appalachians; *Geol. Soc. Amer. Bull.*, v. 2, pp. 141-154.
- _____, 1894, Description of the Ringold Quadrangle, Georgia-Tennessee; *U.S.G.S. Atlas of the U.S.*, Folio no. 2.
- Hoffmeister, J. E., and Multer, H. G., 1968, Geology and origin of the Florida Keys; *Geol. Soc. Amer. Bull.*, v. 79, pp. 1487-1502.
- ✓ Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks; *Geol. Soc. Amer. Bull.*, v. 65, pp. 937-938.

- James, N. P., and Kobluk, D., 1978, Lower Cambrian patch reefs and associated sediments, southern Labrador, Canada; *Sedimentol.*, v. 25, pp. 1-35.
- _____, Ginsburg, R. N., Marszalek, D. S., and Choquette, P. W., 1976, Facies and fabric specificity of early subsea cements in shallow Belize (British Honduras) reefs; *Jour. Sed. Pet.*, v. 46, pp. 523-544.
- Keith, Arthur, 1896, U. S. Geol. Survey Geol. Atlas, Morristown folio (no. 27).
- _____, 1901, U. S. Geol. Survey Geol. Atlas, Maynardville folio (no. 75).
- Ladd, H. S., 1971, Existing reefs—geological aspects, *in* Yochelson, E. L., ed., *North American Paleont. Convention Proc.*, v. II, pt. 5; Lawrence, Kansas, Allen Press, pp. 1273-1300.
- LaFollette, S. G., 1974, Paleoenvironmental and paleoecological analysis of the Vestal Limestone in Knox County, Tennessee; unpubl. Master's thesis, The University of Tennessee, Knoxville, 143 p.
- Land, L. S., and Goreau, T. F., 1970, Submarine lithification of Jamaican reefs; *Jour. Sed. Pet.*, v. 40, pp. 457-462.
- LaPorte, L. F., 1967, Carbonate deposition near mean sea level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State; *Amer. Assoc. Petrol. Geol. Bull.*, v. 51 pp. 73-101.
- _____, 1971, Paleozoic carbonate facies of the Central Appalachian shelf; *Jour. Sed. Pet.*, v. 41, pp. 724-740.
- LeRoux, G. B., 1974, Sedimentological and environmental interpretation of the Chota-Sevier Formations in easternmost Tennessee; unpub. Master's thesis, The University of Tennessee, Knoxville, 105 p.
- ✓ Lindholm, R. C., 1974, Fabric and chemistry of pore filling calcite in septarian veins: Models for limestone cementation; *Jour. Sed. Pet.*, v. 2, pp. 422-428.
- ✓ _____, and Finkelman, R. B., 1972, Calcite staining: Semiquantative determination of ferrous iron; *Jour. Sed. Pet.*, v. 42, pp. 239-241.
- Logan, B. W., 1974, Inventory of Diagenesis in Holocene-Recent Carbonate Sediments, Shark Bay, Western Australia, *in* Logan, B. W., ed., *Evolution and Diagenesis of Quaternary Carbonate Sequences*, Shark Bay, Western Australia; *Amer. Assoc. Pet. Geol., Mem.* 22, pp. 195-249.
- _____, Rezak, R., and Ginsburg, R. N., 1964, Classification and environmental significance of algal stromatolites; *Jour. Geol.*, v. 72, pp. 68-83.

- _____, Hoffman, P., and Gebelein, C. D., 1974, Algal Mats, Cryptalgal Fabrics, and Structures, Hamelin Pool, Western Australia, in Logan, B. W., ed., Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia; Amer. Assoc. Pet. Geol., Mem. 22, pp. 140-194.
- _____, and Semeniuk, V., 1976, Dynamic metamorphism: Processes and products in Devonian carbonate rocks, Canning Basin, Western Australia; Geol. Soc. of Australia, Inc., Spec. Publ., no. 6, 138 p.
- _____, Davies, G. R., Read, J. F., and Cebulski, D. E., 1970, Carbonate sedimentation and environments, Shark Bay, Western Australia; Amer. Assoc. Pet. Geol. Bull., Mem. 13, 223 p.
- MacIntyre, I. G., 1977, Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point, Panama; Jour. Sed. Pet., v. 47, pp. 503-516.
- _____, Mountjoy, E. W., and D'Angejan, B. F. D., 1968, An occurrence of submarine cementation of carbonate sediments off the west coast of Barbados, W. I.; Jour. Sed. Pet., v. 38, pp. 660-664.
- McKee, E. D., and Weir, J. W., 1953, Terminology for stratification and cross-stratification; Bull. Geol. Soc. Amer., v. 64, pp. 381-390.
- McLaughlin, R. E., 1973, Observations on the Biostratigraphy and Stratigraphy of Knox County, Tennessee and Vicinity, in The Geology of Knox County, Tennessee; Tenn. Div. Geol. Bull., v. 70, pp. 25-62.
- McWilliams, E. B., 1975, Paleoenvironmental analysis of the Chapman Ridge sandstone (Middle Ordovician) in the area of Knoxville, Tennessee; unpubl. Master's thesis, The University of Tennessee, Knoxville, 109 p.
- Meyers, W. J., 1974, Carbonate cement stratigraphy of the Lake Valley Formation (Mississippian), Sacramento Mountains, New Mexico; Jour. Sed. Pet., v. 44, pp. 837-863.
- Milici, R. C., and Walker, K. R., 1973, Depositional Environments—Mudbanks and "Lakes" in the Moccasin Formation, Raccoon Valley, Knox County, Tennessee, in The Geology of Knox County, Tennessee; Tenn. Div. Geol. Bull., v. 70, pp. 152-158.
- Miller, S. A., and Gurley, W. F. W., 1894, New genera and species of Echinodermata; Illinois State Mus. Nat. Hist. Bull., v. 5, pp. 5-53.
- _____, 1895, New and interesting species of Palaeozoic fossils. Illinois State Mus. Nat. Hist. Bull., v. 7, pp. 5-89.

- Moore, N. K., 1977, Distribution of the Benthic Algal Flora in Middle Ordovician Carbonate Environmental Units of the Southern Appalachians, in Ruppel, S. C. and Walker, K. R., eds., *Ecostratigraphy of the Middle Ordovician of the Southern Appalachians* (Kentucky, Tennessee, and Virginia), U.S.A.; A field excursion; The University of Tennessee, Knoxville, *Studies in Geol.*, no. 77-1, pp. 18-29.
- _____, 1978, Taxonomy and paleoenvironmental distribution of the benthic algal flora from Middle Ordovician carbonate rocks of East Tennessee; unpubl. Ph.D. dissertation, The University of Tennessee, Knoxville, 119 p.
- _____, and Walker, K. R., 1974, Porosity occlusion in ancient reefal carbonates, with an example from the Holston Formation (Middle Ordovician) of East Tennessee (abstr.); *Geol. Soc. Amer., Southeast Ann. Meeting* (Abstr. with Programs), v. 6, no. 7, p. 1049.
- Multer, H. G., 1977, Field Guide to Some Carbonate Rock Environments, Florida Keys and Western Bahamas; Dubuque, Iowa, Kendall/Hunt Publ. Co., 415 p.
- Newell, N. D., 1955, Deposition fabric in Permian reef limestones; *Jour. Geol.*, v. 63, pp. 301-309.
- Parsley, F. L., and Mintz, L. W., 1975, North American Paracrinoidea: (Ordovician: Paracrinozoa, new Echinodermata); *Bull. Amer. Paleontology*, v. 68, n. 288, 115 p.
- Pitcher, M., 1964, Evolution of Chazyan (Ordovician) reefs of eastern United States and Canada; *Bull. Can. Pet. Geol.*, v. 12, pp. 632-691.
- Prouty, C. E., 1946, Lower Middle Ordovician of southwest Virginia and northeast Tennessee; *Bull. Amer. Assoc. Pet. Geol.*, v. 30, pp. 1140-1191.
- Purdy, E., 1963, Recent calcium carbonate facies of the Great Bahama Bank; pt. 2; *Jour. Geol.*, v. 71, pp. 472-497.
- Ratliff, L. E., 1974, Environmental stratigraphy of the Middle Ordovician carbonates in the Luttrell Belt, Union and Grainger Counties, East Tennessee; unpubl. Ph.D. dissertation, The University of Tennessee, Knoxville, 148 p.
- Read, J. F., 1978, Evolution of lower Middle Ordovician foreland basins, Virginia (abstr.); *Geol. Soc. Amer.; Southeast Ann. Meeting*, (Abstr. with Programs), v. 10, no. 4, p. 195.
- Richter, D. K., and Füchtbauer, H., 1978, Ferroan calcite replacement indicates former magnesium clacite skeletons; *Sedimentology*, v. 25, pp. 843-860.

- Rodgers, J., 1953, Geologic map of East Tennessee with explanatory text; Tenn. Div. Geol. Bull. 58, pt. 2, pp. 64-98.
- Ruppel, S. C., 1977, The Chickamauga Limestone—A Complex Mosaic of Supratidal of Subtidal Carbonate Shelf Environments, in Ruppel, S. C., and Walker, K. R., eds., *Ecostratigraphy of the Middle Ordovician of the Southern Appalachians* (Kentucky, Tennessee, and Virginia), U.S.A.; A field excursion; The University of Tennessee, Knoxville, Studies in Geol., no. 77-1, pp. 39-48.
- _____, 1979, The stratigraphy, carbonate petrology and depositional environments of the Chickamauga Group (Middle Ordovician) of northern East Tennessee; unpubl. Ph.D. dissertation, The University of Tennessee, Knoxville, 226 p.
- Shanmugam, G., 1978, The stratigraphy, sedimentology and tectonics of the Middle Ordovician Sevier Shale Basin in East Tennessee; unpubl. Ph.D. dissertation, The University of Tennessee, Knoxville, 222 p.
- _____, and Walker, K. R., 1978, Tectonic significance of distal turbidites in the Middle Ordovician Blockhouse and lower Sevier Formations in East Tennessee; *Amer. Jour. Sci.*, v. 278, pp. 551-578.
- Shinn, E. A., 1968a, Practical significance of birdseye structures in carbonate rocks; *Jour. Sed. Pet.*, v. 38, pp. 215-223.
- _____, 1968b, Burrowing in Recent carbonate sediments of Florida and Bahamas; *Jour. Paleontology*, v. 42, pp. 879-894.
- _____, Lloyd, R. M., and Ginsburg, R. N., 1969, Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas; *Jour. Sed. Pet.*, v. 39, pp. 1202-1228.
- Sickafoose, D. K., 1979, *Ecostratigraphy of the Lower Middle Ordovician and Paleoecology of Porterfieldian and Wildernessian Biotas at Evans Ferry, Tennessee*; unpubl. Master's thesis, The University of Tennessee, Knoxville, 185 p.
- Sippel, R. F., and Glover, E. D., 1965, Structures in carbonate rocks made visible by luminescence petrography; *Sci.*, v. 150, pp. 1283-1287.
- Sitterly, P. D., 1976, *Paleoecological analysis of the Meadow Marble (Middle Ordovician) in Blount County, Tennessee*; unpubl. Master's thesis, The University of Tennessee, Knoxville, 162 p.
- Sprinkle, J., 1973, Morphology and evolution of blastozoan echinoderms; *Spec. Pub., Mus. Comp. Zool.*, pp. 1-284.
- Stephenson, J. P., 1973, *Paleoenvironmental analysis of the Lenoir Limestone of southern Knox County, Tennessee*; unpubl. Master's thesis, The University of Tennessee, Knoxville, 99 p.

Toomey, D. F., and Finks, R. M., 1969, Middle Ordovician (Chazyan) mounds, southern Quebec: A summary report; New York State Geol. Assoc., 41st Ann. Meeting, Plattsburg, pp. 121-139.

_____, and Ham, W. E., 1967, Pulchrilamina, a new mound-building organism from Lower Ordovician rocks of West Texas and Southern Oklahoma; Jour. Paleo., v. 41, pp. 981-987.

Troost, G., 1850, A list of the fossil crinoids of Tennessee; Amer. Assoc. Adv. Sci., Proc. 2, pp. 59-62.

Turmel, R., and Swanson, R., 1964, Rodriguez Bank, in Ginsburg, R. N., ed., South Florida Carbonate Sediments: Guidebook for Field Trip No. 1, Geol. Soc. Amer. Annual Meeting, Miami, pp. 23-26.

Ulrich, E. O., 1911, Revision of the Paleozoic systems; Geol. Soc. Amer. Bull., v. 22, pp. 281-680.

✓ Van der Plas, L., and Tobi, A. C., 1965, A chart for judging the reliability of point counting results; Amer. Jour. Sci., v. 263, pp. 87-90.

Wachsmuth, C., and Springer, F., 1897, The North American Crinoidea Camerata; Mus. Comp. Zool. Mem., vols. 20 and 21, 897 p.

Walker, K. R., 1973, Stratigraphy and environmental sedimentology of Middle Ordovician Black River in the type area, New York; New York State Museum and Sci. Serv., Geol. Surv. Bull., v. 419, 43 p.

_____, 1974, Mud Substrata, in Zeigler, A. M., Walker, K. R., Anderson, E. J., Kauffman, E. G., Ginsburg, R. N., and James, N. P., Principles of Benthic Community Analysis (Notes for a Short Course), Sedimenta IV, Miami, Florida, pp 5.1-5.11.

_____, 1977a, A Brief Introduction to the Ecostratigraphy of the Middle Ordovician of Tennessee, in Ruppel, S. C., and Walker, K. R., eds., The Ecostratigraphy of the Middle Ordovician of the Southern Appalachians (Kentucky, Tennessee, and Virginia), U.S.A.; The University of Tennessee, Knoxville, Dept. Geol. Sci., Studies in Geology, 77-1, pp. 12-17.

_____, 1977b, Upper Holston Formation: Bryozoan/Pelmatozoan Reefs, in Ruppel, S. C., and Walker, K. R., eds., The Ecostratigraphy of the Middle Ordovician of the Southern Appalachians (Kentucky, Tennessee, and Virginia), U.S.A.; The University of Tennessee, Knoxville, Dept. Geol. Sci., Studies in Geology, 77-1, pp. 60-68.

_____, 1977c, Holston and Chapman Ridge Formations: Shelf Edge Skeletal Sand Banks, Organic Buildups, and Quartzzone Sand-Wave Environments, in Ruppel, S. C., and Walker, K. R., eds., The Ecostratigraphy of the Middle Ordovician of the Southern Appalachians (Kentucky, Tennessee, and Virginia), U.S.A.; The University of Tennessee, Knoxville, Dept. Geol. Sci., Studies in Geology, 77-1, pp. 68-73.

- _____, and Alberstadt, L. P., 1973, A new facies hypothesis concerning the Middle Ordovician of the Southern Appalachians (abstr.); Geol. Soc. Amer., Southeast Ann. Meeting (Program with Abstr.), v. 5, no. 5, pp. 447-448.
- _____, and Ferrigno, K. F., 1973, Major Middle Ordovician reef tract in East Tennessee; Amer. Jour. Sci., v. 273-A (Cooper Volume), pp. 294-325.
- _____, Ruppel, S. C., and Breland, F. C., 1980, Paleoecologic determination of bathymetric position of organic buildups—example from Lower Paleozoic of Appalachians (abstr.); Amer. Assoc. of Pet. Geol. Bull., v. 64, no. 5, p. 798.
- _____, Shanmugam, G., and Ruppel, S. C., 1980, The interplay of tectonic-loading subsidence, terrigenous sediment deposition rate, and carbonate build-up rate in the development of shelf to basin facies patterns (abstr.); Geol. Soc. Amer., 1980 Annual Meeting, Atlanta.
- Wanless, H. T., 1969, Sediments of Biscayne Bay—distribution and depositional history; Tech. Rept. 69-2; Inst. of Marine Sci., Miami, Florida, 260 p.
- Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments; Jour. Geol., v. 30, pp. 377-392.
- White, C. A., 1880, Contributions to paleontology; U.S. Geol. Sur., 12th Ann. Report, 171 p.
- Wood, E., 1909, A critical summary of Troost's unpublished manuscript on the crinoids of Tennessee; U.S. Nat. Mus. Bull., v. 64, 150 p.

APPENDICES

APPENDIX A

DESCRIPTIONS OF STRATIGRAPHIC SECTIONS

Measurement Conventions

The bed thickness measurement conventions used in field descriptions of this investigation are based mainly on the practical suggestions of McKee and Weir (1953) and supplemented by Ingram (1954). Grain sized descriptions are modified after the standardized terminology established by Wentworth (1922). The carbonate rock classification used is the classification developed by Dunham (1962).

Bed Thickness

Very thick bedded	greater than 1.0 m.
Thick bedded	0.3 - 1.0 m.
Medium bedded	0.1 - 0.3 m.
Thin bedded	0.03 - 0.1 m.
Very thin bedded	0.01 - 0.003 m.
Laminated	0.003 - 0.01 m.
Thin laminated	less than 0.003 m.

Grain Size

Coarse grained	grains visible to the unaided eye and readily identifiable (approximately greater than 1 mm.).
Medium grained	grains visible but not readily identifiable (approximately 0.25 - 1.0 mm.).
Fine grained	grains visible only with hand lens (approximately 0.1 - 0.25 mm.).

Very fine grained grains not visible even with hand lens
(generally less than 0.1 mm.).

Localities and Descriptions of Measured Sections

Locality 1. Dry Gap Section (DG)

Approximately 386.0 m. of Chickamauga Group (from Knox/Chickamauga contact to the base of the Moccasin) are exposed in fields situated approximately 150.0 m. west of intersection of Emory Road and Dry Gap Road near Dry Gap, Knox County, Tennessee (NE $\frac{1}{4}$, NW $\frac{1}{4}$, SW $\frac{1}{4}$, Fountain City Quadrangle). Note: the cumulative thickness from the base of the section in the following descriptions is painted on the rocks in the field for reference. Sample numbers are given with measured thickness from the base of the section. Fossil allochems are listed, for the most part, in order of relative abundance.

Unit #	Unit	Cumul.
_____	Thk(m.)	Thk(m.)

KNOX GROUP

Unconformity

CHICKAMAUGA GROUP

1	4.0	4.0	<u>Five Oaks Formation.</u> Light grey with green internal coloration, poorly exposed, fine grained mudstone. Dolomite common. Massive and thick bedded, stylolites and "birdseye" structure abundant. No fossils were observed. <u>Samples:</u> DG1A, 0.0 m.; DG1B, 1.0 m.; DG1C, 3.0 m.
---	-----	-----	--

A Unit 2 was sampled but the validity of the exposure (at approx. 75.0 m.) could not be verified.

	154.0	158.0	COVERED INTERVAL (Fleanor Formation)
3	1.0	159.0	<u>Rockdell Formation.</u> Yellowish brown to buff, poorly exposed, fine to medium grained wackestone/packstone. Badly weathered (located along edge of Beaver Creek), thin to medium bedded. Diverse fauna of pelmatozoans,

bryozoans, trilobites, brachiopods and cephalopods. Abundant pelmatozoan holdfasts on collected sample.

Sample: DG3A, 158.0 m.

- | | | | |
|---|------|-------|---|
| 4 | 7.0 | 166.0 | <u>Rockdell Formation.</u> Grey, poorly exposed (located <u>in</u> Beaver Creek), medium grained grainstone. Medium to thick bedded. Fossil allochems are mostly pelmatozoans.
<u>Sample:</u> DG4A, 165.0 m. |
| 5 | 21.0 | 187.0 | <u>Rockdell Formation.</u> Light grey to buff, poorly exposed, fine grained wackestone. Thin to medium bedded, weathers somewhat nodular. Fossil allochems not abundant, a few pelmatozoans and bryozoans.
<u>Sample:</u> DG5A, 185.0 m.; DG5B, 187.0 m. |
| | 22.0 | 209.0 | COVERED INTERVAL |
| 6 | 16.5 | 215.5 | <u>Rockdell Formation.</u> Light grey to buff, poorly exposed, medium grained packstone. Thick bedded, weathers blocky, stylolites abundant. Fossil allochems include pelmatozoans, bryozoans, brachiopods and trilobites.
<u>Samples:</u> DG6A, 209.0 m.; DG6B, 211.0 m.; DG6C, 215.5 m. |
| | 14.5 | 230.0 | COVERED INTERVAL |
| 7 | 10.0 | 240.0 | <u>Rockdell Formation.</u> Light to dark grey, poorly exposed, fine to medium grained packstone/grainstone (located in small creek feeding Beaver Creek). Medium to thick bedded, weathers blocky, stylolites fairly abundant. Fossil constituents are mostly pelmatozoan debris.
<u>Samples:</u> DG7A, 232.0 m.; DG7B, 232.5 m.; DG7C, 235.0 m.; DG7D, 240.0 m. |
| 8 | 16.0 | 256.0 | <u>Rockdell Formation.</u> Light grey to pinkish, fairly well exposed, medium to coarse grained grainstone. Thick bedded, blocky weathering, abundant stylolitization. Constituent particles consist mainly of pelmatozoan debris.
<u>Samples:</u> DG8A, 249.5 m.; DG8B, 253.0 m.; DG8C, 255.0 m. |
| 9 | 22.0 | 278.0 | <u>Benbolt Formation.</u> Grey, fairly well exposed, fine to medium grained mudstone/wackestone/packstone. Lower portion not well exposed, middle portion weathers to thin slabs and looks nodular. Middle portion of the unit is |

interbedded with fine grained packstones which weather blocky and massive and become coarser grained near top of the unit. Top of the unit weathers to thin slabs, grain size varies from fine to medium grained packstone to fine grained mudstone/wackestone. Fossil allochems include mostly pelmatozoans, ostracods, bryozoans, brachiopods and trilobites.

Samples: DG9A, 263.0 m.; DG9B, 267.0 m.; DG9C, 269.0 m.; DG9D, 270.0 m.; DG9E, 274.0 m.; DG9F, 274.5 m.; DG9G, 278.0 m.

- | | | | |
|----|------|-------|--|
| 10 | 14.0 | 292.0 | <p><u>Benbolt Formation.</u> Maroon and light to dark grey, fairly well exposed, medium to coarse grained packstones. Weathers to thick blocks and thin slabs. Abundant stylo-bedding. Very fossiliferous unit containing pelmatozoans, brachiopods, trilobites, ostracods and bryozoans. A single <u>Receptaculites</u> sp. was observed.</p> <p><u>Samples:</u> DG10A, 281.0 m.; DG10B, 284.0 m.; DG10C, 286.0 m.; DG10D, 289.0 m.; DG10E, 292.0 m.</p> |
| 11 | 12.0 | 304.0 | <p><u>Benbolt Formation.</u> Light grey, fairly well exposed, coarse grained grainstone. Weathers to thick, massive beds. Mostly pelmatozoan debris and bryozoans.</p> <p><u>Sample:</u> DG11A, 304.0 m.</p> |
| 12 | 6.0 | 314.0 | <p><u>Wardell Formation.</u> Yellowish to buff, poorly exposed, fine grained mudstone/wackestone. Weathers into thin to medium beds. Fossil allochems include bryozoans, brachiopods, sponges and pelmatozoans.</p> <p><u>Samples:</u> DG12A, 308.0 m.; DG12B, 312.0 m.; DG12C, 313.0 m.</p> |
| 13 | 18.0 | 333.0 | <p><u>Wardell Formation.</u> Dark grey, not well exposed (located in bottom of small creek), fine grained wackestone. Weathering characteristics are such that thin beds produce resistant ledges in the creek. Upper portion of this unit appears to be very fossiliferous and contains gastropods, sponges, pelmatozoans, brachiopods and bryozoans.</p> <p><u>Samples:</u> DG13A, 315.0 m.; DG13B, 317.0 m.; DG13C, 319.0 m.; DG13D, 321.0 m.; DG13E, 330.0 m.; DG13F, 333.0 m.</p> |

- 14 6.0 357.0 Witten Formation. Dark grey, poorly exposed in the bottom of a small creek, fine grained wackestone. Weathers to thin beds, no structures observed. Fossil allochems include gastropods, bryozoans, trilobite, brachiopods and pelmatozoans.
Samples: DG14A, 350.5 m.; DG14B, 352.0 m.; DG14C, 355.0 m; DG14D, 357.0 m.
- 15 14.0 372.0 Witten Formation. Grey to dark grey, poorly exposed (unit is in bottom of small creek), fine grained wackestone. Weathers to thin, slabby beds. Unit appears to be more fossiliferous near the base. Fossil allochems observed are brachiopods, gastropods, bryozoans, pelmatozoans and cephalopods.
Samples: DG15A, 358.0 m.; DG15B, 360.0 m.; DG15C, 362.0 m.; DG15D, 365.0 m.; DG15E, 369.0 m.; DG15F, 371.0 m.; DG15G, 372.0 m.
- 16 2.0 374.0 Witten Formation. Grey to dark grey, fairly well exposed, fine to medium grained wackestone/packstone. Weathers to thin to medium beds, located in bottom of small creek, stylobedding evident. Fossils included are gastropods, brachiopods, pelmatozoans and bryozoans.
Samples: DG16A, 372.5 m.; DG16B, 374.0 m.
- 6.0 380.0 COVERED INTERVAL
- 17 6.0 386.0 Witten Formation. Grey to dark grey, poorly exposed, fine grained mudstone coarsening upward to fine and medium grained packstone/grainstone. Shale appears to be abundant, weathers to thin beds, no structure evident. Not very fossiliferous near base of unit, fossil allochems near top include bryozoans, pelmatozoans and some trilobites. Moccasin at top of unit.
Samples: DG17A, 380.0 m.; DG17B, 381.0 m.; DG17C, 383.0 m.; DG17D, 384.0 m.; DG17E, 385.0 m.; DG17F, 386.0 m.

Moccasin Formation.

Locality 2. Halls Crossroads Section (HC)

Approximately 553.0 m. of Chickamauga Group (from Knox/Chickamauga contact to the base of the Moccasin) are exposed in fields beginning at the end of Scenic View Drive adjacent to Temple Acres subdivision and extending southeast across Maynardville Pike (State Highway 33) to Emory Road (State Highway 131) near Halls, Knox County, Tennessee (NW $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Fountain City Quadrangle). Note: the cumulative thickness from the base of the section in the following descriptions is painted on the rocks in the field for reference (add 3.0 meters to numbers printed on rocks). Sample numbers are given with measured thickness from the base of the section. Fossil allochems are listed, for the most part, in order of relative abundance.

Unit #	Unit Thk (m.)	Cumul. Thk (m.)
--------	------------------	--------------------

KNOX COUNTY

Unconformity

CHICKAMAUGA

1	30.0	30.0	<u>Tumbez Formation.</u> Maroon, poorly exposed, fine to coarse grained boundstone/packstone/grainstone. Red bryozoan boundstone intimately associated with medium to coarse grained packstone/grainstone. Weathers to massive blocks, stylolites abundant. Fossil allochems consist primarily of bryozoans and pelmatozoans. These lithotypes are exposed along the edge of Copper Ridge which is held up by the Knox. The Knox/Chickamauga contact is not exposed in this vicinity but is chosen at the base of Copper Ridge due to close proximity to Copper Ridge. <u>Samples:</u> HC1A, 3.0 m.; HC1B, 10.5 m.; HC1C, 13.0 m.; HC1D, 20.0 m.; HC1E, 27.0 m.; HC1F, 30.0 m.
---	------	------	--

	99.0	129.0	COVERED INTERVAL (Fleanor Formation)
2	4.0	133.0	<u>Rockdell Formation.</u> Grey and maroon, fairly well exposed, medium grained boundstone/packstone (small reef build-up). Thick bedded, massive blocks exposed against embankment of small creek. Fossil allochems consist of bryozoans, pelmatozoans, brachiopods and trilobites. <u>Samples:</u> HC2A, 129.0 m.; HC2B, 131.0 m.
3	12.0	145.0	<u>Rockdell Formation.</u> Grey and maroon, well exposed on side of creek embankment, medium to coarse grained boundstone/packstone/grainstone (small reef build-up). Very coarse near base of unit, grainstones and boundstones interfingering with each other vertically and laterally. Medium to thick bedded, weathers blocky, stylolites abundant. Dominant fossil allochems are pelmatozoans and bryozoans. <u>Samples:</u> HC3A, 133.0 m.; HC3B, 135.0 m.; HC3C, 136.0 m.; HC3D, 140.5 m.; HC3E, 141.0 m.
4	25.0	170.0	<u>Rockdell Formation.</u> Grey and yellowish to brownish grey, poorly exposed, medium to coarse grained wackestone/packstone/grainstones. Thin to medium bedded. Fossil constituents include pelmatozoans debris, bryozoans, brachiopods and trilobites. <u>Samples:</u> HC4A, 144.0 m.; HC4B, 147.0 m.; HC4C, 158.0 m.; HC4D, 161.0 m.; HC4E, 169.0 m.
5	23.0	193.0	<u>Rockdell Formation.</u> Grey to dark grey and yellowish grey to maroon. Poorly exposed, fine to medium grained wackestone/packstone. Thin to medium bedded, weathers to massive blocks, some stylolitization, oncolites at 184.0 m. Fossil allochems include bryozoans, pelmatozoans, trilobites, brachiopods and ostracods. <u>Samples:</u> HC5A, 173.0 m.; HC5B, 174.0 m.; HC5C, 184.0 m.; HC5D, 187.0 m.; HC5E, 193.0 m.
6	19.0	212.0	<u>Rockdell Formation.</u> Yellowish grey to maroon, well exposed, fine to medium grained wackestone/packstone. Massive and thick bedded, stylolites abundant. Maroon wackestones observed at top of unit. Allochems include bryozoans, pelmatozoans, brachiopods, trilobites and ostracods. <u>Samples:</u> HC6A, 195.0 m.; HC6B, 198.0 m.; HC6C, 205.0 m.; HC6D, 208.0 m.; HC6E, 212.0 m.

- | | | | |
|----|------|-------|--|
| 7 | 11.0 | 223.0 | <p><u>Rockdell Formation.</u> Yellowish grey, poorly exposed, fine to medium grained wackestone. Thin to medium bedded, some stylolites but not well developed. Fossil allochems include pelmatozoans, bryozoans, brachiopods and trilobites.</p> <p><u>Samples:</u> HC7A, 216.0 m.; HC7B, 221.0 m.</p> |
| 8 | 18.0 | 241.0 | <p><u>Rockdell Formation.</u> Brownish and dark grey, poorly exposed, medium to coarse grained packstone/grainstone. Stromatoporoid collected at 224.0 m. Weathers to small, discontinuous blocks, thin to medium bedded, stylolites abundant. Grain size increases from base of unit to top. Fossil constituents include pelmatozoans, bryozoans and stromatoporoids.</p> <p><u>Samples:</u> HC8A, 224.0 m.; HC8B, 231.0 m.; HC8C, 234.0 m.; HC8D, 237.0 m.</p> |
| | 33.0 | 274.0 | COVERED INTERVAL |
| 9 | 14.0 | 288.0 | <p><u>Rockdell Formation.</u> Maroon and grey, poorly exposed, fine to medium grained wackestone. Thin to medium bedded, massive, stylolites observed. Fossil allochems are mostly pelmatozoans and bryozoans.</p> <p><u>Samples:</u> HC9A, 276.0 m.; HC9B, 282.0 m.; HC9C, 288.0 m.</p> |
| | 23.0 | 311.0 | COVERED INTERVAL |
| 10 | 12.0 | 323.0 | <p><u>Chapman Ridge Formation.</u> Maroon, well exposed, medium to coarse grained wackestone/packstone. Medium to thick bedded, somewhat laterally continuous, becomes generally finer grained near top of unit. Stylolites abundant. Fossil allochems are dominated by bryozoans, particularly large ramose types and pelmatozoans.</p> <p><u>Samples:</u> HC10A, 311.0 m.; HC10B, 316.0 m.; HC10C, 323.0 m.</p> |
| 11 | 34.0 | 357.0 | <p><u>Chapman Ridge Formation.</u> Maroon, well exposed, medium grained wackestone/packstone. Thin to medium bedded, dominated by maroon wackestones, coarsens toward top of unit, stylolites fairly abundant. Fossil allochems dominated by bryozoans and pelmatozoans.</p> <p><u>Samples:</u> HC11A, 327.0 m.; HC11B, 335.0 m.; HC11C, 345.0 m.; HC11D, 356.0 m.; HC11E, 357.0 m.</p> |

- | | | | |
|----|------|-------|---|
| 12 | 11.0 | 368.0 | <u>Chapman Ridge Formation.</u> Grey and maroon, poorly exposed, medium to coarse grained wackestone/packstone. Thin to medium bedded, grain size increases from base to top of unit. Fossil constituents are mostly bryozoans, pelmatozoans, trilobites and brachiopods.
<u>Samples:</u> HC12A, 359.0 m.; HC12B, 360.0 m.; HC12C, 363.0 m.; HC12D, 368.0 m. |
| 13 | 33.0 | 401.0 | <u>Chapman Ridge Formation.</u> Grey and maroon, Well exposed near base but less well exposed in top third of the unit, fine to medium grained wackestone/packstone/grainstone. Weathers to massive blocks, some lumpy bedding?, not real cobbles. Fossil constituents consist mainly of bryozoans, pelmatozoans, also some brachiopods and trilobites.
<u>Samples:</u> HC13A, 371.0 m.; HC13B, 373.0 m.; HC13C, 377.0 m.; HC13D, 381.0 m.; HC13E, 385.0 m.; HC13F, 388.0 m.; HC13G, 392.0 m.; HC13H, 399.0 m. |
| | 35.0 | 437.0 | COVERED INTERVAL (Ottosee Formation) |
| 14 | 10.0 | 446.0 | <u>Ottosee Formation.</u> Maroon and grey, well exposed, medium to coarse grained wackestone/packstone/grainstone. General decrease in mud vertically in the unit, grainstones grade laterally to muds (wackestones). Fossil constituents are mostly encrusting bryozoans and pelmatozoans.
<u>Samples:</u> HC14A, 436.0 m.; HC14B, 438.0 m.; HC14C, 440.0 m.; HC14D, 442.0 m.; HC14E, 444.0 m.; HC14F, 446.0 m. |
| | 6.0 | 452.0 | COVERED INTERVAL |
| 15 | 13.0 | 465.0 | <u>Ottosee Formation.</u> Grey, fairly well exposed, medium grained wackestone/packstone/grainstone. Digitate weathering, thick bedded, grainsize varies laterally and vertically. Fossil allochems include bryozoans, pelmatozoans, brachiopods and some trilobites.
<u>Samples:</u> HC15A, 452.0 m.; HC15B, 456.0 m.; HC15C, 459.0 m.; HC15D, 461.0 m.; HC15E, 463.0 m. |
| | 6.0 | 471.0 | COVERED INTERVAL |

16	4.0	475.0	<u>Benbolt Formation.</u> Yellowish grey, poorly exposed, fine to medium grained wackestone. Thin to medium bedded. Fossil allochems consist of bryozoans, pelmatozoans, brachiopods and probably some trilobites. <u>Samples:</u> HC16A, 471.0 m.; HC16B, 474.0 m.; HC16C, 475.0 m.
	3.0	478.0	COVERED INTERVAL
17	20.0	498.0	<u>Benbolt Formation.</u> Grey to dark grey, fairly well exposed, fine to medium grained wackestone/packstone/grainstone. Thick bedded, nodular weathering, styolites relatively abundant, oncolites present at approx. 480.0 m. Fossiliferous near the base. Fossil allochems include bryozoans, brachiopods, pelmatozoans, trilobites and algae. <u>Samples:</u> HC17A, 478.0 m.; HC17B, 479.0 m.; HC17C, 482.0 m.; HC17D, 485.0 m.; HC17E, 490.0 m.; HC17F, 494.0 m.; HC17G, 498.0 m.
18	10.0	511.0	<u>Witten Formation.</u> Grey, poorly exposed, fine grained mudstone/wackestone. Massive, bedding poorly developed. Fossil constituents include brachiopods, gastropods and ostracods. <u>Samples:</u> HC18A, 501.0 m.; HC18B, 511.0 m.
	3.0	514.0	COVERED INTERVAL
19	2.0	515.0	<u>Witten Formation.</u> Grey to dark grey, poorly exposed, fine grained mudstone/wackestone. A few brachiopods observed. <u>Sample:</u> HC19A, 514.0 m.
	10.0	525.0	COVERED INTERVAL
20	7.0	533.0	<u>Witten Formation.</u> Grey, poorly exposed, medium grained packstone. Nodular weathering, oncolites observed. Fossil allochems dominated by algae. <u>Sample:</u> HC20A, 533.0 m.
	10.0	543.0	COVERED INTERVAL
21	10.0	553.0	<u>Witten Formation.</u> Grey, well exposed, medium to coarse grained wackestone. Massive, bedding poorly developed, very fossiliferous. Fossil constituents include bryozoans, stromatoporoids, sponges, corals, brachiopods, trilobites and pelmatozoans. <u>Samples:</u> HC21A, 544.0 m.; HC21B, 544.0 m.; HC21C, 545.0 m.; HC21D, 547.0 m. <u>Moccasin Formation.</u>

Locality 3. Harbison section (HR)

Approximately 432.0 m. of Chickamauga Group (from Knox/Chickamauga contact to the base of the Moccasin) are exposed in fields east and west of Tazewell Pike (State Highway 131) in close proximity to the old Campbell Cave located 2.0 miles north of the intersection at Harbison, Knox County, Tennessee (NE $\frac{1}{4}$, SW $\frac{1}{4}$, SW $\frac{1}{4}$, Graveston Quadrangle). Note: the cumulative thickness from the base of the section in the following descriptions is painted on the rocks in the field for reference (add 10 m. to numbers painted on rocks in the field). Sample numbers are given with measured thickness from the base of the section. Fossil allochems are listed, for the most part, in order of relative abundance.

Unit #	Unit	Cumul.
_____	Thk(m.)	Thk(m.)

KNOX GROUP

Unconformity

CHICKAMAUGA GROUP

1	10.0	10.0	<u>Five Oaks Formation.</u> Grey, poorly exposed, fine grained mudstone. Weathers into thin to thick bedded, massive blocks which reveal abundant rounded chert clasts. No fossils observed. The contact with the Knox below is not clear. <u>Sample:</u> HR1A, 5.0 m.
2	11.0	21.0	<u>Lincolnshire Formation.</u> Grey to dark grey, poorly exposed, medium grained grainstone at base and fine to medium grained wackestone/packstone. Weathers massive and cobbly, oncolites abundant in the middle and upper portion of the unit. Fossil allochems mostly pelmatozoan debris and algae. <u>Samples:</u> HR2A, 10.0 m.; HR2B, 14.5 m.; HR2C, 20.5 m.

- | | | | |
|---|------|-------|---|
| 3 | 15.0 | 36.0 | <p><u>Lincolnshire Formation.</u> Grey, poorly exposed, medium grained grainstone. Medium bedded, weathers blocky, stylolites abundant. Fossil allochems are mostly pelmatozoans and bryozoans.</p> <p><u>Samples:</u> HR3A, 28.0 m.; HR3B, 36.0 m.</p> |
| 4 | 26.0 | 62.0 | <p><u>Lincolnshire Formation.</u> Grey, fairly well exposed, medium grained packstone/grainstone. Weathers cobbly, thin to medium bedded, stylolites and oncolites abundant. Fossils consist of pelmatozoan debris, bryozoans, algae and trilobites.</p> <p><u>Samples:</u> HR4A, 43.0 m.; HR4B, 45.0 m.; HR4C, 48.0 m.; HR4D, 51.0 m.</p> |
| 5 | 8.0 | 70.0 | <p><u>Lincolnshire Formation.</u> Grey, poorly exposed, medium grained grainstone. Weathers blocky and massive, stylolites abundant. Constituent particles include pelmatozoans, encrusting bryozoans and ramose bryozoans.</p> <p><u>Sample:</u> HR5A, 63.0 m.</p> |
| 6 | 30.0 | 100.0 | <p><u>Rockdell Formation.</u> Grey and pinkish to maroon, very well exposed boundstone/packstone/grainstone. This portion of the section is located in close proximity to Campbell Cave and is actually an old quarry site. The unit reveals all the features of a small patch reef. The lithotypes vary from white, grey and pinkish, medium grained grainstones (flank deposits) to reddish bryozoan and red algae (<u>Solenopora</u> sp.) boundstone (core material). Bedding is not well developed, partly due to the interfingering nature of the flank and core lithotypes, however, some crossbedding is evident in the grainstones. Stylolites are also abundant. Fossil constituents of the grainstones are basically pelmatozoans and bryozoans. The boundstones are dominated by encrusting bryozoans and encrusting red algae.</p> <p><u>Samples:</u> HR6A, 70.0 m.; HR6B, 77.0 m.; HR6C, 78.0 m.; HR6D, 82.0 m.; HR6E, 85.0 m.; HR6F, 87.0 m.; HR6G, 89.0 m.; HR6H, 92.0 m.; HR6I, 96.0 m.; HR6J, 97.5 m.; HR6K, 98.0 m.</p> |
| 7 | 10.0 | 110.0 | <p><u>Rockdell Formation.</u> Grey to yellowish grey and maroon, fairly well exposed, medium to coarse grained wackestone/packstone/grainstone. Medium to thick bedded, weathers somewhat blocky, stylolites abundant. Fossil allochems are mostly pelmatozoans, bryozoans and algae.</p> <p><u>Samples:</u> HR7A, 101.0 m.; HR7B, 104.0 m.; HR7C, 107.0 m.; HR7D, 108.0 m.; HR7E, 110.0 m.</p> |

- | | | | |
|----|------|-------|--|
| 8 | 17.0 | 128.0 | <p><u>Rockdell Formation.</u> Grey to yellowish grey and pinkish, poorly exposed, medium grained wackestone/packstone/grainstone. Thin to thick bedded, stylolites abundant. Fossil allochems include pelmatozoan debris and bryozoans.</p> <p><u>Samples:</u> HR8A, 114.0 m.; HR8B, 120.0 m.; HR8C, 123.0 m.; HR8D, 124.5 m.; HR8E, 126.0 m.</p> |
| 9 | 31.0 | 158.0 | <p><u>Rockdell Formation.</u> Light grey to grey and maroon, well exposed, medium to coarse grained wackestone/packstone/grainstone. Medium to thick bedded, massive and blocky, stylolites abundant. The maroon wackestones (mudmounds) often have abundant encrusting bryozoans and pelmatozoan holdfasts associated with them. Fossil allochems are mostly bryozoans, pelmatozoans and rare broken brachiopods.</p> <p><u>Samples:</u> HR9A, 130.0 m.; HR9B, 137.0 m.; HR9C, 140.5 m.; HR9D, 144.0 m.; HR9E, 146.0 m.; HR9F, 147.5 m.; HR9G, 149.0 m.; HR9H, 156.0 m.</p> |
| 10 | 12.0 | 170.0 | <p><u>Rockdell Formation.</u> Pinkish brown and grey to dark grey, well exposed, medium grained packstone/grainstone. Thick bedded, blocky and nodular weathering, abundant stylolites. Fossil allochems are mostly pelmatozoans.</p> <p><u>Samples:</u> HR10A, 159.0 m.; HR10B, 161.0 m.; HR10C, 162.0 m.; HR10D, 167.0 m.; HR10E, 170.0 m.</p> |
| | 12.0 | 182.0 | COVERED INTERVAL |
| 11 | 22.0 | 204.0 | <p><u>Rockdell Formation.</u> Grey to dark grey, well exposed, medium grained packstone. Medium to thick bedded, weathers blocky, some nodular weathering, stylolites abundant. Fossil constituents are mostly pelmatozoans and bryozoans.</p> <p><u>Samples:</u> HR11A, 185.0 m.; HR11B, 190.0 m.; HR11C, 193.0 m.; HR11D, 198.0 m.; HR11E, 202.0 m.; HR11F 204.0 m.</p> |
| | 28.0 | 232.0 | COVERED INTERVAL |
| 12 | 24.0 | 256.0 | <p><u>Rockdell Formation.</u> Pinkish grey and maroon, poorly exposed, fine to medium grained wackestone/packstone/grainstone. Thick, massive blocks (samples difficult to get), stylolites much in evidence. Typical fossil components are pelmatozoans and bryozoans.</p> <p><u>Samples:</u> HR12A, 232.0 m.; HR12B, 237.0 m.; HR12C, 244.0 m.</p> |

- 13 23.0 279.0 Rockdell Formation. Light grey to grey, well exposed, medium grained packstone/grainstone. Thin bedded, cobbly weathering in portions of the unit, styolites abundant. Pelmatozoans are the dominant fossil allochem.
Samples: HR13A, 258.0 m.; HR13B, 261.0 m.; HR13C, 264.0 m.; HR13D, 267.0 m.; HR13E, 272.0 m.; HR13F, 275.0 m.; HR13G, 279.0 m.
- 14 17.0 296.0 Rockdell Formation. Grey to maroon and brownish, well exposed, medium grained wackestone/packstone. This portion of the section was quarried at one time, medium to thick bedded, weathers into large blocks and massive, some cobbly, crumbly, grey and red bryozoan wackestone. Styolites are abundant. Dominant fossil allochems are pelmatozoans and bryozoans.
Samples: HR14A, 281.0 m.; HR14B, 287.0 m.; HR14C, 290.0 m.; HR14D, 292.0 m.; HR14E, 296.0 m.
- 15 21.0 317.0 Chapman Ridge Formation. Maroon to brownish, well exposed mudstone. Thin to medium bedded, laterally discontinuous. Styolites in evidence. Fossil allochems consist mostly of bryozoans and pelmatozoans.
Samples: HR15A, 301.0 m.; HR15B, 305.0 m.; HR15C, 310.0 m.
- 16 18.0 335.0 Chapman Ridge Formation. Maroon and brownish to grey, well exposed, fine to medium grained wackestone/packstone. Weathers to somewhat massive blocks, medium to thick bedded. Dominant fossil allochems consist of bryozoans and pelmatozoans. Distinct litho and faunal change with the overlying unit.
Samples: HR16A, 319.0 m.; HR16B, 326.0 m.; HR16C, 329.0 m.; HR16D, 331.0 m.; HR16E, 332.0 m.
- 17 17.0 352.0 Benbolt Formation. Grey to yellowish grey and brownish grey, well exposed, fine to medium grained mudstone/packstone/grainstone. Weathers to thin, medium and thick beds, styolites abundant. Fossil allochems include pelmatozoans, bryozoans, brachiopods, trilobites, sponges (Allosaccus sp.) and algae (Receptaculites sp.).
Samples: HR17A, 336.0 m.; HR17B, 239.0 m.; HR17C, 342.0 m.; HR17D, 344.0 m.; HR17E, 347.0 m.; HR17F, 352.0 m.

- 18 19.0 371.0 Benbolt Formation. Dark grey to yellowish grey, well exposed, fine to medium grained mudstone/packstone/grainstone. Weathers to thin, medium and thick beds, vertically discontinuous but laterally somewhat continuous, stylolites abundant. Fossil allochems dominated by bryozoans, pelmatozoans, brachiopods and trilobites.
Samples: HR18A, 354.0 m.; HR18B, 359.0 m.; HR18C, 362.0 m.; HR18D, 365.0 m.; HR18E, 367.0 m.; HR18F, 371.0 m.
- 19 19.0 390.0 Benbolt Formation. Grey to dark grey, well exposed, fine to medium grained mudstone/wackestone/packstone. Weathers into thin to medium beds, cobbly in places, stylolites abundant, oncolites near top of unit. Very fossiliferous. Fossil allochems include bryozoans, pelmatozoans, brachiopods, trilobites, sponges and algae.
Samples: HR19A, 372.0 m.; HR19B, 374.0 m.; HR19C, 378.0 m.; HR19D, 380.0 m.; HR19E, 383.0 m.; HR19F, 386.0 m.; HR19G, 389.0 m.
- 20 24.0 414.0 Wardell Formation. Dark grey to yellowish grey, poorly exposed, fine grained mudstone/wackestone. Very shaly, weathers to small chips, stylolites evident, also mudcracks. Fossil allochems include brachiopods and trilobites.
Samples: HR20A, 394.0 m.; HR20B, 395.0 m.; HR20C, 398.0 m.; HR20D, 413.0 m.
- 21 1.0 415 Bowen Formation. Maroon, poorly exposed, fine grained, mudstone. Thin bedded, mudcracked. No fossil allochems observed. No samples taken.

Unit 21 (continued)

- 21 17.0 432.0 Witten Formation. Dark grey to maroon, well exposed mudstone. Shaly, thin to medium bedded, "birdseye" structures observed, mudcracks abundant. Not very fossiliferous.
Samples: HR21A, 416.0 m.; HR21B, 418.0 m.; HR21C, 419.0 m.; HR21D, 421.0 m.; HR21E, 423.0 m.; HR21F, 424.0 m.; HR21G, 428.0 m.; HR21H, 428.0 m.

Moccasin Formation.

Locality 4. Graveston Section (GA)

Approximately 408.5 m. of Chickamauga Group (from Knox/Chickamauga contact to the base of the Moccasin) are exposed in fields north and south of Tazewell Pike (State Highway 131) and immediately east of Scott Road near Graveston, Knox County, Tennessee (NW $\frac{1}{4}$, SE $\frac{1}{4}$, SW $\frac{1}{4}$, Graveston Quad-range). Note: the cumulative thickness from the base of the section in the following descriptions is painted on the rocks in the field for reference. Sample numbers are given with measured thickness from the base of the section. Fossil allochems are listed, for the most part, in order of relative abundance.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)
--------	-----------------	-------------------

KNOX COUNTY

Unconformity

CHICKAMAUGA GROUP

1	.5	.5	<u>Lincolnshire Formation.</u> Light grey, poorly exposed, fine to medium grained packstone. Bedding poorly developed, weathers somewhat nodular, abundant oncolites (<u>Girvanella</u> sp. and <u>Solenopora</u> sp.) and some styolites. Mostly pelmatozoan debris, red algae and some trilobites. Contact with underlying Knox determined by nature of color of weathered soils. <u>Samples:</u> GA1A, .5 m.; GA1B, .5 m.
	2.5	3.0	COVERED INTERVAL
2	4.5	7.5	<u>Lincolnshire Formation.</u> Light to medium grey, fairly well exposed, medium to coarse grained packstone/grainstone. Bedding poorly developed, weathers blocky to nodular, abundant oncolites (<u>Girvanella</u> sp. and <u>Solenopora</u> sp.) and some styolites. Mostly pelmatozoan debris, red algae, gastropods, bryozoans, trilobites and ostracods. <u>Samples:</u> GA2A, 3.0 m.; GA2B, 4.0 m.; GA2C, 5.0 m.; GA2D, 6.0 m.

	20.5	28.0	COVERED INTERVAL
3	.5	28.5	<u>Lincolnshire Formation.</u> Light to medium grey, poorly exposed, fine to medium grained wackestone/packstone. Bedding poorly developed, nodular weathering and oncolites (<u>Girvanella</u> sp.). Fossil constituents include pelmatozoan debris, algae, bryozoans, trilobites, ostracods and rare gastropods. <u>Samples:</u> GA3A, 28.0 m.; GA3B, 28.0 m.; GA3C, 28.0 m.
	29.0	57.5	COVERED INTERVAL
4	5.5	63.0	<u>Rockdell Formation.</u> Light grey and pinkish, fairly well exposed, fine to coarse grained packstone/grainstone. Weathering is blocky and somewhat massive. Bedding is generally poorly developed but the upper portion of the unit does reveal some thick bedding. Mostly pelmatozoans, bryozoans (encrusting and ramose), brachiopods, ostracods and rare trilobites. The limestones in this unit can be characterized by two general types: a light to medium grey, medium to coarse grained grainstone and a pinkish, fine to medium grained wackestone/packstone. <u>Samples:</u> GA4A, 57.5 m.; GA4B, 61.5 m.; GA4C, 62.0 m.; GA4D, 63.0 m.
	4.5	67.5	COVERED INTERVAL
5	6.0	73.5	<u>Rockdell Formation.</u> Light grey to pinkish, fairly well exposed, medium to coarse grained packstone/grainstone at base and fine grained wackestone toward top of unit. Bedding poorly developed, weathers to blocky, laterally discontinuous beds which vary in lithotype from grainstones to wackestones. Algal fragments (<u>Solenopora</u> sp.) are observed at the base of the unit. Fossils observed include pelmatozoans, bryozoans (encrusting and ramose), algae and some brachiopods, ostracods and trilobites. Basically two types of limestones: grey, coarse grained grainstones, which in many cases have abundant pelmatozoan holdfasts, and pinkish, fine grained wackestone/packstone "mudmounds" which have abundant encrusting and ramose bryozoans, pelmatozoan holdfasts and an occasional cephalopod. <u>Samples:</u> GA5A, 67.5 m.; GA5B, 68.0 m.; GA5C, 70.0 m.; GA5D, 71.0 m.; GA5E, 73.0 m.

- | | | | |
|----|-----|------|---|
| 6 | 1.5 | 75.0 | <p><u>Rockdell Formation.</u> Light grey to pink, poorly exposed, medium grained grainstone at base and medium grained packstone at top of unit. Bedding poorly developed, weathering to blocky, laterally discontinuous beds. Mostly pelmatozoan debris, a few bryozoans (bifoliate), trilobites and rare brachiopods.</p> <p><u>Samples:</u> GA6A, 74.5 m.; GA6B, 75.0 m.</p> |
| 7 | 1.0 | 76.0 | <p><u>Rockdell Formation.</u> Medium grey with pinkish tones, medium to coarse grained grainstone. Bedding poorly developed, weathers blocky and massive, no stylolites. Fossil allochems consist of pelmatozoan debris, bryozoans (mostly bifoliate) and some rare trilobite debris.</p> <p><u>Sample:</u> GA7A, 75.5 m.</p> |
| 8 | 9.5 | 85.5 | <p><u>Rockdell Formation.</u> Light grey to pink, fairly well exposed, medium grained grainstone grading upward into medium to very coarse grained packstone. Weathers to medium to thick bedded blocks which are vertically somewhat continuous but laterally discontinuous. Constituent particles consists mostly of pelmatozoan debris, bryozoans, algae (<i>Solenopora</i> sp.), trilobites and ostracods.</p> <p><u>Samples:</u> GA8A, 76.5 m.; GA8B, 77.0 m.; GA8C, 78.5 m.; GA8D, 81.0 m.; GA8E, 83.0 m.; GA8F, 84.0 m.; GA8G, 84.5 m.</p> |
| 9 | 3.5 | 89.0 | <p><u>Rockdell Formation.</u> Light grey to yellowish to pink, fairly well exposed, alternating medium to coarse grained packstone/grainstone with fine grained wackestone. Weathers to thin to medium beds which are laterally discontinuous. Constituent particles consist mostly of pelmatozoan debris, bryozoans, trilobite fragments and ostracods.</p> <p><u>Samples:</u> GA9A, 85.5 m.; GA9B, 86.5 m.; GA9C, 88.5 m.; GA9D, 88.5 m.</p> |
| | 2.5 | 91.5 | COVERED INTERVAL |
| 10 | 2.5 | 94.0 | <p><u>Rockdell Formation.</u> Grey with pink cast, well exposed, coarse grained packstone/grainstone. Blocky weathering, laterally discontinuous, poorly developed bedding. Stylolites fairly abundant. Fossil allochems are mostly pelmatozoan debris, bryozoans and trilobite fragments. These grainstones grade vertically into similar lithotypes, contact between overlying material is difficult to determine due</p> |

to weathering characteristics (exposure is discontinuous both vertically and laterally).

Samples: GA10A, 91.5 m.; GA10B, 92.5 m.; GA10C, 94.0 m.

- | | | | |
|----|-----|-------|---|
| 11 | 1.5 | 95.5 | <p><u>Rockdell Formation.</u> Grey with pink cast, well exposed, coarse grained packstone. Very similar to Unit 10 except red bryozan "mud-mounds" appear to be more abundant. Blocky weathering, laterally discontinuous, bedding poorly developed. Styolites fairly abundant. Fossil constituents are mostly pelmatozoan debris and bryozoans, rare trilobites and brachiopod fragments. At 94.5 m. is a good exposure of a mudmound studded with pelmatozoan columnals and holdfasts and abundant encrusting and ramose bryozoans.</p> <p><u>Samples:</u> GA11A, 94.5 m.; GA11B, 95.5 m.</p> |
| 12 | 7.0 | 102.5 | <p><u>Rockdell Formation.</u> Grey and pinkish to maroon, well exposed, coarse grained wackestone/packstone. Blocky weathering, medium to thick bedded, laterally and vertically discontinuous. Fossil constituents are mostly pelmatozoans, bryozoans and some brachiopods. Unit is interpreted as being anastomosing red bryozoan mudmounds and grey grainstones.</p> <p><u>Samples:</u> GA12A, 98.0 m.; GA12B, 98.0 m.; GA12C, 100.0 m.; GA12D, 101.m.</p> |
| 13 | .5 | 103.0 | <p><u>Rockdell Formation.</u> Similar to Unit 12.</p> <p><u>Sample:</u> GA13A, 102.5 m.</p> |
| 14 | 2.5 | 105.5 | <p><u>Rockdell Formation.</u> Light to medium grey, well exposed, coarse grained packstone/grainstone. Blocky weathering, thin to medium bedding (1 to 2 mm. clay lens produced along styolite contacts), exposure laterally and vertically discontinuous. Fossil constituents are mostly pelmatozoans, bryozoans, some brachiopods and rare trilobites.</p> <p><u>Samples:</u> GA14A, 104.0 m.; GA14B, 105.0 m.; GA14C, 105.5 m.</p> |
| 15 | 5.5 | 111.0 | <p><u>Rockdell Formation.</u> Similar to Unit 14.</p> <p><u>Samples:</u> GA15A, 107.0 m.; GA15B, 108.0 m.; GA15C, 109.5 m.</p> |
| 16 | 6.0 | 117.0 | <p><u>Rockdell Formation.</u> Light grey to yellowish, fairly well exposed, fine to medium grained wackestone/packstone. Blocky to fissile weathering. Fossil constituents are mostly</p> |

- bryozoans with some pelmatozoans and brachiopods. Styolites abundant.
Samples: GA16A, 111.5 m.; GA16B, 114.0 m.; GA16C, 117.0 m.
- 17 3.0 120.0 Rockdell Formation. Light grey to grey, fairly well exposed, medium to coarse grained packstone/grainstone. Blocky to fissile weathering, thin to medium bedded, exposure laterally and vertically discontinuous. Very fossiliferous: pelmatozoans, bryozoans, brachiopods and rare trilobites and ostracods.
Samples: GA17A, 117.5 m.; GA17B, 118.0 m.; GA17C, 118.5 m.
- 18 7.5 127.5 Rockdell Formation. Grey, fairly well exposed, medium to coarse grained packstone/grainstone. Blocky weathering, poorly developed bedding and abundant stylitization. Exposure discontinuous both laterally and vertically. Fossil allochems are mostly pelmatozoans, bryozoans and some ostracods, brachiopods and trilobites.
Samples: GA18A, 120.5 m.; GA18B, 122.5 m.; GA18C, 126.0 m.
- 13.5 141.0 COVERED INTERVAL
- 19 15.0 156.0 Rockdell Formation. Light grey to grey, fairly well exposed, generally coarsening upward unit from fine to medium grained wackestones near base to medium to coarse grained packstone/grainstone near top of unit. Blocky weathering, poorly developed bedding and abundant stylitization. Exposure continuous laterally as well as vertically. Fossil constituents are most pelmatozoans with some bryozoans and brachiopods.
Samples: GA19A, 141.0 m.; GA19B, 142.5 m.; GA19C, 143.5 m.; GA19D, 147.0 m.; GA19E, 150.0 m.; GA19G, 156.0 m.
- 20 3.0 159.0 Rockdell Formation. Light grey, poorly exposed, medium grained grainstone. Weathers to small, laterally and vertically discontinuous blocks. Bedding poorly developed, stylites present. Fossil constituents are mostly pelmatozoan debris.
Samples: GA20A, 156.0 m.; GA20B, 157.0 m.
- 21 10.5 169.5 Rockdell Formation. Light grey, well exposed, medium grained packstone/grainstone at base grading upward to a fine to medium grained

			wackestone near top of unit. Weathers to fairly large, thick bedded blocks which are continuous vertically but not laterally. Fossil allochems include pelmatozoan debris, bryozoans and some brachiopod fragments. <u>Samples:</u> GA21A, 159.0 m.; GA21B, 160.5 m.; GA21C, 164.0 m.; GA21D, 166.0 m.; GA21E, 167.0 m.
22	5.5	175.0	<u>Rockdell Formation.</u> Very similar to Unit 21. <u>Samples:</u> GA22A, 169.5 m.; GA22B, 171.5 m.; GA22C, 173.0 m.
23	4.5	179.5	<u>Rockdell Formation.</u> Light grey to grey, well exposed, medium grained grainstone. Massive, thick bedded and abundant stylitization. Fossil allochems are predominately pelmatozoans with some bryozoans. <u>Samples:</u> GA23A, 176.0 m.; GA23B, 179.0 m.
	4.5	184.0	COVERED INTERVAL
24	4.0	188.0	<u>Rockdell Formation.</u> Grey to pinkish, fairly well exposed, medium grained grainstones. Weathers to thin laterally discontinuous beds. Mostly pelmatozoan debris. <u>Samples:</u> GA24A, 184.0 m.; GA24B, 185.0 m.; GA24C, 186.5 m.; GA24D, 188.0 m.
	10.0	198.0	COVERED INTERVAL
25	.5	198.5	<u>Rockdell Formation.</u> Grey, poorly exposed, medium grained packstone/grainstone. Weathers blocky and at surface is flaggy, bedding poorly developed. Stylites are abundant. Mostly pelmatozoan debris. <u>Sample:</u> GA25A, 198.5 m.
	16.5	215.0	COVERED INTERVAL
26	10.0	225.0	<u>Rockdell Formation.</u> Grey to yellowish grey and pink to maroon, poorly exposed, fine to medium grained wackestone/packstones. Bedding not well developed, stylites abundant. Fossil allochems are mostly pelmatozoans and bryozoans. This unit is characterized generally as red "mudmounds" intercalated with current winnowed grey packstones/grainstones. <u>Samples:</u> GA26A, 215.0 m.; GA26B, 219.0 m.; GA26C, 220.0 m.

- | | | | |
|----|------|--------|---|
| 27 | 5.0 | 230.0 | <p><u>Rockdell Formation.</u> Pinkish grey to yellowish grey, poorly exposed, medium to coarse grained packstone/grainstone. Weathers blocky and at surface is flaggy and nodular, bedding poorly developed. Fossil constituents are mostly pelmatozoans and bryozoans.</p> <p><u>Samples:</u> GA27A, 225.0 m.; GA27B, 230.0 m.</p> |
| | 17.5 | 247.5 | COVERED INTERVAL |
| 28 | 18.5 | 266.0 | <p><u>Benbolt Formation.</u> Grey to yellowish grey, fairly well exposed, fine to medium grained wackestone/packstone. Weathers to medium to thick beds, discontinuous laterally. Constituent particles are predominately pelmatozoans and bryozoans. This unit is much more shaly than units of the Rockdell below. Small clusters (20 cm. in diameter) of ramose bryozoans are fairly abundant.</p> <p><u>Samples:</u> GA28A, 249.5 m.; GA28B, 256.0 m.; GA28C, 265.0 m.; GA28D, 266.0 m.</p> |
| 29 | 12.0 | 278.0 | <p><u>Benbolt Formation.</u> Light grey to yellowish grey, poorly exposed, fine to medium grained wackestones/packstones at base and medium grained grainstone at top of unit. Weathers to thin, flaggy, laterally and vertically discontinuous beds. Bedding is generally poorly developed and stylolites are fairly abundant. Weathering produces abundant float material which reveals a diverse fauna of pelmatozoans, bryozoans, trilobites, cephalopods and brachiopods.</p> <p><u>Samples:</u> GA29A, 268.5 m.; GA29B, 270.5 m.; GA29C, 273.0 m.</p> |
| 30 | 12.0 | 290.0 | <p><u>Benbolt Formation.</u> Grey, fairly well exposed fine grained mudstone/wackestone. Thin to thick bedded, laterally and vertically discontinuous, stylolites abundant. Fossil allochems are mostly bryozoans, some trilobites and brachiopods.</p> <p><u>Samples:</u> GA30A, 278.0 m.; GA30B, 282.5 m.</p> |
| 31 | 12.0 | 302.00 | <p><u>Benbolt Formation.</u> Grey, well exposed, medium grained packstone at base to fine grained mudstone/wackestone at top of unit. Thin to thick bedded, fairly continuous laterally and vertically. Fairly diverse fauna of bryozoans, pelmatozoans, trilobites and brachiopods. Stylolites abundant.</p> <p><u>Samples:</u> GA31A, 290. m.; GA31B, 296.5 m.; GA31C, 299.5 m.; GA31D, 301.0 m.</p> |

32	14.0	316.0	<u>Wardell Formation.</u> Grey to yellowish grey, poorly exposed, fine to medium grained wackestone/packstone. Thin to medium bedded, laterally and vertically discontinuous. Styolites abundant. Fossil constituents are mostly pelmatozoans. <u>Samples:</u> GA32A, 309.5 m.; GA32B, 310.0 m.
	5.5	321.5	COVERED INTERVAL
33	4.5	325.0	<u>Wardell Formation.</u> Grey, poorly exposed, fine to medium grained packstone/grainstone. Thin to medium bedded, somewhat continuous laterally and vertically. Abundant styolites. Fossil allochems include pelmatozoans, bryozoans, trilobites and brachiopods. <u>Samples:</u> GA33A, 322.0 m.; GA33B, 322.5 m.; GA33C, 325.0 m.
	26.0	351.0	COVERED INTERVAL
34	13.0	364.0	<u>Wardell Formation.</u> Light grey to yellowish grey, poorly exposed mudstone. Thin to medium bedded, mudcracks, burrows and "birdseye" structures. Fairly abundant float material. Fossil allochems include gastropods, brachiopods, bryozoans and cephalopods. <u>Samples:</u> GA34A, 352.0 m.; GA34B, 357.0 m.; GA34C, 357.5 m.; GA34D, 361.0 m.
			Unit 34 (continued)
34	2.0	366.0	<u>Bowen Formation.</u> Maroon, poorly exposed mudstone. Poorly developed bedding, mudcracks and vertical burrows. No fossil allochems observed. <u>Sample:</u> GA34E, 364.0 m.
	10.0	376.0	COVERED INTERVAL
35	32.5	408.5	<u>Witten Formation.</u> Light grey, fairly well exposed, fine to medium grained mudstone/wackestone. Medium to thick bedded, burrowed, styolites are abundant. Fairly diverse fauna of gastropods, bryozoans, cephalopods and brachiopods. <u>Samples:</u> GA35A, 376.0 m.; GA35B, 384.0 m.; GA35C, 384.5 m.; GA35D, 387.0 m.; GA35E, 391.0 m.; GA35F, 396.0 m.; GA35G, 402.5 m.

Moccasin Formation.

APPENDIX B

PETROGRAPHIC CONSTITUENT ANALYSES

Petrographic constituent particle analysis was done on 171 petrographic thin sections using a technique described by Chayes (1954). Two hundred points were counted per slide. The reliability of the results of the point counts was determined by a method described by van der Plas and Tobl (1965). The maximum range of values (i.e., confidence limits) for a particular constituent particle $\pm 7\%$, with a 95% confidence. For example, if the count leads to an estimated content of 50% micrite by volume this means that the content of micrite in that thin section lies between 43% and 57%, with a 95% confidence.

Constituent particles which were observed in thin section but did not register in the count were designated trace particles (T). Oncolites were noted as being present (P) to avoid confusion with the percentage volume of algae.

The petrographic thin sections described and/or point counted during the course of this investigation are part of a permanent collection of The University of Tennessee, Knoxville, Department of Geological Sciences. The location of samples is provided in Appendix A.

Table B-1. Constituent particle analysis (rock volume percent) for selected thin sections (DG1A-DG9A) at the Dry Gap stratigraphic section.

Sample no.	Micrite	Spar	Intraclasts	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
DG1A	5.0	5.5	5.5	62.5	0.0	0.5	0.0	7.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0
DG3A	46.0	0.5	0.0	0.0	0.0	1.5	T	1.5	T	2.0	13.0	22.5	0.0	0.0	0.0	0.0	2.0	0.5	10.5
DG4A	10.0	27.5	0.0	0.0	2.5	0.0	0.0	0.5	T	0.0	54.0	3.5	0.0	0.0	0.0	0.0	0.5	0.5	1.0
DG5B	49.0	8.0	0.0	0.0	0.0	0.0	T	8.0	1.5	3.0	7.5	2.0	0.5	0.0	9.0	0.0	1.5	0.0	10.0
DG6A	32.0	22.5	0.0	7.5	0.0	0.5	T	8.5	2.5	0.5	10.0	4.0	6.0	P	0.0	0.0	1.5	0.0	4.5
DG6C	7.5	39.5	0.0	1.0	0.0	1.5	2.5	13.0	2.5	1.5	26.0	4.0	T	0.0	0.0	0.0	1.0	0.0	0.0
DG7B	14.5	36.0	0.0	3.0	0.0	T	T	3.0	2.0	2.5	24.5	12.5	0.0	0.0	0.5	0.0	0.5	0.0	1.0
DG7D	1.0	31.0	0.0	0.0	0.0	0.0	0.0	0.5	2.5	0.0	36.5	28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DG8C	1.5	24.5	0.0	0.0	0.0	0.0	T	0.5	1.5	0.0	44.0	28.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DG9A	24.5	10.5	0.0	4.0	0.0	0.0	0.5	3.5	1.5	1.5	30.0	13.5	2.0	0.0	0.0	0.0	4.5	0.0	4.0

Table B-2. Constituent particle analysis (rock volume percent) for selected thin sections (DG9C-DG14C) at the Dry Gap stratigraphic section.

Sample no.	Microite	Spar	Intraclasts	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Tritolite debris	Molluscan debris	Echinoderm debris	Brachiozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
DG9C	79.5	4.0	0.0	8.5	0.0	0.0	0.0	1.5	1.0	0.5	T	5.0	0.0	0.0	T	0.0	0.0	0.0	0.0
DG9C	25.5	14.0	0.0	8.5	0.0	T	5.5	1.5	0.5	1.0	24.5	10.5	2.5	P	0.0	0.0	0.0	0.0	5.0
DG10C	38.5	8.0	0.0	4.5	0.0	0.5	0.0	2.0	1.0	1.5	21.5	17.0	0.5	P	T	0.0	0.0	0.0	5.0
DG10E	54.0	8.0	0.0	1.5	0.0	0.5	T	1.0	2.0	2.5	14.0	16.5	0.0	0.0	T	0.0	0.0	0.0	0.0
DG11A	4.5	22.0	0.0	0.0	0.0	0.5	0.0	4.5	1.0	0.0	47.0	19.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0
DG12C	79.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.5	5.5	8.5	0.0	0.0	3.0	0.0	0.5	0.0	1.0
DG13C	88.0	0.0	0.0	0.0	0.0	T	0.5	1.5	1.0	1.0	3.5	0.5	0.5	P	0.0	0.0	0.0	0.0	3.5
DG13F	67.5	1.5	0.0	1.0	0.0	T	1.5	1.5	0.5	1.5	14.0	5.0	4.5	P	0.5	0.0	1.0	0.0	0.0
DG14A	47.0	4.5	0.0	0.0	0.0	1.5	T	1.0	2.5	0.5	6.0	11.5	14.0	0.0	0.0	0.0	3.5	0.0	8.0
DG14C	79.5	2.0	0.0	T	0.0	T	2.0	1.5	3.0	0.0	2.5	6.0	T	0.0	0.5	0.0	2.0	0.0	1.0

Table B-4. Constituent particle analysis (rock volume percent) for selected thin sections (HC1A-HC3E) at the Halls Crossroads stratigraphic section.

Sample no.	Microite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HC1A	17.0	20.0	0.0	0.0	0.0	T	0.0	0.5	0.5	0.0	55.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HC1B	15.0	6.5	0.0	15.0	0.0	1.5	T	T	0.0	1.5	27.5	21.0	11.5	0.0	0.0	0.0	0.0	0.0	0.5
HC1D	14.5	6.0	0.0	0.0	0.0	T	0.0	T	1.0	0.0	18.0	41.5	15.5	0.0	0.0	0.0	1.0	0.0	2.5
HC1E	57.5	3.0	0.0	0.0	0.0	0.5	T	1.5	T	0.5	2.0	32.0	0.0	0.0	2.0	0.0	0.0	T	0.0
HC2A	60.5	3.0	0.0	0.0	0.0	T	0.0	T	1.5	1.5	18.5	15.0	T	0.0	T	0.0	0.0	0.0	0.0
HC2B	49.0	1.5	0.0	0.0	0.0	T	0.0	1.0	T	0.0	1.5	47.0	0.0	0.0	T	0.0	T	T	0.0
HC3A	27.0	14.5	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	14.5	39.5	4.0	0.0	0.0	0.0	0.0	0.0	0.5
HC3C	35.5	2.0	0.0	0.0	0.0	0.0	0.0	T	T	T	1.5	53.0	6.5	0.0	1.5	0.0	0.0	0.0	0.0
HC3D	3.0	25.5	1.0	0.0	0.0	1.5	0.5	0.5	1.0	0.0	47.0	8.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0
HC3E	34.0	0.5	0.0	0.0	0.0	1.5	0.0	T	1.0	0.0	22.5	35.5	1.0	0.0	2.5	0.0	0.0	0.0	2.0

Table B-5. Constituent particle analysis (rock volume percent) for selected thin sections (HC4B-HC8A) at the Halls Crossroads stratigraphic section.

Sample no.	Microite	Spar	Intraclasts	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Tribolite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital quartz	Other Minerals
HC4B	82.5	0.0	0.0	0.0	0.0	0.0	0.0	T	T	0.5	6.5	10.0	0.0	0.0	0.5	0.0	0.0	T	0.0
HC4C	24.0	19.0	2.5	0.0	0.0	0.0	0.5	0.0	T	0.0	34.5	15.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0
HC4E	67.5	2.5	0.0	6.0	0.0	T	T	T	1.0	1.5	5.0	10.5	T	0.0	6.0	0.0	0.0	0.0	0.0
HC5B	75.0	2.5	0.0	1.5	0.0	0.5	0.0	T	T	1.5	1.5	14.5	0.0	0.0	0.5	0.0	0.5	0.5	1.5
HC5C	35.5	16.5	1.0	0.0	0.0	0.5	0.5	0.5	0.0	1.0	31.5	6.5	1.0	P	0.0	0.0	2.0	0.0	4.5
HC5E	73.5	1.0	0.0	0.0	0.0	0.0	0.0	T	T	T	2.0	15.0	0.5	0.0	7.0	0.0	T	0.0	1.0
HC6A	35.5	4.0	0.0	17.5	0.0	0.0	0.0	T	T	3.5	12.5	13.5	3.0	0.0	T	0.0	5.0	T	5.5
HC6C	59.5	2.5	0.0	0.0	7.5	0.5	0.5	T	1.5	1.0	13.5	10.5	0.0	0.0	0.5	0.0	0.0	0.0	2.5
HC7A	68.0	4.5	0.0	0.0	0.0	0.0	0.0	T	T	0.5	14.0	5.0	0.0	0.0	3.0	0.0	0.0	0.0	5.0
HC8A	55.0	3.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	10.5	T	0.0	T	26.5	0.0	0.0	1.5

Table B-6. Constituent particle analysis (rock volume percent) for selected thin sections (HC8C-HC13A) at the Halls Crossroads stratigraphic section.

Sample no.	Microite	Spar	Intraclasts	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HC8C	13.5	25.0	1.5	8.0	0.0	4.0	0.5	1.0	T	0.5	28.0	13.0	T	0.0	0.0	0.0	5.0	0.0	0.0
HC9A	58.5	3.5	0.0	0.0	0.0	0.5	T	T	0.5	1.0	14.0	21.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
HC9C	64.5	2.5	3.0	0.0	0.0	0.0	T	T	T	3.0	17.5	10.5	0.5	0.0	1.5	0.0	0.0	0.0	0.0
HC10A	41.0	4.5	0.0	0.0	0.0	0.0	0.0	T	T	0.0	17.5	37.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HC11A	67.5	2.0	0.0	10.0	0.0	0.0	0.0	T	T	T	3.0	10.0	4.5	0.0	3.0	0.0	0.0	0.0	0.0
HC11B	57.5	8.5	0.0	0.0	0.0	0.0	T	T	1.0	1.0	7.0	22.0	1.5	0.0	1.5	0.0	0.0	0.0	0.0
HC11D	63.0	1.5	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.0	19.0	10.5	T	0.0	T	0.0	0.0	0.0	4.5
HC12A	68.5	0.0	0.0	6.5	0.0	0.0	3.0	1.5	T	1.5	4.5	10.5	0.5	0.0	3.5	0.0	0.0	0.0	0.0
HC12D	37.0	6.5	0.0	0.0	0.0	0.5	1.0	0.5	T	5.0	10.0	31.0	8.0	0.0	0.5	0.0	0.0	0.0	0.0
HC13A	42.0	9.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0	T	32.0	7.5	7.5	0.0	T	0.0	0.0	0.0	1.0

Table B-7. Constituent particle analysis (rock volume percent) for selected thin sections (HCl3C-HCl15E) at the Halls Crossroads stratigraphic section.

Sample no.	Microite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Tritolite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HCl3C	77.5	0.5	0.0	5.0	0.0	0.0	T	T	T	1.5	7.0	3.5	0.0	0.0	5.0	0.0	0.0	0.0	0.0
HCl3D	24.0	34.5	0.0	0.0	0.0	T	T	0.5	0.5	1.0	22.5	15.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0
HCl3F	64.0	5.0	0.0	6.5	0.0	T	T	T	T	2.5	9.0	5.5	0.0	0.0	7.5	0.0	0.0	0.0	0.0
HCl3H	67.5	0.5	0.0	1.0	0.0	1.0	T	0.5	2.0	3.0	8.0	11.0	5.0	0.0	0.5	0.0	0.0	0.0	0.0
HCl4B	67.5	2.5	0.0	2.5	0.0	0.0	0.0	0.5	0.0	0.0	3.5	19.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0
HCl4C	32.5	11.5	0.0	0.0	0.0	0.0	T	T	0.0	0.0	30.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCl4E	73.0	2.0	0.0	2.0	0.0	0.0	T	0.5	0.5	1.5	9.0	9.5	T	0.0	2.0	0.0	0.0	0.0	0.0
HCl4F	16.5	32.5	13.5	0.0	0.0	0.0	0.0	T	T	0.0	33.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCl5C	66.5	4.0	0.0	4.0	0.0	T	0.0	0.5	1.0	2.0	6.0	15.5	0.0	0.0	T	0.0	0.0	0.0	0.0
HCl5E	73.5	2.0	0.0	3.5	0.0	0.0	T	0.5	T	2.5	9.5	7.0	0.0	0.0	T	0.0	0.5	0.0	0.0

Table B-8. Constituent particle analysis (rock volume percent) for selected thin sections (HC16B-HC21D) at the Halls Crossroads stratigraphic section.

Sample no.	Matrix	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HC16B	82.0	7.5	0.0	0.0	0.0	1	0.0	1	1	1.5	1	3.5	0.0	0.0	3.0	0.0	0.0	0.0	2.5
HC17B	8.5	30.0	5.0	0.0	0.0	0.0	0.5	1	1	0.0	20.0	3.0	25.5	P	0.0	0.0	7.5	0.0	0.0
HC17D	72.5	4.5	0.0	2.5	0.0	1	0.0	1	0.0	0.0	2.5	2.0	T	0.0	15.0	0.0	0.5	0.0	0.0
HC17E	60.5	3.0	2.5	14.0	0.0	1.0	T	1.5	1.5	2.5	4.5	6.5	0.0	0.0	T	0.0	T	0.0	2.5
HC17G	87.0	0.0	0.0	0.0	0.0	0.5	T	T	0.5	1.5	4.5	3.0	T	0.0	0.0	0.0	1.0	0.0	2.0
HC18A	87.0	0.0	0.0	0.0	0.0	T	T	1.5	T	2.0	3.0	0.5	1.0	0.0	0.0	0.0	2.0	0.0	2.5
HC18B	89.5	0.0	0.0	3.0	0.0	T	T	0.0	0.0	0.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5
HC20A	34.5	14.0	0.0	1.5	0.0	1.5	0.5	0.5	T	4.0	15.5	6.0	21.0	P	0.0	0.0	0.5	0.0	0.5
HC21A	58.0	0.0	0.0	0.0	0.0	0.0	1.5	0.5	0.5	2.0	2.5	1.0	4.0	0.0	0.0	30.0	0.0	0.0	0.0
HC21D	65.0	0.5	0.0	0.0	0.0	0.0	5.0	T	0.5	1.0	3.0	24.0	1.0	0.0	0.0	T	0.0	0.0	0.0

Table B-9. Constituent particle analysis (rock volume percent) for selected thin sections (HR1A-HR6E) at the Harbison stratigraphic section.

Sample no.	Microite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Tritolite debris	Molluscan debris	Echinoderm debris	Brizoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HR1A	0.0	0.0	0.0	97.5	0.0	0.0	2.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR2A	2.0	15.5	0.0	7.5	0.0	0.0	0.0	2.5	4.5	0.0	50.0	15.0	1.0	0.0	0.0	0.0	0.0	0.0	2.0
HR2B	28.5	10.0	0.0	T	0.0	0.0	0.5	1.5	1.0	0.0	9.5	6.5	42.5	P	0.0	0.0	0.0	0.0	0.0
HR3B	0.0	27.0	0.0	4.0	0.0	0.0	0.0	3.5	3.5	0.0	46.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR4A	5.0	21.0	0.0	10.0	0.0	0.0	0.0	T	T	0.0	42.0	14.0	7.5	P	T	0.0	0.0	0.0	0.5
HR5A	3.5	13.5	0.0	6.0	0.0	0.0	0.0	3.0	1.5	0.0	38.0	27.5	T	0.0	4.0	0.0	3.0	0.0	0.0
HR6A	52.0	3.0	0.0	0.0	0.0	0.0	0.5	3.0	0.5	0.0	9.0	21.0	10.0	0.0	1.0	0.0	0.0	0.0	0.0
HR6B	0.5	36.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	0.0	30.5	29.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
HR6C	1.5	29.0	0.0	0.0	0.0	T	0.0	0.5	1.0	0.0	33.0	34.5	T	0.0	0.0	0.0	0.0	0.0	0.5
HR6E	15.5	22.5	0.0	0.0	0.0	T	0.0	T	1.0	0.0	28.0	24.5	3.5	0.0	0.0	0.0	0.0	0.0	0.0

Table B-10. Constituent particle analysis (rock volume percent) for selected thin sections (HR6G-HR9C) at the Harbison stratigraphic section.

Sample no.	Matrix	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HR6G	22.0	21.5	0.0	0.0	0.0	0.0	0.0	1.5	1.0	0.0	28.5	24.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0
HR6H	4.0	22.0	0.0	0.0	0.0	0.0	0.0	0.5	T	0.0	26.0	35.0	0.5	0.0	0.0	0.0	0.0	0.0	2.0
HR6I	52.5	4.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	11.5	9.5	21.0	0.0	0.5	0.0	0.0	0.0	0.0
HR6J	54.0	1.5	0.0	0.0	0.0	0.0	T	2.0	0.0	T	6.5	28.5	0.5	0.0	5.0	0.0	0.0	0.0	0.0
HR7C	34.5	12.0	0.0	1.5	0.0	0.0	1.0	1.0	0.5	0.0	15.0	10.0	19.0	0.0	T	0.0	3.0	0.0	0.0
HR7D	74.5	4.5	0.0	0.0	0.0	0.0	T	0.0	0.0	T	7.5	10.5	T	0.0	T	0.0	0.0	0.0	3.0
HR8A	12.0	28.5	0.0	0.0	0.0	T	0.0	0.5	1.5	0.0	36.0	21.0	0.5	0.0	T	0.0	0.0	0.0	0.0
HR8C	78.0	1.5	0.0	0.0	0.0	T	0.0	0.5	T	T	8.5	9.5	T	0.0	0.0	0.0	T	0.0	0.0
HR9A	9.5	26.0	1.5	1.5	0.0	0.0	0.0	1.5	T	0.0	29.0	29.0	1.5	0.0	0.0	0.0	T	0.0	0.0
HR9C	13.0	23.5	1.5	0.0	0.0	T	1.5	1.5	0.5	1.0	17.0	39.0	1.5	P	0.0	0.0	0.0	0.0	0.0

Table B-11. Constituent particle analysis (rock volume percent) for selected thin sections (HR9D-HR13A) at the Harbison stratigraphic section.

Sample no.	Micrite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HR9D	71.0	4.5	0.0	0.0	0.0	T	0.0	1.0	0.5	0.0	15.0	7.5	T	P	0.5	0.0	0.0	0.0	2.0
HR9E	65.0	3.0	0.0	16.0	0.0	0.0	0.0	1.5	0.0	T	2.0	7.5	T	0.0	5.0	0.0	0.0	0.0	0.0
HR10A	31.0	5.5	0.0	2.0	0.0	0.5	0.0	0.5	1.0	0.0	28.0	30.0	1.5	0.0	T	0.0	0.0	0.0	0.0
HR10B	3.0	29.0	5.0	0.0	11.0	T	0.0	1.5	2.0	0.0	27.0	19.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0
HR10D	43.5	8.5	0.0	2.0	0.0	1.5	0.0	0.5	1.0	0.0	26.5	12.0	T	0.0	0.5	0.0	1.5	0.0	2.5
HR11A	36.5	10.0	0.0	0.0	0.0	0.5	T	2.5	0.0	0.5	24.0	20.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0
HR11B	5.5	25.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	48.5	19.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR11F	5.5	3.0	0.0	2.5	0.0	0.0	0.0	0.0	0.5	0.0	21.5	9.5	0.0	0.0	5.0	0.0	0.0	0.0	3.0
HR12A	47.5	12.5	0.0	0.0	0.0	0.5	T	2.0	0.5	0.0	21.0	16.0	0.0	0.0	T	0.0	0.0	0.0	0.0
HR13A	19.5	14.5	0.0	14.5	0.0	0.5	0.0	0.5	0.5	T	30.5	19.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0

Table B-12. Constituent particle analysis (rock volume percent) for selected thin sections (HR13C-HR17D) at the Harbison stratigraphic section.

Sample no.	Wcrite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HR13C	59.0	7.0	0.0	T	0.0	0.5	0.0	T	T	0.0	24.5	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR13D	57.0	5.0	0.0	0.0	0.0	0.0	T	T	1.0	0.5	14.5	22.0	0.0	0.0	T	0.0	0.0	0.0	0.0
HR13F	12.0	23.0	0.0	0.0	0.0	T	0.0	T	1.0	0.0	58.0	6.0	0.0	0.0	T	0.0	0.0	0.0	0.0
HR14B	80.0	4.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	1.0	11.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
HR14D	59.5	3.0	0.0	0.0	0.0	0.0	0.5	0.5	T	0.0	1.0	28.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
HR15C	63.0	5.0	0.0	0.0	0.0	0.0	1.0	1.5	T	0.0	14.0	15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR16B	65.5	0.5	0.0	0.0	0.0	0.0	0.0	0.5	T	0.0	20.0	9.5	0.0	0.0	2.5	0.0	0.0	0.0	1.5
HR16E	70.5	2.5	0.0	18.0	0.0	0.0	0.0	T	T	0.0	2.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR17A	56.0	3.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	2.0	0.0	0.0	39.0	0.0	0.0	0.0	0.0
HR17D	48.5	13.0	T	8.0	0.0	0.5	0.5	0.5	T	0.0	25.5	2.5	0.0	0.0	T	0.0	0.0	0.0	1.0

Table B-13. Constituent particle analysis (rock volume percent) for selected thin sections (HR17F-HR20B) at the Harbison stratigraphic section.

Sample no.	Micrite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
HR17F	83.0	0.0	0.0	0.0	0.0	0.5	T	0.5	T	0.5	6.5	8.5	0.0	0.0	T	0.0	0.0	0.0	0.0
HR18A	87.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.5	3.5	0.0	0.0	3.5	0.0	0.0	0.0	0.0
HR18C	74.5	1.5	0.0	2.5	0.0	0.5	1.5	3.0	1.5	1.0	9.5	1.5	0.0	0.0	0.0	0.0	1.5	0.0	1.5
HR18D	87.0	0.0	0.0	1.5	0.0	1.0	0.5	1.0	0.5	0.5	4.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
HR18F	45.0	1.0	0.0	43.5	0.0	T	0.0	0.0	T	0.0	5.0	3.0	0.0	0.0	0.0	0.0	2.5	0.0	0.0
HR19A	97.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR19C	6.0	20.0	0.0	6.0	0.0	0.0	0.0	0.0	1.0	0.0	59.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HR19E	45.5	10.0	0.0	9.0	0.0	3.0	T	0.5	1.0	4.5	13.0	5.5	8.0	P	T	0.0	0.0	0.0	0.0
HR19F	59.5	1.5	0.0	0.0	0.0	T	T	0.5	1.5	0.5	5.5	4.5	25.5	P	0.0	0.0	0.0	0.0	1.5
HR20B	0.0	0.0	0.0	90.0	0.0	0.0	0.0	T	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	7.0	2.5	0.0

Table B-15. Constituent particle analysis (rock volume percent) for selected thin sections (GALA-GA9A) at the Graveston stratigraphic section.

Sample no.	Micrite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
GALA	5.5	38.0	0.0	0.0	0.0	0.5	0.0	1.5	1.0	0.0	20.5	3.5	29.5	P	0.0	0.0	0.0	0.0	0.0
GA2C	2.0	33.5	0.0	0.0	0.0	T	0.0	2.0	2.0	0.0	13.5	9.0	37.0	P	0.0	0.0	1.0	0.0	0.0
GA3A	10.0	20.5	0.0	0.0	0.0	0.0	0.0	1.0	0.5	1.0	16.0	12.5	38.0	P	0.0	0.0	0.0	T	0.5
GA4D	37.0	27.0	0.0	0.0	0.0	T	0.0	1.5	0.5	0.0	12.5	20.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0
GA5A	15.5	25.5	0.0	0.0	0.0	1.0	0.0	3.0	0.5	0.0	38.0	9.5	4.5	P	0.0	0.0	2.5	0.0	0.0
GA6A	4.0	25.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	55.0	13.5	1.5	0.0	0.0	0.0	T	0.0	0.0
GA7A	2.0	29.5	0.0	0.0	0.0	0.0	T	T	0.0	0.0	50.0	16.5	2.0	0.0	0.0	0.0	0.0	0.0	0.0
GA8A	1.0	25.0	0.0	0.0	0.0	0.0	0.0	2.0	0.5	0.0	45.0	22.0	3.5	0.0	0.0	0.0	1.0	0.0	0.0
GA8F	27.0	17.5	1.5	0.0	0.0	0.0	9.0	0.5	0.5	0.0	14.5	10.0	17.5	0.0	T	2.0	0.0	0.0	0.0
GA9A	6.5	16.5	0.0	29.5	0.0	0.0	T	0.0	0.0	0.0	39.0	5.5	0.5	0.0	0.0	0.0	T	0.0	0.0

Table B-16. Constituent particle analysis (rock volume percent) for selected thin sections (GAL1B-GAL18B) at the Graveston stratigraphic section.

Sample no.	Microite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bravoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
GAL1B	26.5	5.0	0.0	0.0	0.0	T	0.0	1.0	T	0.0	29.5	32.5	0.5	0.0	0.0	0.0	0.5	0.5	4.5
GAL12A	29.0	1.5	1.5	0.0	0.0	T	T	0.5	1.0	0.0	31.0	10.0	0.0	0.0	0.0	0.0	4.5	8.5	12.5
GAL12C	66.0	3.5	0.0	5.0	0.0	0.5	1.0	T	1.0	0.0	2.5	11.0	2.5	0.0	0.0	0.0	0.5	1.0	5.5
GAL13A	8.0	7.5	2.0	0.0	0.0	1.0	0.0	0.0	1.5	0.0	46.0	29.5	2.0	0.0	0.0	0.0	2.0	0.5	2.0
GAL14C	21.5	22.0	0.0	0.0	0.0	0.5	1.0	0.5	1.5	0.0	30.5	16.0	5.0	0.0	0.0	0.0	1.5	0.0	0.0
GAL15C	18.5	20.5	0.0	0.0	0.0	T	0.0	1.5	1.5	0.0	39.0	12.0	0.5	0.0	0.0	0.0	6.0	0.0	0.5
GAL16B	77.5	5.0	0.0	3.5	0.0	0.0	T	T	T	T	1.0	12.0	0.0	0.0	0.5	0.0	0.0	0.0	0.5
GAL16C	29.5	13.5	1.5	T	0.0	0.0	1.5	0.0	T	0.0	39.5	13.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0
GAL17C	19.5	22.5	T	0.0	0.0	0.5	T	2.0	1.0	0.5	38.0	11.5	2.5	0.0	0.0	0.0	1.0	0.0	1.0
GAL18B	18.0	23.0	0.0	1.5	0.0	0.0	0.0	2.5	0.5	T	37.0	13.5	0.0	0.0	0.0	0.0	4.0	0.0	0.0

Table B-17. Constituent particle analysis (rock volume percent) for selected thin sections (GA19C-GA26C) at the Gravelton stratigraphic section.

Sample no.	Micrite	Spar	Intraclasts	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
GA19C	8.5	30.5	0.0	16.5	0.0	1.0	0.0	4.0	1.0	0.5	23.5	12.0	0.0	0.0	0.0	0.0	2.5	0.0	0.0
GA19E	5.5	48.0	0.0	0.0	0.0	T	0.0	5.5	2.5	1.5	13.0	22.0	T	0.0	0.0	0.0	0.5	0.0	1.5
GA20A	42.5	12.0	T	T	0.0	1.0	0.0	T	T	1.0	17.5	14.0	0.0	0.0	0.0	0.0	8.0	0.0	4.0
GA21C	10.5	33.0	2.0	7.5	19.0	1.0	0.0	0.5	1.0	0.0	19.5	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA21E	56.0	17.0	0.0	9.0	T	0.0	0.0	0.5	1.0	0.0	3.0	7.0	0.0	0.0	0.0	0.0	6.5	0.0	0.0
GA22C	6.5	31.0	0.0	0.0	0.0	0.5	0.0	1.5	1.0	0.0	32.5	24.0	0.0	0.0	0.0	0.0	0.5	0.0	2.5
GA23A	1.5	34.0	1.0	0.0	0.0	0.0	T	1.0	0.0	0.0	48.0	14.0	T	0.0	0.0	0.0	0.5	0.0	0.0
GA24D	15.5	28.0	0.0	0.0	0.0	0.0	0.0	0.5	3.0	0.0	46.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA25A	26.0	16.5	0.0	5.0	0.0	0.5	0.0	0.5	1.5	0.0	30.0	16.0	1.0	0.0	0.0	0.0	0.0	0.0	3.0
GA26C	40.5	10.0	0.0	0.0	0.0	0.0	0.0	1.0	T	0.5	22.5	18.0	2.0	0.0	0.0	0.0	0.5	1.0	4.0

Table B-18. Constituent particle analysis (rock volume percent) for selected thin sections (GA27A-GA34D) at the Gravenston stratigraphic section.

Sample no.	Micrite	Spar	Intracrystals	Pellets	Ooids	Brachiopod fragments	Gastropods	Ostracod valves	Trilobite debris	Molluscan debris	Echinoderm debris	Bryozoan debris	Algae	Oncolites	Sponge debris	Other fossils	Dolomite rhombs	Detrital Quartz	Other Minerals
GA27A	39.0	15.5	0.5	3.0	0.0	0.0	T	0.5	0.0	0.0	24.5	16.5	0.0	0.0	T	0.0	0.0	0.0	0.5
GA28A	50.0	17.0	0.0	0.0	0.0	0.5	0.0	T	1.0	1.5	12.5	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA28D	70.0	6.5	0.0	22.5	0.0	0.0	0.0	0.0	0.0	0.0	T	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA29B	62.0	13.5	0.0	0.0	0.0	0.0	0.5	2.5	2.5	1.0	13.0	0.5	T	0.0	0.0	0.0	0.0	0.0	4.5
GA30A	77.5	2.0	0.0	0.0	0.0	T	T	2.5	1.0	0.5	2.5	0.5	11.0	0.0	0.0	0.0	0.0	0.0	2.5
GA31C	0.5	3.0	0.0	92.5	0.0	T	0.0	1.0	0.0	0.0	1.0	T	0.0	0.0	0.0	0.0	2.0	0.0	0.0
GA31D	56.0	13.5	4.0	4.0	0.0	0.5	0.0	3.0	0.5	0.5	8.0	3.0	0.0	0.0	0.0	0.0	6.5	0.5	0.0
GA32A	75.5	13.0	0.0	0.0	0.0	0.0	0.5	1.5	1.0	0.5	1.5	1.5	4.0	0.0	T	0.0	1.0	0.0	0.0
GA34C	28.5	11.5	0.0	57.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	2.0
GA34D	22.0	15.5	0.0	38.0	0.0	0.0	0.0	10.0	0.5	5.0	1.5	T	0.0	0.0	0.0	0.0	3.5	3.0	1.0

APPENDIX C

PETROGRAPHIC CONSTITUENT ANALYSIS OF THE
PATCH REEF AT THE HARBISON LOCALITY

Petrographic constituent particle analysis was done on 12 petrographic thin sections using a technique described by Chayes (1954). Constituent particle parameters (e.g., pelmatozoans, bryozoans, mosaic spar, etc.) were slightly modified from Walker and Ferrigno (1973) to allow for comparison of constituent particles. Three hundred points were counted per slide. The reliability of the results of the point counts was determined by a method described by van der Plas and Tobi (1965). The maximum range of values (i.e., confidence limits) for a particular constituent particle is $\pm 5.8\%$, with a 95% confidence. For example, if the count leads to an estimated content of 50% micrite by volume this means that the content of micrite in that thin section lies between 44.2% and 55.8%, with a 95% confidence.

The petrographic thin sections described and/or point counted during the course of this investigation are part of a permanent collection of The University of Tennessee, Knoxville, Department of Geological Sciences.

Table C-1. Constituent particle analysis (rock volume percent) for selected thin sections from the patch reef at Harbison (HR).

SAMPLE NO.	HR6-4PR	HR6-7PR	HR6-8PR	HR6-9PR	HR6-10PR	HR6-11PR	HR6-12PR	HR6-13PR	HR6-14PR	HR6-16PR	HR6-17PR	HR6-17PR
PELMATOZOANS (P)	25.7	30.7	39.3	5.3	16.7	3.0	18.3	5.7	2.7	26.7	2.3	2.3
BRYOZOAN FRAGMENTS (B)	17.7	19.0	19.3	9.3	10.0	7.7	11.7	10.7	0.3	22.3	2.0	2.7
RAMOSE ECTOPROCTS (R)	4.0	6.3	7.3	2.7	5.3	4.0	4.3	3.0	0.3	4.0	0.3	2.0
INCrustING ECTOPROCTS (I)	2.0	1.0	3.0	9.0	2.0	3.7	3.6	0.3	36.4	4.0	16.0	11.3
STROMATOLACTIS STRUCTURES (S)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OTHER FOSSILS (F)	1.3	0.7	1.7	0.0	2.0	0.0	0.3	1.0	2.0	2.3	2.3	0.3
MOSAIC SPAR (C)	31.0	33.0	27.0	7.3	14.7	8.0	24.3	1.0	2.3	21.7	1.0	0.0
RADIAL, FIBROUS SPAR (RS)	13.7	0.0	0.3	13.7	12.6	0.7	1.6	0.0	0.0	10.0	0.3	0.0
FINE GRAINED MATRIX (M)	4.3	8.3	1.7	49.7	35.7	73.3	29.3	78.3	56.0	8.0	54.4	81.4
ALGAE (A)	0.3	1.0	0.7	3.0	1.0	0.6	6.3	0.0	0.0	1.0	21.4	0.0

APPENDIX D

INSTRUMENT AND PHOTOGRAPHIC PARAMETERS USED IN CATHODOLUMINESCENCE STUDY

Instrument and Photographic Parameters

Microscope: Bausch and Lomb, 3 1/2 x objective, 10X ocular
Instrument: Nuclide LUMINOSCOPE, Model ELM-2A
Chamber Window: Colorless to light yellow
Sample Preparation: Petrographic thin sections, 600-grit finish,
unstained

Instrument Parameters

Beam energy: 10-12 kilovolts
Beam current: 50-60 microampres
Spot diameter: 5-10 mm
Gun type: Cold cathode
Ambient gas: Air @ approx. 150 millitor¹

Photographic Parameters

Camera: Zeiss Ikon
Film type: Kodak, Tri-X
Film size and speed: 35 mm, 400 ASA
Development: Normal
Exposure: Plain light² - 1 to 2 seconds
Cathodoluminescence - 3 to 5 minutes

¹These values were read from the instrument's vacuum gauge which is not calibrated.

²Exposure times will vary depending on the intensity and type of light source.

APPENDIX E

ECHINODERM PLATES WITH

EXPLANATIONS

The echinoderms illustrated in the following plates and selected specimens collected during the course of this investigation are part of a permanent fossil collection of The University of Tennessee, Knoxville, Geological Museum.

Plate E-1. Crinoidea Camerata.

1. Diabolocrinus vesperalis, base of calyx, 3X, Rockdell Formation (HC), (UTGSM 10053).
2. Diabolocrinus vesperalis, base of calyx, 3X, Rockdell Formation (HC), (UTGSM 10054).
3. Unidentified camerata, lateral view of calyx, 4X, Rockdell Formation (HC), (UTGSM 10055).
- 4, 5. Diabolocrinus vesperalis, lateral view, basal view of calyx, 3X, Benbolt Formation (GA), (UTGSM 10056).
- 6 - 8. Diabolocrinus vesperalis, base, summit, lateral view of calyx, 4X, Benbolt Formation (GA), (UTGSM 10057).
9. Archaeocrinus peculiaris, plate, 5X, Wardell Formation (DG), (UTGSM 10105).
- 10 - 11. Archaeocrinus peculiaris, base, lateral view of calyx, 2.5X, Wardell Formation (DG), (UTGSM 10106).

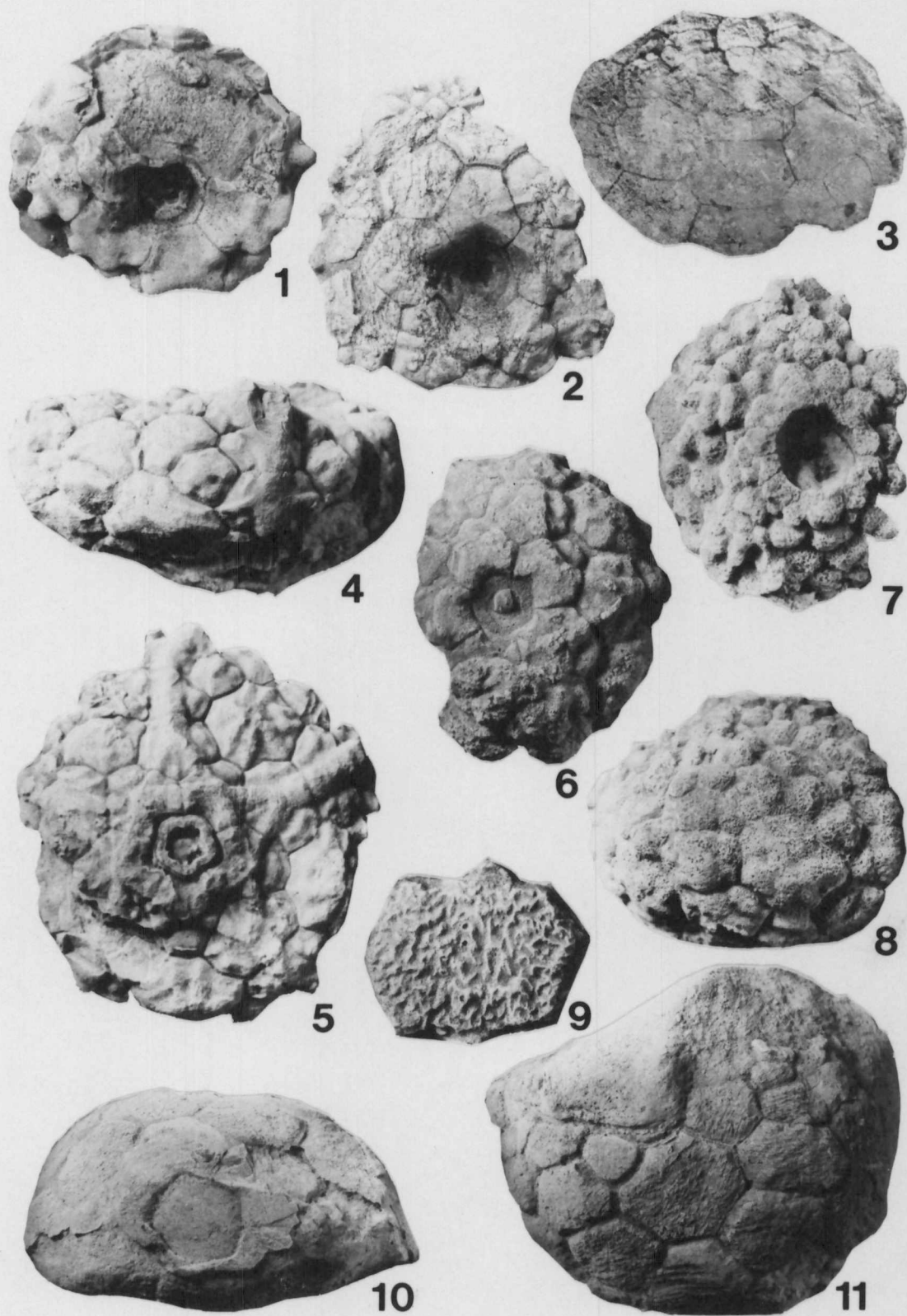


Plate E-1.

Plate E-2. Crinoidea Inadunata.

1. Carabocrinus micropunctatus, basal plate, 6X, Rockdell Formation (HC), (UTGSM 10058).
2. Carabocrinus sp., radial plate, 4X, Wardell Formation (DG), (UTGSM 10059).
3. Ristnacrinus sp. cf. altobasalis, lateral view of calyx, 4X, Benbolt Formation (GA), (UTGSM 10060).
4. Palaeocrinus avondalensis, radial plate, 6X, Rockdell Formation (HC), (UTGSM 10061).
5. Carabocrinus stellifer, radial plate, 6X, Rockdell Formation (HC), (UTGSM 10062).
6. Hybocrinus punctatus, lateral view of calyx, 6X, Rockdell Formation (HC), (UTGSM 10063).
7. Palaeocrinus planobasalis, basal plate, 6X, Wardell Formation (DG), (UTGSM 10064).
8. Carabocrinus stellifer, calyx, 6X, Rockdell Formation (HC), (UTGSM 10065).
9. Palaeocrinus avondalensis, basal plate, 4X, Rockdell Formation (HC), (UTGSM 10066).
10. Hybocrinus sp., base of calyx, 6X, Benbolt Formation (GA), (UTGSM 10067).
11. Palaeocrinus planobasalis, top of calyx, 5X, Rockdell Formation (HC), (UTGSM 10068).
12. Palaeocrinus sp., partial plate, 6X, Rockdell Formation (HC), (UTGSM 10069).
13. Palaeocrinus planobasalis, base of calyx, 4X, Rockdell Formation (HC), (UTGSM 10070).

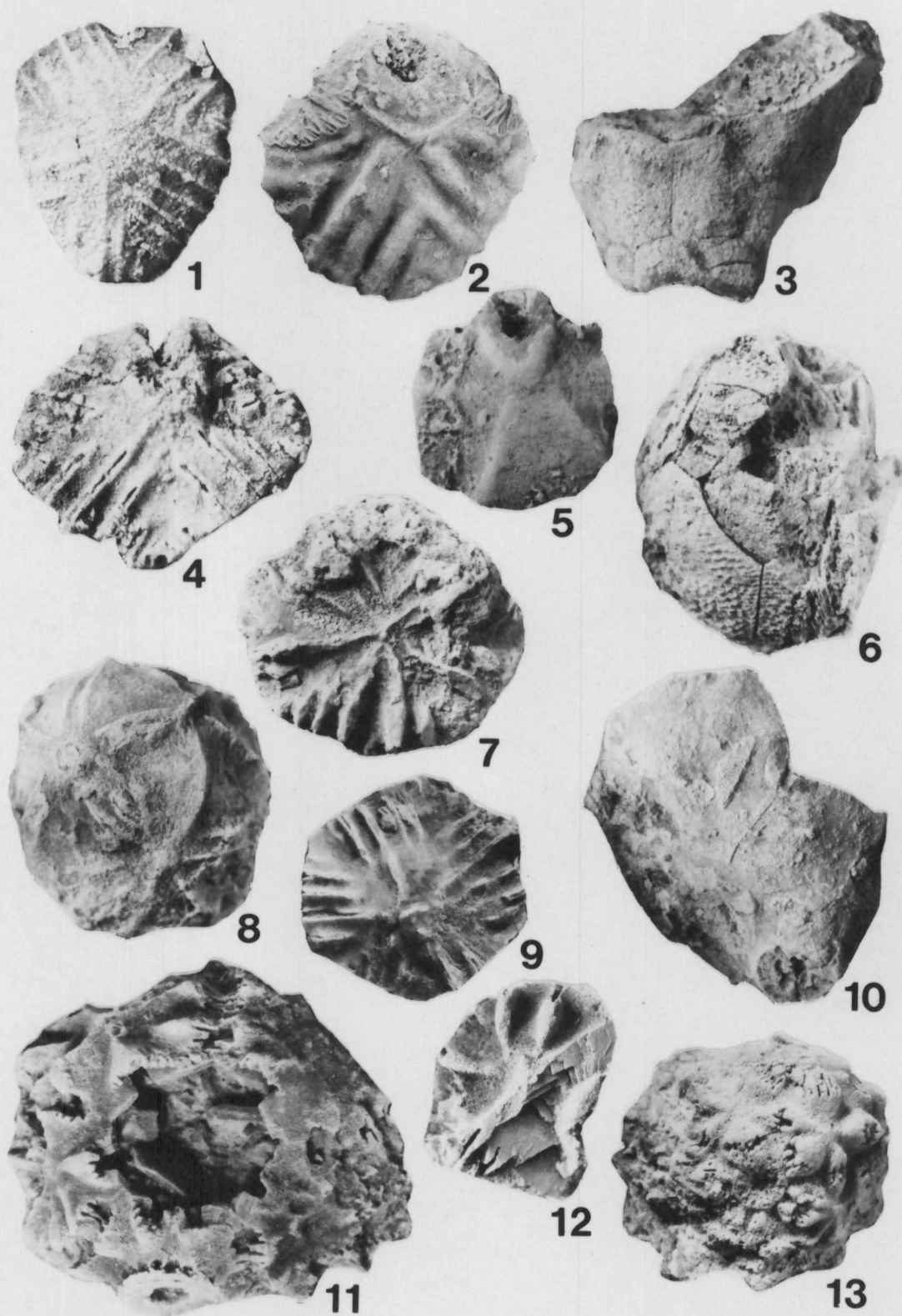


Plate E-2.

Plate E-3. Crinoidea (1-3), Rhombifera (4-8), Edrioasteroidea (9-10),
Edrioblastoidea (11), and Eocrinoidea (12).

1. Cleioocrinus sp., partial calyx (internal view), 5X, Rockdell Formation (HC), (UTGSM 10071).
2. Cleioocrinus sp., partial calyx, 2.5X, Witten Formation (HC), (UTGSM 10072).
3. Cleioocrinus sp., partial calyx, 2.5X, Benbolt Formation (DG), (UTGSM 10073).
4. Regulaecystis pyriformis, partial theca, 3X, Rockdell Formation (HC), (UTGSM 10074).
5. Regulaecystis sp., plate, 6X, Wardell Formation (DG), (UTGSM 10075).
6. Regulaecystis sp., plate, 6X, Benbolt Formation (GA), (UTGSM 10076).
7. Coronocystis angulatus, plate, 5X, Rockdell Formation (HC), (UTGSM 10077).
8. Coronocystis angulatus, plate, 5X, Rockdell Formation (HC), (UTGSM 10078).
9. Cyathocystis sp., theca, 5X, Benbolt Formation (GA), (UTGSM 10079).
10. Cyathocystis sp., theca, 5X, Rockdell Formation (HC), (UTGSM 10080).
11. Astrocystites sp., deltoid plate, 5X, Rockdell Formation (HC), (UTGSM 10081).
12. Batherocystis appressa, marginal plates, 4X, Rockdell Formation (HR), (UTGSM 10082).

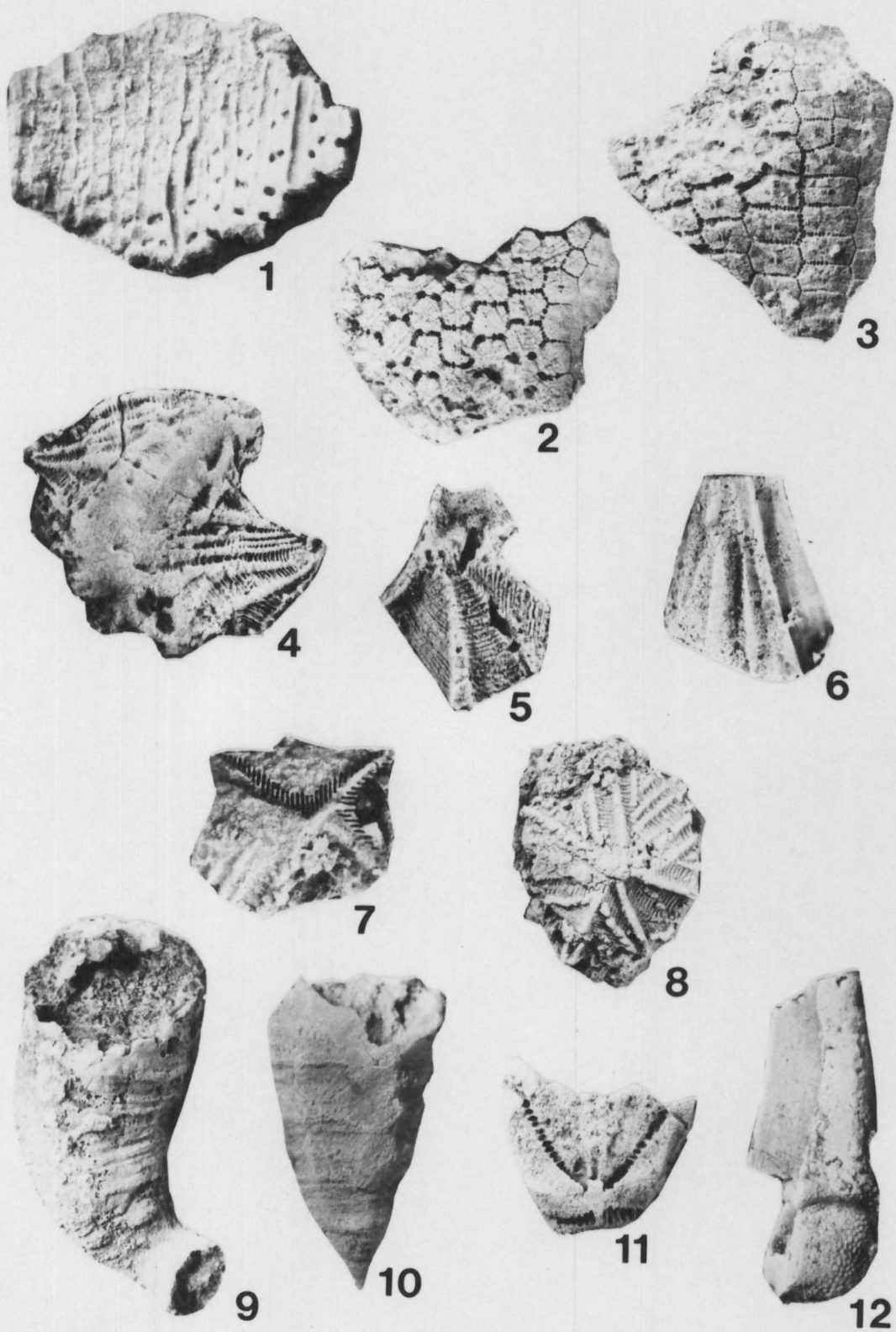


Plate E-3.

Plate E-4. Paracrinoidea and Parablastoidea.

1. Springerocystis sp., theca, 5X, Benbolt Formation (HR), (UTGSM 10083).
2. Springerocystis sp., theca, 5X, Rockdell Formation (HC), (UTGSM 10084).
3. Springerocystis sp., theca, 5X, Rockdell Formation (HC), (UTGSM 10085).
4. Paracrinoid, theca, 5X, Rockdell Formation (HC), (UTGSM 10086).
5. Undescribed paracrinoid, theca, 6X, Rockdell Formation (HC), (UTGSM 10087).
6. Ulrichocystis eximia, partial plate (internal view), 5X, Benbolt Formation (DG), (UTGSM 10088).
7. Ulrichocystis eximia, partial plate (external view), 5X, Chapman Ridge Formation (HC), (UTGSM 10089).
8. Ulrichocystis eximia, plate (external view), 6X, Rockdell Formation (HC), (UTGSM 10090).
9. Ulrichocystis eximia, plate (internal view), 6X, Rockdell Formation (HC), (UTGSM 10091).
10. Platycystites sp., marginal plate, 2X, Rockdell Formation (HC), (UTGSM 10092).
- 11, 12. Meristoschisma hudsoni, deltoid plate (internal view, external view), 5X, Benbolt Formation (GA), (UTGSM 10093).
13. Meristoschisma hudsoni, deltoid plate, 5X, Benbolt Formation (GA), (UTGSM 10094).
14. Meristoschisma hudsoni, deltoid plate, 5X, Benbolt Formation (GA), (UTGSM 10095).
15. Meristoschisma hudsoni, radial plate (external view), 4X, Wardell Formation (DG), (UTGSM 10096).

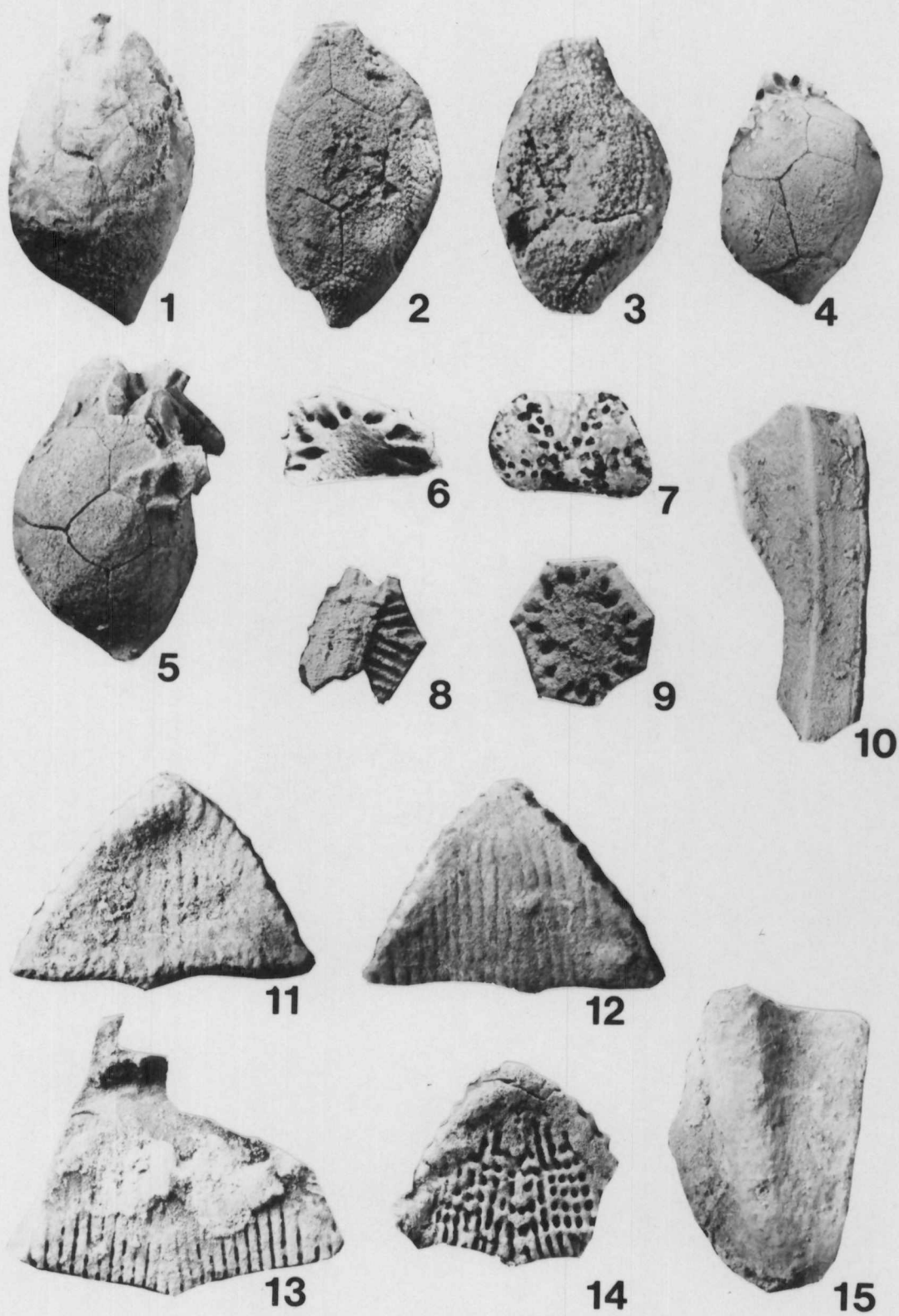


Plate E-4.

Plate E-5. Columnals and holdfasts.

1. Cleioocrinus sp. columnal?, 3X, Rockdell Formation (HC), (UTGSM 10097).
2. Camerate columnal?, 2X, Rockdell Formation (HC), (UTGSM 10098).
3. Columnal, 2X, Rockdell Formation (HC), (UTGSM 10099).
4. Bored columnal, 3X, Rockdell Formation (HC), (UTGSM 10100).
5. Holdfast, 4X, Chapman Ridge Formation (HC), (UTGSM 10101).
6. Holdfast, 5X, Chapman Ridge Formation (HC), (UTGSM 10102).
7. Holdfast, 1.5X, Rockdell Formation (HC), (UTGSM 10103).
8. Holdfasts, 7X, Rockdell Formation (HC), (UTGSM 10104).

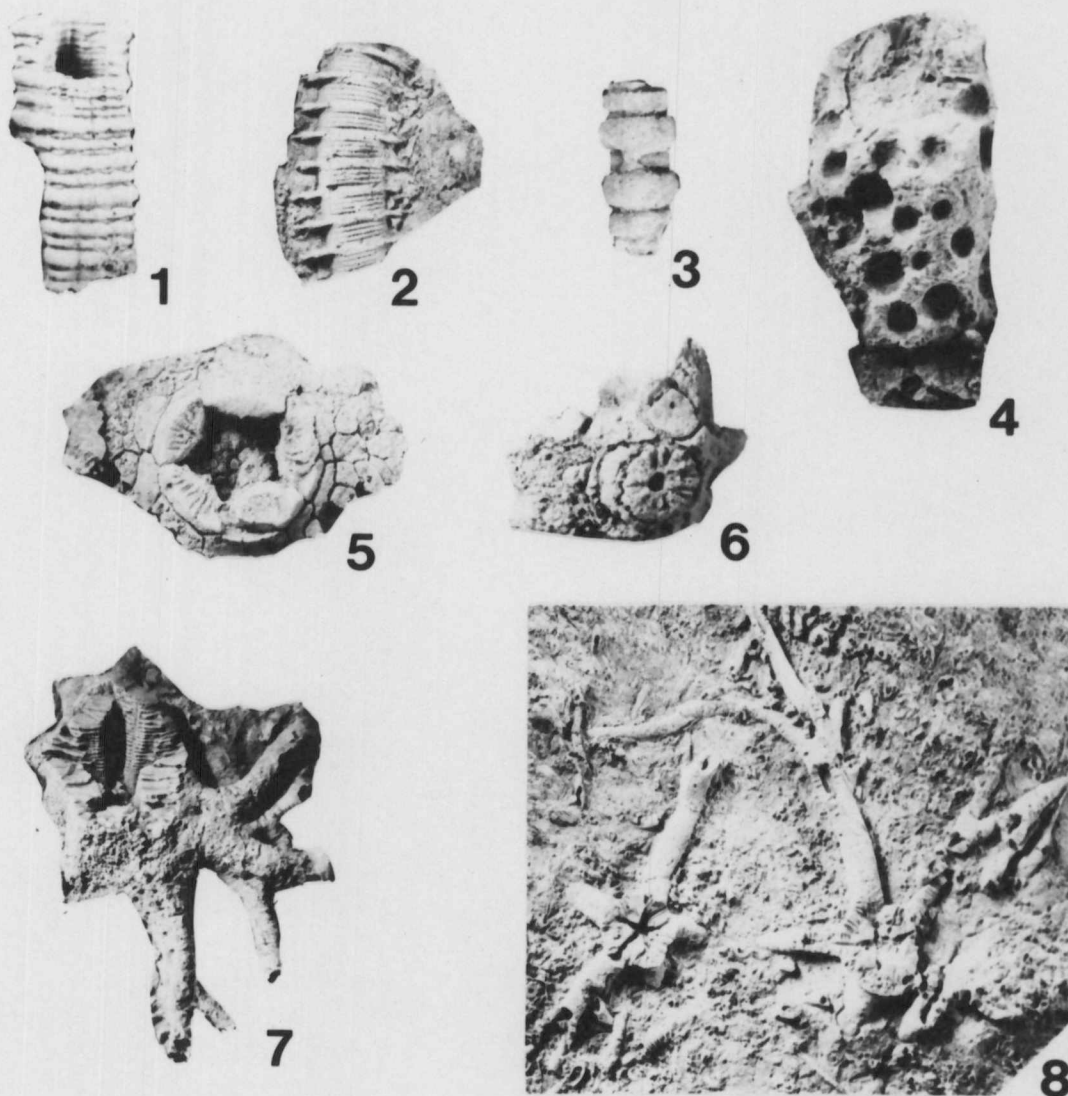


Plate E-5.

VITA

Fritz Clayton Breland, Jr. was born on August 10, 1947 in Pascagoula, Mississippi. He was graduated from Pascagoula High School in 1965. In the fall of that year, he entered Millsaps College in Jackson, Mississippi where he majored in geology. He was graduated from that institution in June 1970 with a Bachelor of Science degree. He continued his studies in geology at the University of Mississippi at Oxford and in August 1972 graduated with a Master of Science degree. While at the University of Mississippi, he worked as a graduate teaching assistant and as a research assistant with the University of Mississippi Seismological Observatory. Immediately following graduation, he accepted a teaching position at Northwest Junior College in Senatobia, Mississippi. He taught at this institution until the summer of 1976 when he entered The University of Tennessee, Knoxville, to further his education in geology. While at The University of Tennessee, Knoxville, he worked as a graduate teaching assistant and was awarded a Gulf Oil Company Fellowship. In August 1980 he was granted the Doctor of Philosophy degree. In September 1980 he accepted a position in the Geoscience Division of the Gulf Oil Company in Oklahoma City, Oklahoma.

Clayton is a member of the Society of Economic Paleontologists and Mineralogists, the American Association of Petroleum Geologists, Sigma Xi, and Sigma Gamma Epsilon.