Winter 1987

Depositional and Diagenetic History of the Middle Ordovician Carbonates of the Shenandoah Valley, Northern Virginia

Lynn Ellen Weyenberg
Old Dominion University

DEPOSITIONAL AND DIAGENETIC HISTORY OF THE MIDDLE ORDOVICIAN CARBONATES OF THE SHENANDOAH VALLEY, NORTHERN VIRGINIA

by
Lynn Ellen Weyenberg
B.S. May 1984, University of Wisconsin-Oshkosh

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE
GEOLOGY

OLD DOMINION UNIVERSITY

December, 1987

Approved by:

Dennis A. Darby (Director)

ABSTRACT

DEPOSITIONAL AND DIAGENETIC HISTORY OF THE
MIDDLE ORDOVICIAN CARBONATES OF THE
SHENANDOAH VALLEY, NORTHERN VIRGINIA

Lynn Ellen Weyenberg
Old Dominion University
Director: Dr. Dennis A. Darby

An examination of the Middle Ordovician carbonates in northwest Virginia has revealed a particularly sensitive record of deposition and subsidence. Two-hundred acetate peels from six measured stratigraphic sections in Shenandoah County, Virginia were examined to interpret the depositional and diagenetic history. Two major lithofacies have been recognized within the New Market Limestone and three have been recognized in the Lincolnshire Formation. These five lithofacies represent an overall transgressive sequence. This transgression was not uniform but paused several times to allow carbonate deposition to reach sea-level. These shoaling events suggest a slowly subsiding basin in this region. The carbonate rocks within the study area have been compared to the sediments of the modern Andros Island, Bahamas to establish a depositional and diagenetic model. The models proposed for the study area are in agreement with models proposed for adjacent areas along strike.

DEDICATION

To my mother,

Marilynn C. Weyenberg

and to my father,

Robert H. Weyenberg

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my thesis advisor, Dr. Dennis Darby, for his guidance, support, and especially his patience throughout this endeavor. I would also like to thank my committee members, Dr. Stephen Culver, Dr. Ramesh Venkatakishan and Mr. Eugene Rader for their assistance and advice on the final manuscript.

A note of thanks is also extended to Dr. Robert Milici and Eugene Rader of the Virginia Division of Mineral Resources (VDMR) for their assistance in the field and to the VDMR for the use of equipment and for thin section preparation. My gratitude is also extended to Ruth Strauss, Bill Decker and Rich Barringer for their assistance in the field. A special thanks to Lisa Doan for typing and to Sue Hoebeke, Debbie Miller, and Pandora Mazzo for drafting.

A very special thanks is given to Joan and Mark Strauss for their friendship and for taking me into their home during the summer of 1985 which gave me the opportunity to do my field work, and to Ruth Strauss, my friend, who suggested that I stay with her family. Thanks also to Mrs. Helen Wilkens, Mr. and Mrs. Harold Fleming, and to Riverton Corporation for allowing me to work on their land. I would also like to thank my friends: Kathy Conko, Lisa Doan, Megan Jones and Ruth Strauss for their continuous support and helpful suggestions.

I would like to extend my appreciation to the following for their financial assistance. The Virginia Division of Mineral Resources; the Grant-In-Aid of Research from Sigma Xi, the Scientific Research Society of North America, and to the Department of Geological Sciences at Old Dominion University.

And finally, a special thanks to my family and my fiancé for their encouragement and unending support.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

CHAPTER I: INTRODUCTION

No modern detailed sedimentologic studies exist for the Middle Ordovician carbonates in northern Virginia with the exception of the shelf-to basin model proposed by Rader and Henika (1978). Northern Virginia appears to have represented an initially "stable" platform located between two subsiding subbasins (or depocenters) to the north and south (Read, 1980; Mitchell, 1982). The carbonate depositional record on such a stable to slowly subsiding platform between two active depocenters should provide information on the relationship of the lithofacies from one subbasin to the other, hence insight into the relative timing, rate and aerial extent of tectonic subsidence; the direction of marine transgression; the depositional and environmental parameters controlling sedimentation on the platform; and the burial history of the study area.

The purpose of this study is to develop a depositional model for six measured stratigraphic sections of the Middle Ordovician carbonates (New Market Limestone and Lincolnshire Formation) located in Shenandoah County in northern Virginia. Comparison of this model to depositional models in adjacent areas along strike will be useful in determining the stratigraphic, sedimentologic and paleotectonic relationships of the Middle Ordovician carbonates from the northern subbasin to the southern subbasin. Inasmuch as the diagenetic modifications of ancient carbonates provide insight into paleoenvironmental and paleotectonic conditions, an analysis of the diagenetic features in these limestones will also be made.

CHAPTER II: GEOLOGIC AND STRATIGRAPHIC SETTING

The Appalachian Valley and Ridge - Great Valley Province from Newfoundland to Alabama contains carbonate platform deposits (1200 to 3500 m thick) that range in age from Early Cambrian to Middle Ordovician (Mitchell, 1982). In general, the Cambro-Ordovician carbonates form an eastward-thickening wedge and reach a maximum thickness in the central and southern Appalachians along the eastern boundary of the Valley and Ridge Province. Along the entire length of the pericratonic platform of eastern North America, the carbonates rest conformably upon a Late Precambrian to Lower Cambrian clastic sequence. These Cambro-Ordovician carbonates are overlain by Middle and Upper Ordovician graptolitic black shales.

The Middle Ordovician (Chazyan) New Market Limestone and Lincolnshire Formation of northwestern Virginia are part of this thick Cambro-Ordovician shallow platform carbonate deposit. These carbonates formed on a carbonate ramp which fringed eastern North America and extended southeastward into a rapidly subsiding foreland basin (Kay, 1951; Rodgers, 1971; Read, 1980). Sedimentation on the carbonate ramp was strongly influenced by shelf depocenters, located in Tennessee and Pennsylvania. These shelf-depocenters evolved into subsiding subbasins which are characterized by a thickening of shallow water carbonates (Colton, 1970). These carbonates were progressively overlain by thick basinal deposits.

The New Market Limestone crops out in the Valley and Ridge Province of Virginia (north of Roanoke, Virginia; Eugene Rader, personal commun., 1987) and thickens to the north becoming the St. Paul Group in the Great Valley Province of Maryland and southern Pennsylvania. The Lincolnshire Formation is exposed in the Valley and Ridge Province of Virginia. The furthest northern extent of the Lincolnshire Formation is near the Virginia-West Virginia border where the formation is bordered by a fault (Neuman, 1951). The Mosheim and Lenoir limestones which out-crop in southwest Virginia may contain facies that are similar to but not time-correlative to the New Market and Lincolnshire limestones in the study area. These limestones (Mosheim/Lenoir) were not considered in the discussions of this paper.

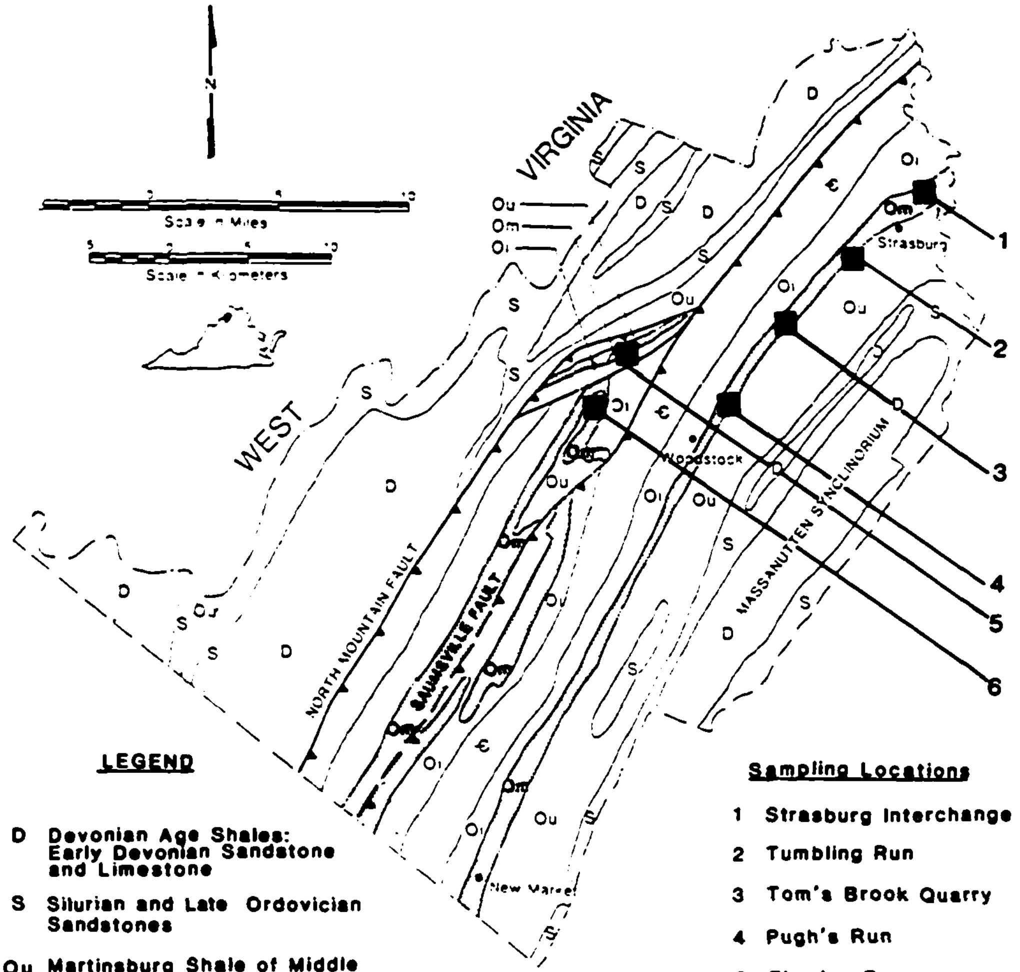
Neuman (1951) suggested that the St. Paul Group (which includes the New Market Limestone) migrated southward into northern Virginia by overlap. This transgression of the northern subbasin is supported by a great thickening and development of more marine facies of the St. Paul Group northward into Pennsylvania. Neuman (1951) and Read (1980) suggested that the New Market/Mosheim Limestones in Virginia and the St. Paul Group in Maryland and Pennsylvania may be peritidal facies of two initially separate sedimentary basins, one in the southwest and the other to the north. These sedimentary subbasins apparently became connected following submergence of the Knox-Beekmantown beds in Virginia.

The study area lies within the folded and thrust faulted Valley and Ridge Province west of the Massanutten synclinorium (Fig. 1). The synclinorium extends from Harrisonburg, Virginia northeastward into western Maryland and south central Pennsylvania. The North Mountain Fault is the major thrust fault in this region. The fault trends northeast-to-southwest from the Maryland-Pennsylvania border to Lexington, Virginia (Williams, 1978). The fault displaces Cambrian age carbonate rocks over the Devonian clastics to the west.

The six measured sections lie on the western limb of the Massanutten synclinorium in the Shenandoah Valley of northwestern Virginia (Fig. 1 and Appendix A). The sections are located within the Toms Brook (Rader and Biggs, 1976) and Woodstock (Young and Rader, 1974) 7.5 minute quandrangles. Sections 1 through 4 are found along a northeast to southwest trending linear ridge between Strasburg and Woodstock, Virginia. No faults occur within these sections and they are considered to be continuous. Sections 5 and 6 are located to the west of this linear belt within as large detached footwall slices (Rader and Biggs, 1976) or "horse" features. The faults bordering these features are the North Mountain Fault and the Alonzaville Fault. These two sections are non-continuous and often poorly exposed.

The Middle Ordovician limestones rest unconformably on the Lower to Middle Ordovician dolomites and limestones (Knox Group/Beekmantown Formation) in south and central Virginia (Read, 1980; Mussman and Read, 1986). In northern Virginia, the Middle Ordovician limestone sequence is believed to be conformable with Beekmantown beds by some (Cooper and Cooper, 1946; Neuman, 1951;

FIGURE 1. Generalized geologic map of the Shenandoah County, Northwest Virginia which shows the major geologic structures, faults, and the location of the six measured sections (modified after Hack, 1965).



LEGEND

D Devonian Age Shales: Early Devonian Sandstone and Limestone

S Silurian and Late Ordovician Sandstones

Ou Martinsburg Shale of Middle and Late Ordovician Age

Om Middle Ordovician Limestones

Oı Beekmantown Dolomite of Early Ordovician Age

Є Cambrian Age Sandstone and Impure Limestone: Early Cambrian Shale, Sandstone, and Argillite

——— Geologic Contact

—▼▼-- Thrust Fault: dashed where approximate or concealed

—·—·— County Boundary Line

Sampling Locations

1 Strasburg Interchange

2 Tumbling Run

3 Tom's Brook Quarry

4 Pugh's Run

5 Fleming Farm

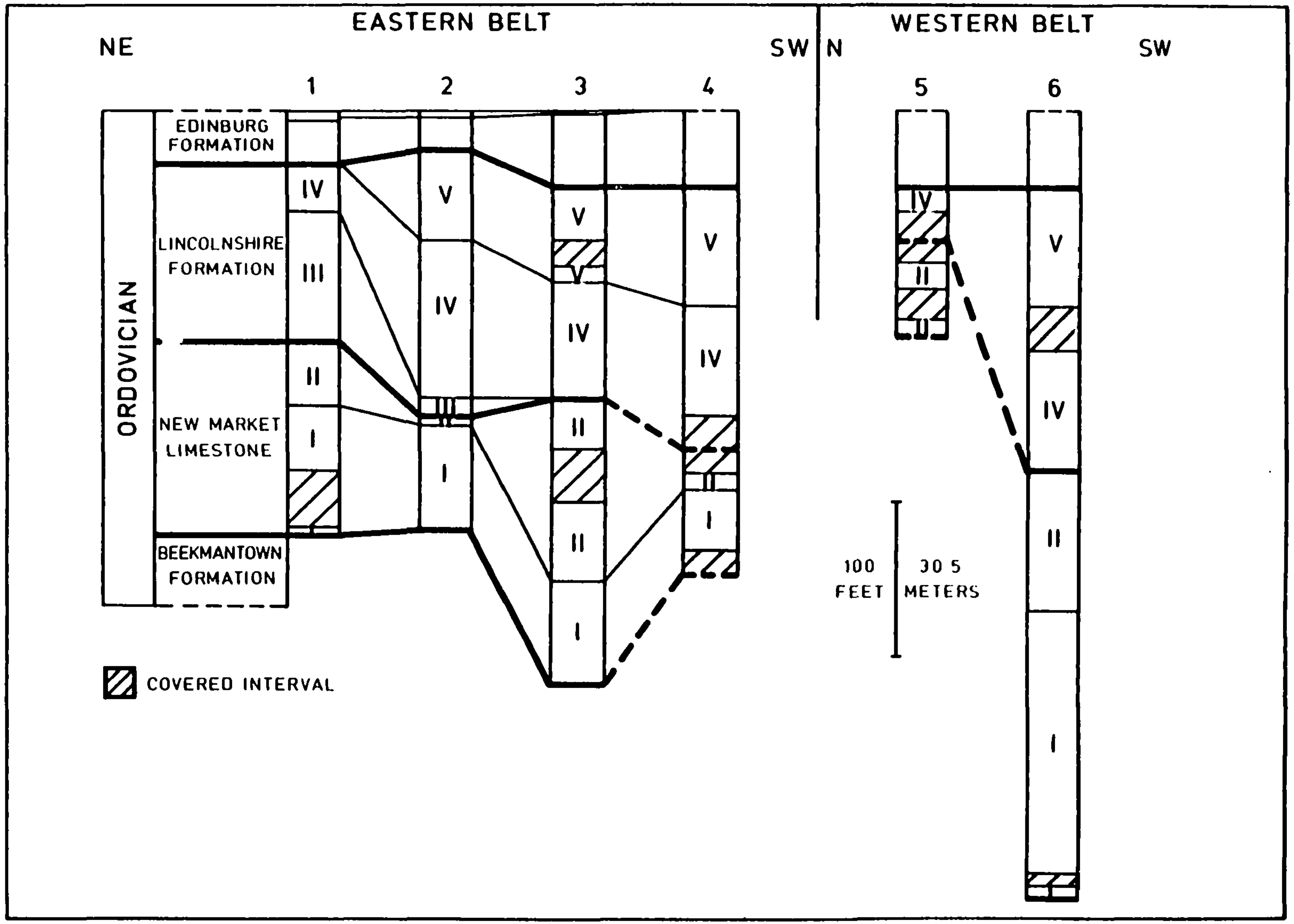
6 Narrow Passage Creek

Anita Harris, personal commun., 1986) and unconformable by others (Mussman and Read, 1986). Although no break is evident in northern Virginia based on paleontologic data, Mussman and Read have found sedimentological evidence which suggests a short duration of non-deposition and erosion (few tens to hundreds of thousands of years) that formed distinctive karstic features. The shallow ramp facies grade into skeletal sheets followed by progressively more basinal facies.

The New Market Limestone is the basal formation of the Middle Ordovician sequence. The unit (20 to 76 meters thick) consists primarily of two lithofacies: a lower laminated and an upper mudstone facies (Fig. 2). The upper contact of the New Market Limestone is commonly marked by an erosional surface. Such erosional contacts have been reported by Read and Grover (1977) in southwestern Virginia.

The Lincolnshire Formation overlies the New Market Limestone. It either overlies the erosion surfaces cut into the underlying mudstones or the burrowed mudstones of the New Market Limestone. The Lincolnshire Formation (30 to 50 meters thick) consists of three lithofacies: (1) a discontinuous, basal bioclastic-peloidal-oncoidal packstone; (2) a thinly bedded, bioclastic wackestones, and packstones; and (3) mudstones (Fig. 2). The Lincolnshire Formation is conformably overlain by the Edinburg Formation, an argillaceous limestone interbedded with shaly limestone and black shale (Cooper and Cooper, 1946).

FIGURE 2. Diagram correlating the lithofacies of the Middle Ordovician New Market Limestone (Lithofacies I and II) and the Lincolnshire Formation (Lithofacies II, IV, and V). The measured sections include. 1) Strasburg Interchange, I-81, 2) Tumbling Run, 3) Tom's Brook Quarry, 4) Pugh's Run, 5) Fleming Farm, and 6) Narrow Passage Creek. Measured sections 1-4 are located in the eastern belt and sections 5 and 6 in the western belt.


EASTERN BELT
NE
SW
1
2
3
4
WESTERN BELT
N
SW
5
6
ORDOVICIAN
EDINBURG FORMATION
LINCOLNSHIRE FORMATION
NEW MARKET LIMESTONE
BEEKMANTOWN FORMATION
V
IV
III
II
I
100 FEET
30 5 METERS
COVERED INTERVAL

CHAPTER III: PROCEDURES

Six sections of Middle Ordovician limestones were measured within the Toms Brook and Woodstock 7.5 minute quandrangles of the Shenandoah Valley, northwestern Virginia (Appendix A). In measuring the sections, rock types were defined by sediment type and fabric, sedimentary structures, faunal diversity and early to late diagenetic features. Upon later petrographic analysis, the rock types were then grouped into subfacies and facies based on associated sedimentary features of these ancient rocks with modern analogs containing similar features (Fig. 2). These sedimentary features include all mechanical and organic structures, textures, depositional and diagenetic fabrics, and aspects of fossil remains. A subfacies may be a uniform rock type, or a few intricately interbedded rock types with a similar inferred depositional setting. The basis for these interpretive "genetic" subdivisions is what Ginsburg (1974) termed "comparative sedimentology", where modern sediments are used to understand ancient deposits.

Studies of modern tidal flat complexes have shown that the characteristics of a deposit (such as sedimentary structures, faunal diversity, and early diagenetic features, etc.) are controlled by specific physical, chemical and biological parameters: tidal range and hydrology, climate, salinity, and organic activity, etc. (Mitchell, 1982). As these parameters vary, the characteristic of the deposits will change (Table 1). In general, these environments are the "high-energy" deposits of the semi-arid Shark Bay of western Australia, the relatively "low-energy" deposits of the arid Persian Gulf, and the "low-energy" deposits of the temperate Andros Island. Mitchell (1982) has shown that the St. Paul Group, in Maryland and adjacent states, is most similar to the Andros Island tidal flats. The features which differentiate these low energy and temperate deposits from the Persian Gulf and Shark Bay examples are: (1) the dominance of peloidal muds instead of coarser oolitic sands; (2) the dominance of cryptalgal layering over mechanical layering; and (3) the lack of evaporites and associated features (Mitchell, 1982).

The Bahama Andros Island tidal flat environment is divided into the levee crest, levee backslope, channel, subtidal pond, and freshwater algal marsh subenvironments (Hardie and Ginsburg, 1977). Each of these subenvironments leaves a distinct, recognizable record. The record may be composed of a uniform rock type such as the bioturbated muds of the subtidal pond subenvironment or a complex of interbedded rock types as found in the algal marsh subenvironment composed of algal tufas alternating with peloidal sands deposited during storms. The interbedding of these rock types is the result of different sedimentary processes in the same depositional environment. By comparing the modern Bahama analogs

TABLE 1. Sedimentary structures and sediment types in the modern tidal flats of the Persian Gulf, Shark Bay, and Andros Island, and in the Ordovician St. Paul Group and the New Market Limestone (modified after Mitchell, 1982).

TABLE 1. SEDIMENTARY STRUCTURES AND SEDIMENT TYPES IN MODERN FLATS AND IN ORDOVICIAN CARBONATES

	TRUCIAL COAST TIDAL FLATS, ABU DHABI, PERSIAN GULF	SHARK BAY TIDAL FLATS, WESTERN AUSTRALIA	ANDROS ISLAND TIDAL FLATS AND THE GREAT BAHAMA BANKS	THE ST. PAUL GROUP MARYLAND AND SOUTHERN PENNSYLVANIA	NEW MARKET LIMESTONE NORTHERN VIRGINIA
I. SEDIMENTARY TEXTURE					
1. OOID, SKELETAL, AND INTRACLASTIC GRAINSTONES	X	X			
2. PELOIDAL LIME MUD			X	X	X
II. MECHANICAL LAYERING					
1. PLANAR LAMINATES	X	X			
2. GRADED LAMINAE-BEDS	X	X			
3. THIN BEDS			X	X	X
4. WAVE-CURRENT CROSS-BEDDING	X	X		VERY RARE	
5. CROSS-BEDDING	X	X			
6. MUD-CHIP (INTRACLAST) CONGLOMERATE	X	X	X	X	X
III. ORGANIC LAYERING-STRUCTURES					
1. STROMATOLITE HEADS WITH GRAINSTONE		X			
2. WAVY ALGAL LAMINAE	X	X	X	X	X
3. FLAT-PLANAR ALGAL LAMINAE		X	X	X	X
4. ALGAL TUFA*			X	X	X
IV. DISRUPTED FEATURES					
1. MUD CRACKS AND PRISM CRACKS	X	X	X	X	X
2. SHEET CRACKS	X	X	X	X	X
3. FENESTRAE	X	X	X	X	X
4. BURROWS-	RARE		X	X	X
TOTALLY BIOTURBATED PLACES			X	X	X
V. CHEMICALLY PRODUCED STRUCTURES					
1. CEMENTED CRUSTS AND CLASTS	X	X	X	X	X
2. CALICHE PROFILES		X			
3. SALINE MINERALS, CASTS, MOLDS, OR NODULES (E.G. GYPSIUM, ANHYDRITE, AND HALITE)	X	X			

* THE TERM ALGAL TUFA IS USED FOR CARBONATE MINERALS, PRECIPITATED AS SHEATHS AROUND THE OUTSIDE OF ALGAL FILAMENTS OR BUNDLES OF ALGAL FILAMENTS

Modified after Mitchell (1982)

with the Middle Ordovician Limestone, the character of the environment of deposition and the spacial relationship, or depositional history of the deposit might be determined.

The petrographic analysis was conducted through the use of staining and acetate peel techniques, utilizing procedures outlined by Wolf et. al. (1967) and Friedman and Johnson (1982) (Appendix B). More than 200 representative samples were collected and slabbed for a more detailed petrographic study. All slabs of rock specimens were then stained with alizarin red S in 30% NaOH (Wolf et. al., 1967) to distinguish calcite from dolomite. Stained acetate peels were prepared and examined using conventional petrography with a Nikon Polarizing microscope (Appendix C). Black-and-white photographs were taken with a mounted Leitz camera.

CHAPTER IV: DEPOSITIONAL LITHOFACIES: DESCRIPTION, ENVIRONMENTAL INTERPRETATION AND MODERN BAHAMIAN ANALOGS

A. INTRODUCTION

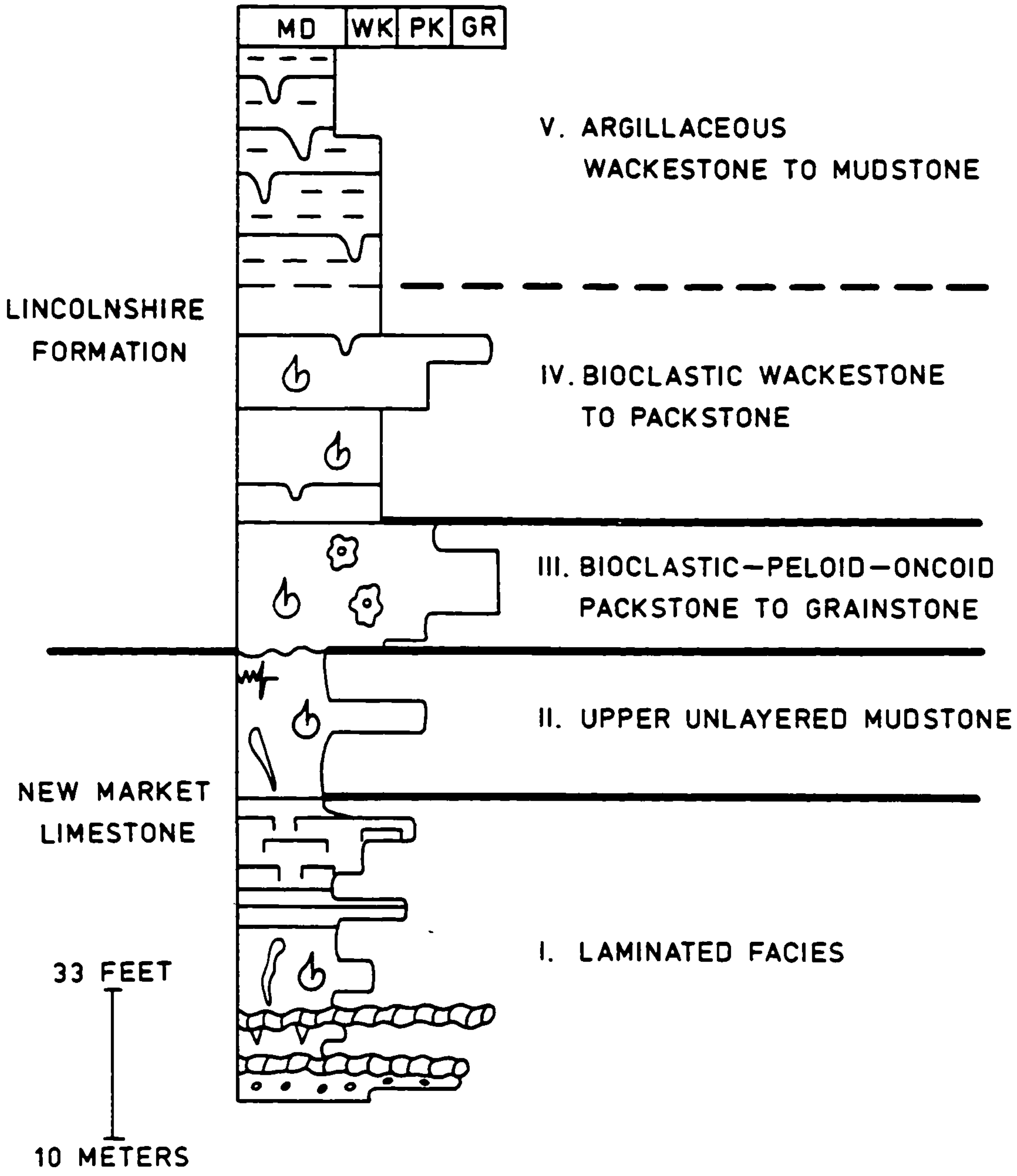
The Middle Ordovician New Market and Lincolnshire Formations in northern Virginia are composed mainly of limestone and minor dolomite. A third constituent is chert seen in the Lincolnshire Formation as bedding parallel chert beds or nodules and as secondary replacement of bioclasts.

The following lithofacies have been recognized in this study of the Middle Ordovician carbonates:

New Market Lithofacies	1.	Laminated Facies
	2.	Unlayered Mudstone
Lincolnshire Lithofacies	3.	Bioclastic-Peloidal-Oncoidal Packstone
	4.	Bioclastic Wackestone/ Packstone
	5.	Argillaceous Wackestone/ Mudstone

These lithofacies comprise an overall transgressive sequence (60 to 120 meters thick) with minor shoaling or regressive phases indicated by erosional surfaces (Fig. 3). Following is a detailed sedimentologic description, environmental interpretation, and modern analog for each of these lithofacies.

FIGURE 3. Schematic diagram of the Middle Ordovician New Market and Lincolnshire Lithofacies in northern Virginia. These lithofacies comprise an overall transgressive sequence with shoaling or minor regressive phases indicated by erosional surfaces (wavy bedding symbol). See Appendix A for an explanation of the symbols. The vertical scale represents the average thickness of each of the lithofacies in the study area.


MD
WK
PK
GR
LINCOLNSHIRE FORMATION
V. ARGILLACEOUS WACKESTONE TO MUDSTONE
IV. BIOCLASTIC WACKESTONE TO PACKSTONE
III. BIOCLASTIC–PELOID–ONCOID PACKSTONE TO GRAINSTONE
II. UPPER UNLAYERED MUDSTONE
NEW MARKET LIMESTONE
I. LAMINATED FACIES
33 FEET
10 METERS

B. NEW MARKET LIMESTONE

The New Market Limestone contains cryptalgal laminates, thinly bedded rocks, mud-cracks, desiccation fenestrae, vadose diagenetic fabrics, and marine fossils (Table 1). All of these features characterize deposits of the modern Andros Island tidal flat environments, indicating that the New Market Limestone in northern Virginia was deposited in a low energy and temperate marginal marine setting. The New Market Limestone is composed of two main lithofacies: (1) laminated (Fig. 4) and (2) unlayered mudstones (Fig. 5).

1. Lithofacies I: Laminated Facies

The Laminated Facies is composed of five subfacies:

a. very thinly bedded

b. thinly bedded mudstone

c. planar laminates

d. disrupted flat laminates

e. disrupted dololaminates

Each subfacies is defined by sediment texture, layering style, and the types of disruption features. Lithofacies I is characterized by a rapid bed-to-bed variation of five subfacies (Fig. 6), a restricted fauna, cryptalgal layering, and desiccation features.

FIGURE 4. Photograph of the New Market Limestone, Lithofacies 1: Laminated Facies that outcrop at measured section No. 1. Lens cap is 5.5 cm in diameter.

5. Photograph of the New Market Limestone, Lithofacies II: Unlayered Mudstone that outcrop at measured section No. 1. The darker irregular features are calcite spar-filled fenestrae (arrow). Lens cap is 5.5 cm in diameter.


4

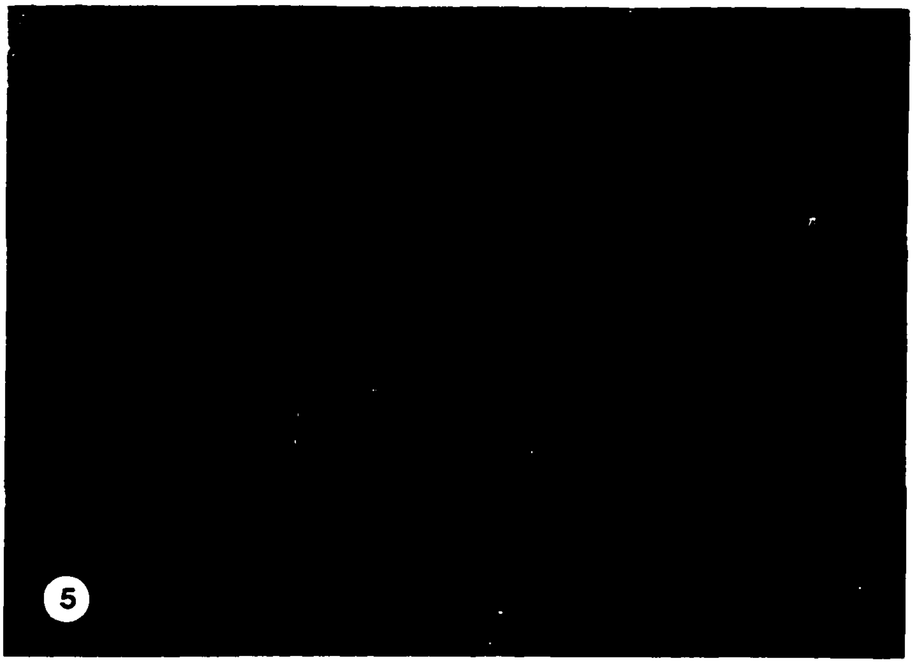
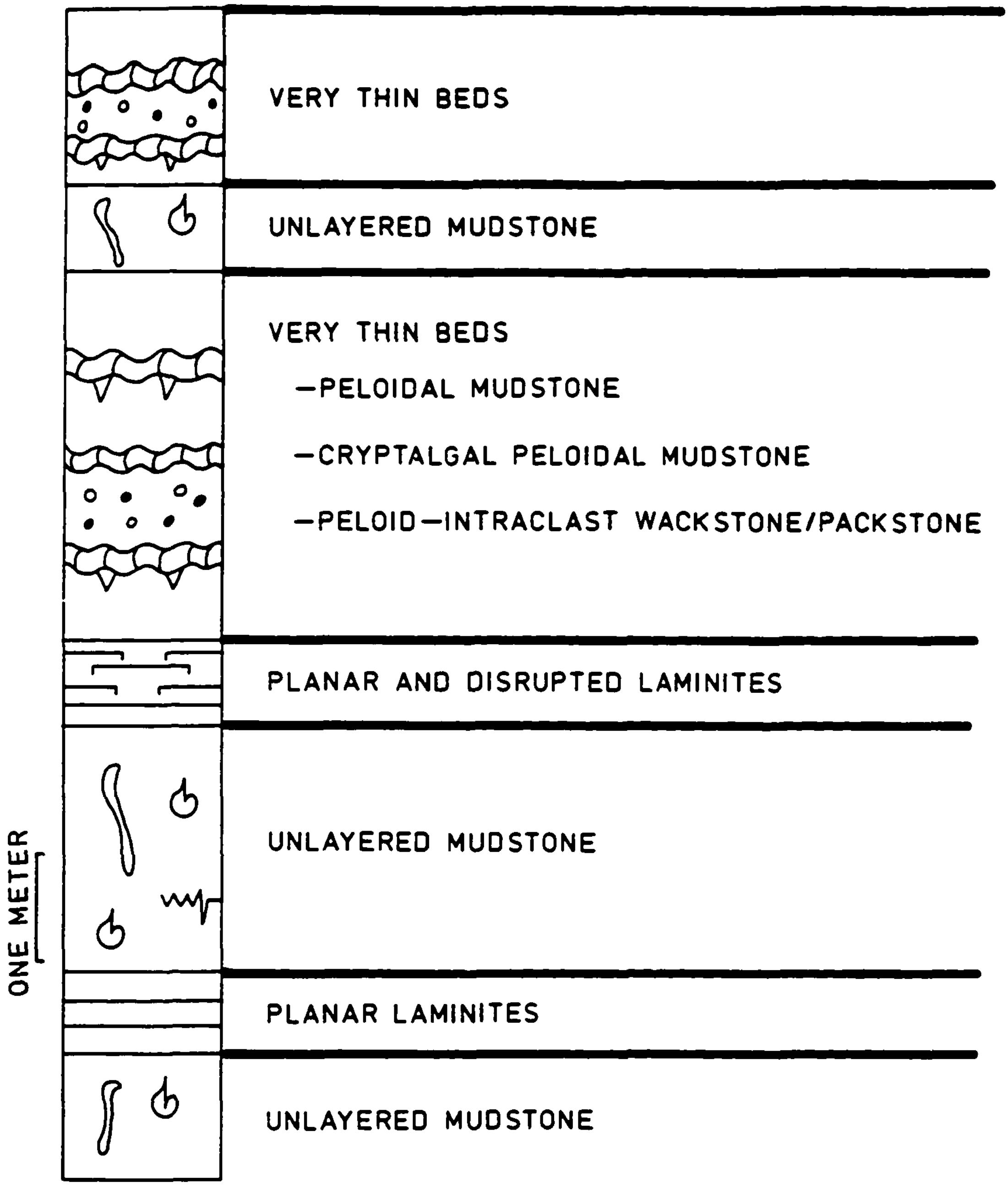

5

FIGURE 6. Schematic representation of 11 meters of Lithofacies I, at measured section No. 2, showing the rapid bed-to-bed variation of four subfacies and the close association of the Planar Laminates with the Disrupted Laminates. The Disrupted Laminates include the disrupted flat laminates and the disrupted dololaminates. See Appendix A for an explanation of the symbols.


VERY THIN BEDS
UNLAYERED MUDSTONE
VERY THIN BEDS
-PELOIDAL MUDSTONE
-CRYPTALGAL PELOIDAL MUDSTONE
-PELOID-INTRACLAST WACKSTONE/PACKSTONE
PLANAR AND DISRUPTED LAMINITES
UNLAYERED MUDSTONE
PLANAR LAMINITES
UNLAYERED MUDSTONE
ONE METER

To the north of the study area, Mitchell (1982) has documented a laminated facies in the St. Paul Group, similar to Lithofacies I in this paper. Subfacies, similar to those listed above, are described within his Laminated Facies II and IV. The Laminated Facies of the St. Paul Group contains additional facies and minor subfacies which were not seen in the New Market Limestone of northern Virginia. A laminated lithofacies does not crop out in the New Market Limestone of south and central Virginia (Grover and Read, 1978; Read, 1980).

a. Very Thinly Bedded Subfacies A

Description

The very thinly bedded subfacies occurs in beds of less than 30 cm to a meter thick. This subfacies is composed of thin beds to laminations of three distinct rock types: (1) peloidal mudstones; (2) cryptalgal peloidal mudstones; and (3) sand-to pebble-sized, peloid-intraclast wackestones/packstones. The very thinly bedded subfacies is the most abundant rock unit of the Laminated Lithofacies I.

(1) Peloidal Mudstones

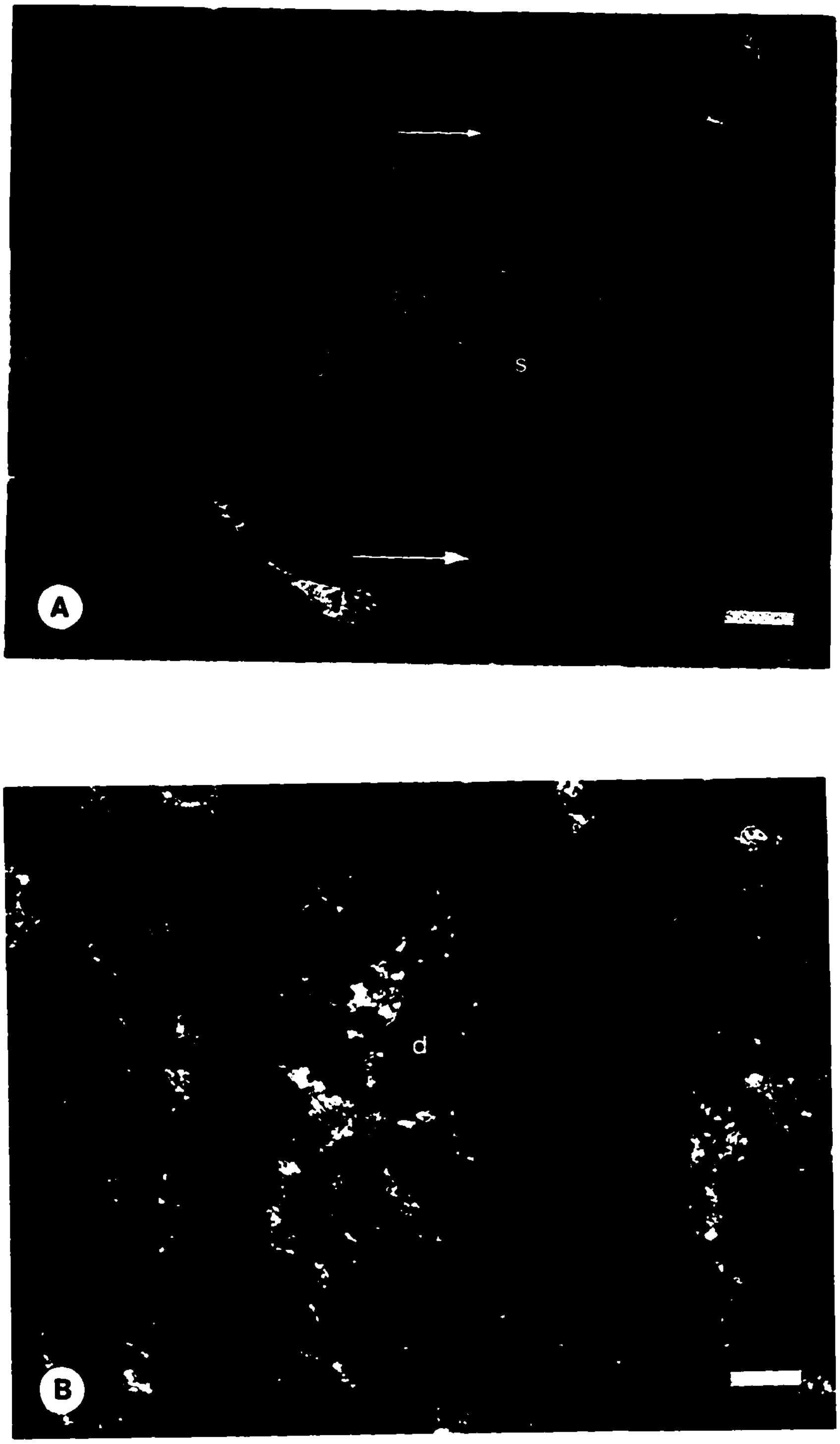
The peloidal mudstones consist of silt-to fine-sand mud peloids and lime mud in a clotted mudstone to wackestone fabric (Fig. 7). Other constituents are numerous, disseminated dolomite rhombs and rare rounded quartz grains. Finer dolomite rhombs occur in thin laminae between beds and in thin stylolitized seams within beds. These dolomitic partings and seams also contain thin, wavy, irregular and anostomosing bituminous films.

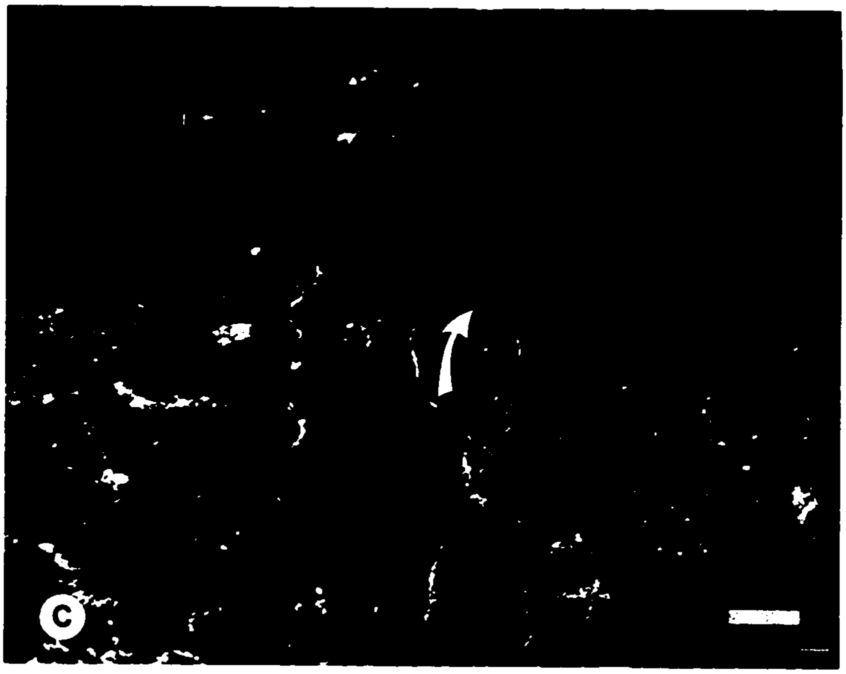
FIGURE 7. Photomicrographs of the New Market Limestone: Lithofacies I, very thinly bedded subfacies A -- peloidal mudstone.

A. Whole and fragmented ostracods with preserved shell structure. The articulated ostracod are floored with geopetal, crystal silt (s). Dolomite rhombs (arrows) are disseminated in the mudstone and geopetal silt and are concentrated along stylolitized seams. Irregular-to tubular-desiccation fenestrae (f) are filled with calcite spar. Scale bar: 0.2 mm.

B. Irregular fenestrae that are filled with calcite-spar (white). Irregular fenestra (center) is surrounded by a dolomitic halo (d). Scale bar: 2 mm.

C. Intraformational erosional surface (arrow) between peloidal mudstone (bottom) and disrupted dololaminates (top). The contact is irregular due to later stylolitization. Intraclasts (i) of peloidal mudstone are seen in the overlying unit. Scale bar: 1.3 mm.


s
A
d
B


C

The mudstones are generally unfossiliferous except for relatively rare, whole and fragmented fossils of leperditid ostracodes (Fig. 7A) and unidentified gastropods. Ostracodes are more common and generally are more abundant along the dolomitic seams and partings. Ostracode valves vary in length from 0.1 mm to 5.0 mm. The disarticulated valves which are convex-up often display shelter porosity that are filled with calcite-spar. Many of the articulated valves display geopetal fabrics (Fig. 7A). These whole fossils are floored by internal sediment of crystal silt or peloidal micrite with or without dolomite rhombs and are overlain by calcite-spar. Whole gastropods are generally filled with peloidal micrite: less commonly they display geopetal fabrics.

The peloidal mudstones contain relatively few disruption features including: fenestrae, solution features, and dissolution surfaces. The irregular fenestrae have complex shapes varying from very irregular, conical and subspherical. The conical-shaped irregular fenestrae resemble desiccation cracks (Fig. 7B; Tebbut et. al., 1965; Logan, 1974; Hardie and Ginsburg, 1977). The tops of these irregular fenestrae are often truncated by the stylotized dolomitic seams or by dissolution surfaces. Few samples display a "stylobrecciated fabric" (Flugel, 1982) where the stylotized seams cross the unit at angles that connect the spar-filled fenestrae. The irregular fenestrae are usually filled with calcite-spar; they rarely display geopetal fabrics or dolomitic halos (Fig. 7B).

Rare samples contain larger subspherical-shaped features which are believed to have formed by dissolution of gastropod tests. These solution molds are generally filled with calcite-spar. Spar-filled molds of whole ostracodes are also relatively common.

The third feature is dissolution surfaces or "intraformational erosional surfaces" (Fig. 7C; Read and Grover, 1977). In the field, intraformational erosional surfaces may be seen as a sharp contact between light gray mudstones and tan weathering dolomitic mudstones. These surfaces are generally planar and parallel to bedding. In slabs and acetate peels, they are slightly irregular due to stylolitization (Fig. 7C). The erosional surfaces truncate sediments and spar-filled fenestrae in the underlying peloidal mudstones. Intraclasts of lithified mudstone are seen in the overlying unit. These underlying peloidal mudstones are rarely mud-cracked at the erosion contact. Mud-cracks are filled with the overlying sediments and intraclasts of peloidal mudstone.

(2) Cryptalgal Peloidal Mudstones

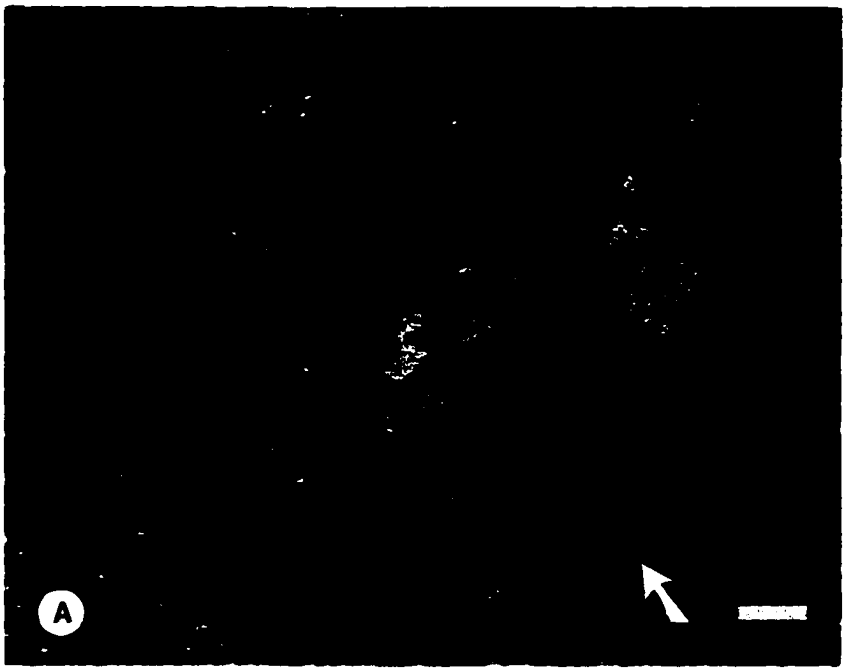
Cryptalgal peloidal mudstones consist of alternating laminae of lime mud and silt to fine-sand peloids (Figs. 8A and 8B). The mud laminae are composed of lime mud and mud peloids in a clotted mudstone fabric. These laminae are wavy to planar and continuous, ranging from 0.1 to 1 mm thick, and also occurring in rare thin beds of 1 cm or more. The peloidal laminae are composed of well-sorted, silt-sized mud peloids in a wackestone

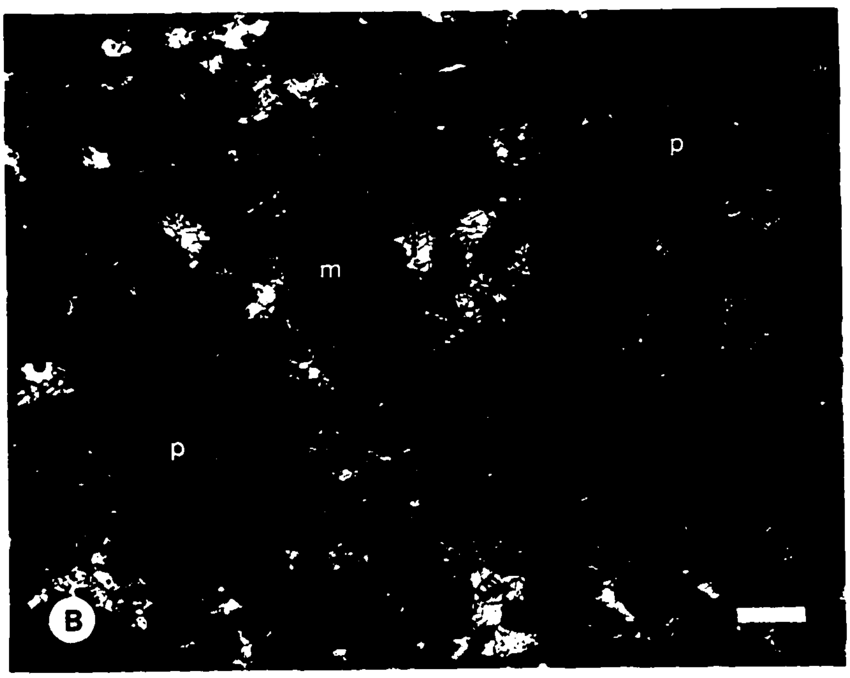
FIGURE 8. Photomicrographs of the New Market Limestone: Lithofacies I, very thinly bedded subfacies A -- cryptalgal peloidal mudstone.

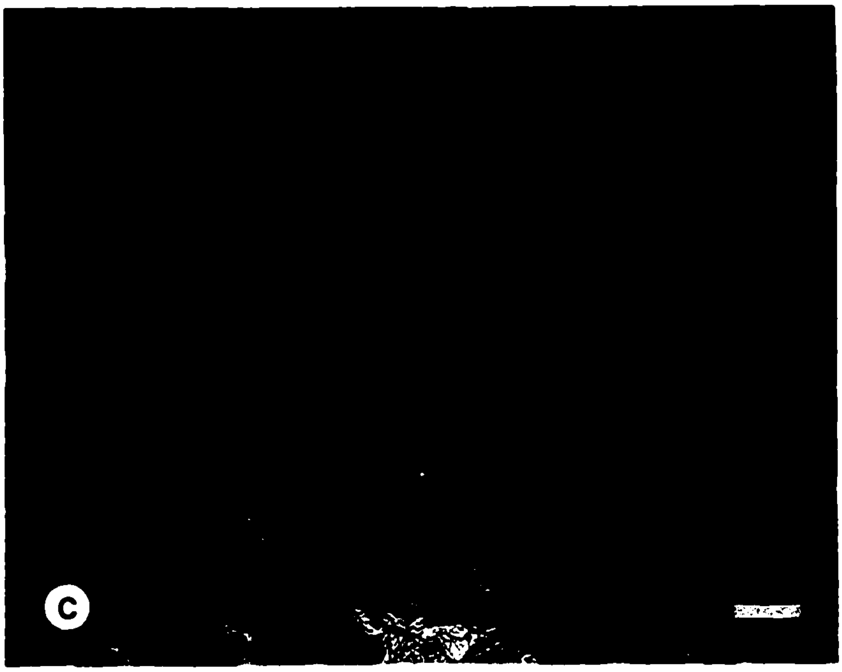
A. Cryptalgal peloidal mudstone consisting of alternating laminae of lime mud and peloids with thin, dolomitic, stylolitic seams (arrow). Large tubular fenestrae (center) that are filled with calcite-spar disrupt the laminae producing patches of homogenized mudstone. Scale bar: 1 mm.

B. Close-up of cryptalgal peloidal laminae. Micrite laminae (m) may contain subvertical, irregular-shaped, spar-filled fenestrae (i). The peloidal laminae (p) contain numerous irregular- and tubular-shaped fenestrae. Scale bar: 0.5 mm.

C. Cryptalgal peloidal laminae with laminoid (l) and irregular (i), calcite-spar filled fenestrae. These fenestrae may have formed by algal growth and decay or by dessication. Scale bar: 0.7 mm.


A


p
m
p
B


C

to packstone fabric. These laminae average about 1 mm in thickness. Rare beds of peloidal laminae are 1 to 1.5 cm thick and may contain low angle cross-beds. The peloidal laminae are generally capped by the dolomitic stylotized seams which contain thin bituminous films (Fig. 8A). These films, where they become more abundant, often exhibit an irregular anastomosing fabric between peloid grains. The cryptalgal beds may be disrupted, forming sand-sized intraclasts of peloidal mudstone in a wackestone to packstone fabric. Some clasts are coated with or surrounded by dolomitic sediment.

Various fenestral fabrics are found within this rock type. In general, the micrite laminae contain relatively few fenestrae. These consist of elongate, subvertical, irregular-shaped, spar-filled fenestrae (Fig. 8B). The irregular fenestrae are probably due to desiccation. Where these fenestrae cut across several laminae, they may indicate repeated exposure and desiccation during accumulation. The fenestrae are commonly more abundant within the peloidal laminae. These laminae contain numerous very fine irregular- and tubular-shaped fenestrae which appear to represent interparticle void space (Fig. 8B).

Other fenestrae include rare laminoid fenestrae as "sheet cracks" between laminae or within some of the dolomitic seams (Fig. 8C). Laminoid fenestrae are curved to planar in shape, and are oriented parallel or subparallel to bedding. Large tubular fenestrae (2 to 3 mm wide and 2 to 8 mm long) also disrupt the cryptalgal peloidal laminae producing patches of homogenized mudstone (Fig. 8A). These fenestrae support a burrow origin.

Ginsburg and Hardie (1977) show abundant burrows in recent Bahama tidal flat sediments that are exposed up to 70 percent of the time. Disrupted layers consist of a mixture of all the above fenestral fabrics with the exception of the "sheet cracks."

(3) Peloid-intraclast Wackestones/Packstones

The peloid-intraclast wackestone/packstones consist of poorly sorted silt-to sand-sized mud peloids and sand-to pebble-sized intraclasts of peloidal mudstone (Fig. 9A). This unit occurs as thin beds (averaging 5 cm thick) and wavy laminae. Intraparticle spaces are filled with calcite spar, geopetal fabric, and/or by thin irregular stylotized dolomitic seams with thin bituminous films (Fig. 9B). In some cases, intraclasts float in a dolomitic matrix. When the thin seams become more dense and continuous, they form dolomitic laminae with bituminous films.

A very restricted fauna of leperditid ostracodes, whole to fragmented, are found in both the cryptalgal peloidal mudstones and in the peloid-intraclast wackestones/packstones. These fossils often display features, such as the geopetal fabric and umbrella effect, identical to the peloid mudstones.

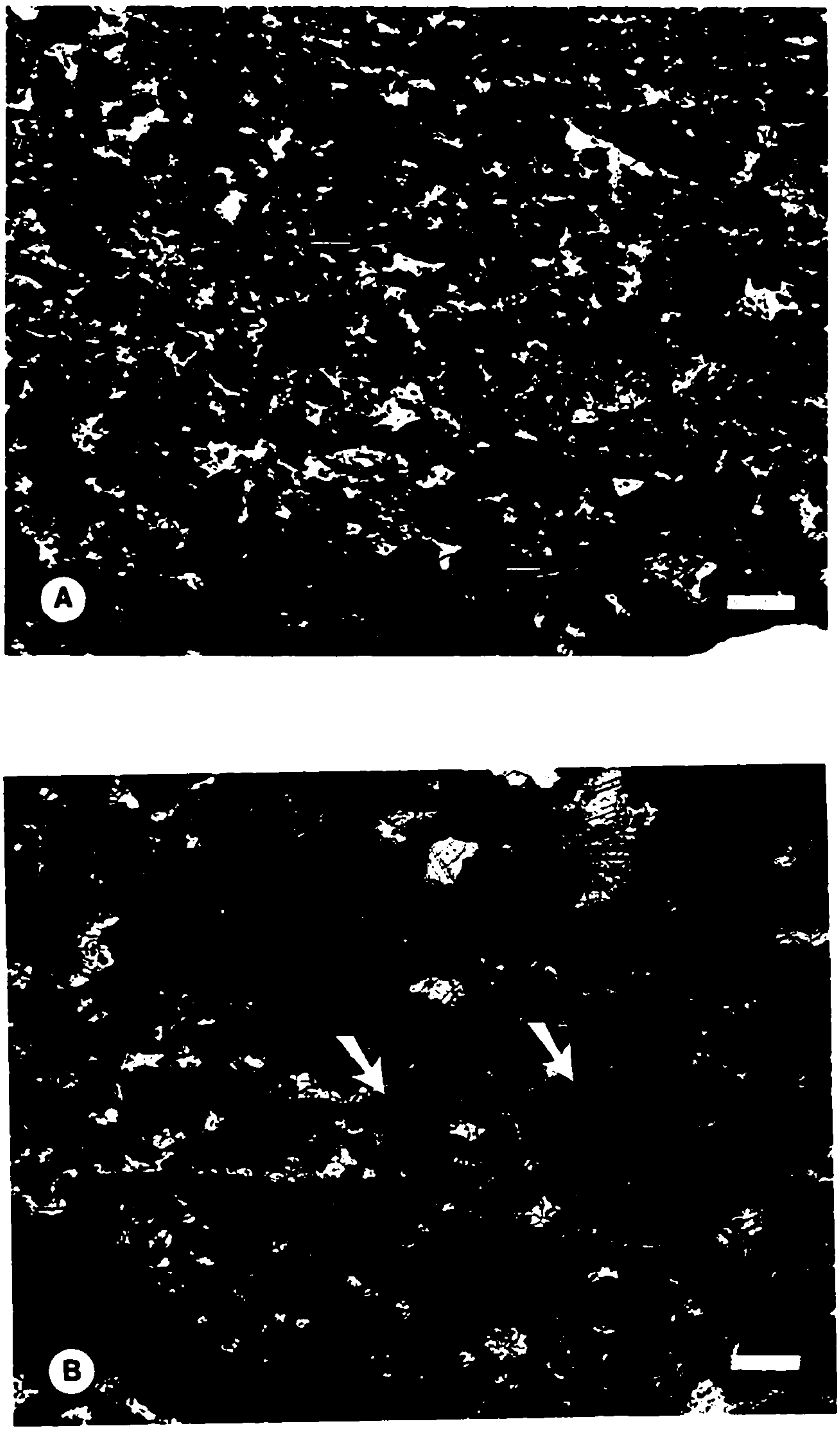
Interpretation

Mitchell (1982) described a very thin bedded subfacies in his Facies II and IV from the St. Paul Group which is similar to the very thinly bedded subfacies A in this paper. In Mitchell's interpretation of this subfacies, he suggests that the intricate interbedding of the three rock types indicate that the environment in which they formed

FIGURE 9. Photomicrographs of the New Market Limestone: Lithofacies I, very thinly bedded subfacies A-peloid-intraclast wackestone/packstone.

A. Peloid-intraclast wackestones/packstones consisting of poorly sorted silt- to sand-sized peloids (p) and sand-sized intraclasts (i) of peloidal mudstone. The interparticle spaces are filled with calcite-spar (white) and by dolomitic seams (arrow). Some peloids and intraclasts are coated with the dolomitic material (arrow). Scale bar: 1 mm.

B. The intraparticle spaces are in some cases floored by geopetal sediments (arrows). The remainder of the spaces are filled with calcite-spar (white). Scale bar: 1 mm.


A
B

was subjected to short-term variations in the parameters controlling deposition. Therefore, normal environmental conditions may be recorded by one or more of these rock types and more atypical conditions may have resulted in deposition of the remaining rock type(s).

The very thinly bedded subfacies A is interpreted to have been deposited in a tidal flat setting under a restricted environment that was not subjected to extensive subaerial exposure. This depositional setting is supported by the intricate interbedding of this subfacies with the mud-cracked laminated subfacies. Also, the restricted fauna and lack of bioturbation indicates that these sediments were not deposited in a normal marine subtidal setting.

The cryptalgal peloidal mudstones were formed under normal depositional conditions of relatively quiet, restricted, shallow water. The term cryptalgal, defined by Aitken (1967), is applied to rock structures and sediments that resulted from sediment-binding and/or carbonate precipitating activities of blue-green algae and bacteria. Cryptalgal laminates are known to occur in modern tidal flat environments (Monty and Hardie, 1976; Monty, 1976; Hardie and Ginsburg, 1977).

Minor thin disrupted layers contain sand- to pebble-sized intraclasts of the cryptalgal laminates in a wackestone to packstone fabric. These disrupted layers indicate that the depositional conditions were interrupted by short-lived events of current activity, perhaps due to storm events.

The peloid-intraclast wackestones/packstones were deposited under conditions similar to the disrupted layers discussed earlier. This rock type differs from Mitchell's (1982) coarse sand- to pebble-sized intraclast-skeletal packstones which contain bioclasts of a relatively diverse fauna. These bioclasts are found only in Mitchell's very thinly bedded subfacies implying that invertebrates did not live in this subenvironment. Using this criteria Mitchell suggested that the coarse packstones recorded short periods of strong currents which transported the bioclastic debris into this subenvironment.

Although current activity did not supply bioclastic debris to the peloid-intraclast beds in northern Virginia, they disrupted sediment layers and perhaps supplied additional lithoclasts to the subenvironment. The lack of bioclasts may be due, in part, to a lower current energy or lack of a bioclastic source. These thin peloid-intraclast layers may be produced during minor storms (equivalent to daily thunderstorms). This type of deposition is known to occur in the intertidal areas of modern marine algal environments (Logan, 1961; Logan et al., 1964; Shinn, 1983). The clasts generated from these storms would have consisted primarily of poorly sorted local material and would have been randomly packed.

The origin of the peloidal mud sediment is a difficult question to answer because these sediments contain little information about the depositional conditions. Mitchell (1982) proposed the possibility of direct precipitation as the origin of these homogeneous muds. Direct precipitation has been reported in algal tufas from modern terrestrial settings in fresh and saline waters. See Hardie (1977) for a review of literature on algal tufa.

Intraformational erosion surfaces are observed at the top of some peloidal mudstone layers (Fig. 7C). These surfaces truncate the sediment and cements of the mudstone layer and lithified, reworked intraclasts of mudstone are found in the overlying sediments. Similar intraclasts are seen elsewhere (Read and Grover, 1977; Grover and Read, 1978; Mitchell, 1982). These features indicate that the peloidal muds were lithified prior to deposition of the overlying sediments. The sediments surrounding these erosion surfaces are from laterally contiguous depositional subenvironments of the tidal flat environment. These erosion surfaces probably resulted from emergence, early lithification, mud-cracking and desiccation of peritidal sediments followed by limited erosion and deposition of overlying sediments during storm washovers (Grover and Read, 1978). The intraformational surfaces are similar to the interformational erosional surface developed at the top of the New Market Unlayered Mudstone Lithofacies II, except that the former are overlain by more open marine sediments.

These thinly bedded mudstones contain a few features indicative of subaerial exposure such as desiccation fenestrae, rare solution features, and dissolution surfaces. These criteria and the intricate interbedding of the three rock types of subfacies A, suggest a similar depositional setting. Therefore, the depositional environment of the peloidal muds, based on sedimentologic evidence such as fenestrae, solution features and dissolution surfaces, is considered to be a shallow restricted environment with evidence of periodic emergence and little current or wave activity.

In summary, the sediment of the very thinly bedded subfacies are interpreted to have been deposited in a restricted, shallow water environment. Depositional conditions were normally quiet but were subjected to short, infrequent periods of current activity, perhaps storm events. The currents disrupted the cryptalgal peloidal mudstones and deposited the peloid-intraclast beds. The sediments contain a few features which indicate infrequent subaerial exposure, such as desiccation fenestrae and mud cracks. Infrequent exposure suggests that these sediments were not deposited in a normal, mud-cracked supratidal or intertidal environment. Algal growth is believed to be responsible for some of the layering features seen in this subfacies, based on similar layering observed in modern Bahamian sediments (Hardie and Ginsburg, 1975).

Modern Bahamian Analog

Laminated to thinly bedded sediments, similar to the very thinly bedded subfacies A of northern Virginia, are seen on the northwestern coastal belt of Andros Island (Shinn et al., 1969; Monty and Hardie, 1976; Monty, 1976; Hardie and Ginsburg, 1977). The thinly bedded sediments of Andros Island are currently being deposited in a coastal and inland freshwater algal marsh subenvironment bordered on the seaward side by mud-cracked tidal flat laminates. Hardie and Ginsburg report that thin bedding is the most abundant style of layering being deposited at Three Creeks area of northwest Andros Island. The layering varies vertically and laterally and thinner layers commonly pinch out (Shinn et al., 1969)

The deposits consist of alternating layers of algal tufa and carbonate sediment. The carbonate sediment layers are composed of lime mud and mud peloids. The sediment layers are of two types: (1) dense, clotted mud layers which contain peloids and scattered bioclasts of foraminifera and gastropods; and (2) well-sorted peloidal packstone to grainstone layers with similar whole to fragmented bioclasts. The sediment layers have a thin "paper crust" cap of dense aragonitic mud which is commonly fragmented. Many of the sediment layers are disrupted by desiccation cracks and root holes. These fragmented sediment layers occur as discontinuous layers or pockets of flat-pebble conglomerates.

The algal tufa is composed of fragile molds of Scytonema algal filaments and lime mud. The molds are 10 to 20 microns wide and filled with high magnesium calcite crystals. In situ carbonate precipitation appears to have occurred around the algal filaments. The metabolism of the Scytonema colony and/or the bacterial decay of the filaments may have nucleated the carbonate precipitation (Hardie and Ginsburg, 1977). Compaction and decomposition of the algal filaments destroys the tufa structure, leaving a generally structureless mudstone.

In summary, the Andros Island coastal freshwater algal marsh deposits contain alternating thin beds and laminae which are comprised of three units: (1) well sorted peloidal sediment and mud layers with bioclastic debris and flat-pebbles, (2) carbonate mud with remnants of algal tufa, and (3) thin aragonitic crusts. The tufa layers record several years of Scytonema growth. Precipitation of calcite microspar occurs upon burial. The growth of tufa layers is interrupted by storm layers of peloidal mud which contain lithified clasts of the underlying unit. After subsidence of flood waters the surface is covered with a Schizothrix mat. Calcification of this mat produces the aragonitic thin crust. Eventually, the surface is recolonized by Scytonema and the cycle is repeated.

The very thinly bedded subfacies of the New Market Limestone, northern Virginia is remarkably similar to the coastal and inland freshwater algal marshes of northern Andros Island. The similarities in layering style, sediment type, and faunal diversity of these deposits suggest similar depositional conditions. This analog is further supported by the interbedding of this subfacies with the laminated subfacies. The levee deposits of Andros Island are located seaward of the freshwater algal marsh and are characterized by mud cracked, laminated sediments.

b. Thinly Bedded Mudstone Subfacies B

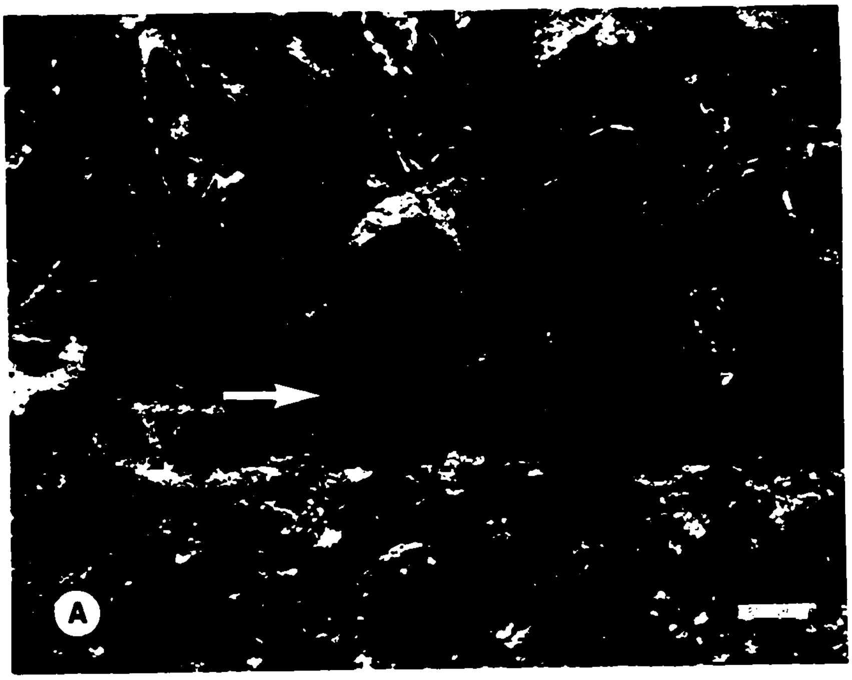
Description

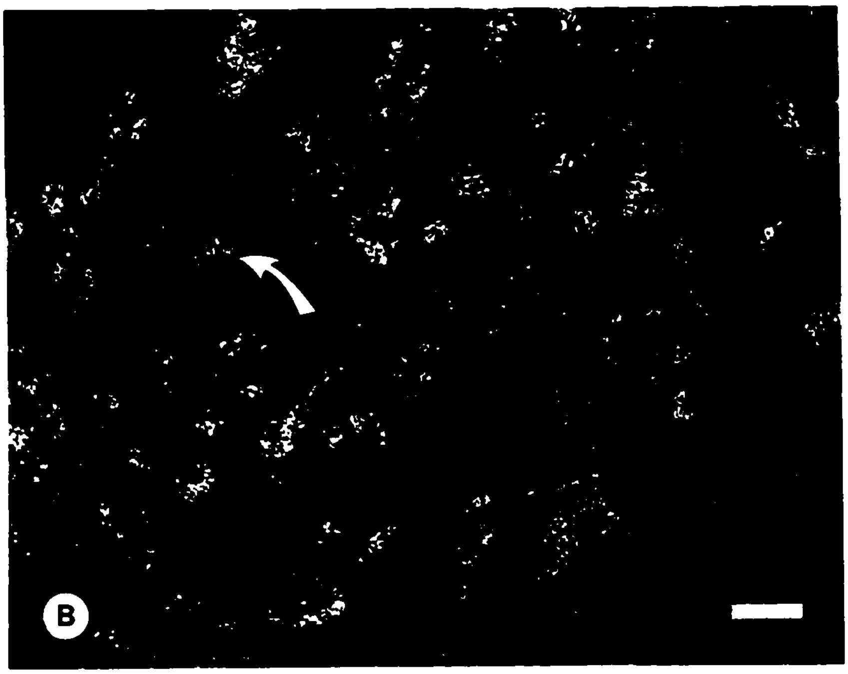
The thinly bedded mudstone subfacies is composed of peloidal mudstones to wackestones with patches or lenses of packstones (Fig. 10A). The sediment consist of lime mud, silt- to sand-sized mud peloids and up to 15 percent bioclasts. The bioclastic fraction of this subfacies varies from unit to unit in quantity and diversity of identifiable fossil debris. Generally, these beds have a very restricted fauna of whole to fragmented ostracodes or gastropods. The ostrocod valves are scattered throughout or occur as packstones in thin (up to 1 cm thick) laminae (Fig. 10A).

FIGURE 10. Photomicrographs of the New Market Limestone: Lithofacies I, thinly bedded mudstone subfacies B.

A. Thinly bedded mudstone subfacies with thin bioclastic packstone laminae (center). The bioclasts are thin-shelled molds of what are believed to be ostracode fragments (arrow). Scale bar: 0.8 mm.

B. Thinly bedded mudstone with randomly oriented, spar-filled molds of the Tetradium sp. schizocoral. In transverse section these molds are square- to rhombohedral- or subspherically shaped (arrow). Scale bar: 1 mm.





A few beds have a more diverse faunal assemblage including: ostracodes, gastropods, bryozoans, pelmatazoans, trilobites, and the schizocoral, Tetradium sp. These corals are often preserved as randomly oriented, spar-filled molds which have straight sides and are tubular-shaped. They are up to 12 mm long, 2 to 3 mm wide and are square-to rhombohedral- or subspherical-shaped in transverse sections (Fig. 10B). These larger tubular spar-filled molds may be mistaken for fenestrae although some display remnant shell structure. Most of the bioclasts occur as spar-filled molds, others have been neomorphically replaced with spar.

The thinly bedded mudstone, in field outcrop, is compact and bedding is generally not determinable. In polished slabs and acetate peels an apparent bedding is suggested by thin wavy shell hash beds (Fig. 10A) or by bedding parallel, dolomitized stylolite seams. In some samples the stylotized seams coalesce and bifurcate. The homogeneous nature of this subfacies is presumably due to bioturbation. Some tubular-shaped, spar-filled fenestrae may be remnant burrows. These tubular-shaped fenestrae are seen in beds which contain little fossil remains or a restricted marine fauna of ostracodes.

Interpretation

The thinly bedded mudstone subfacies of the New Market Limestone in northern Virginia is similar to the unlayered micrite subfacies described by Mitchell (1982) of the St. Paul Group to the north. Both subfacies lack primary layering and evidence of subaerial exposure. They both contain tubular-shaped fenestrae believed to be formed by burrowing organisms. These features suggest that the thinly bedded mudstones were deposited in the subtidal environment. The sediments are muddy and poorly sorted indicating little or no mechanical reworking. These sedimentologic characteristics along with interbedding of this subfacies with the very thinly bedded and laminated subfacies, indicate deposition in a shallow restricted, subtidal environment adjacent to sediments of intertidal and supratidal areas.

Modern Bahamian Analog

The subtidal deposits of Andros Island resemble the thinly bedded mudstones of Lithofacies 1. These sediments consist of subtidal, bioturbated, peloidal aragonite mud with no internal layering (Shinn et al., 1969; Hardie and Ginsburg, 1977). At Three Creeks, these muds occur in the shelf lagoon, tidal pond and subtidal channel bars. Tidal pond and channel sediment usually can not be distinguished except where channel deposits display cross-bedding. The pond and channel deposits usually contain a restricted fauna of low diversity. Garret (1977) reported two gastropod species, a bivalve and a foraminifer in these deposits. The characteristic which distinguishes the pond and channel deposits from the shelf lagoon deposits is the higher degree of faunal diversity in the shelf lagoon deposits.

c. Planar Laminates Subfacies C

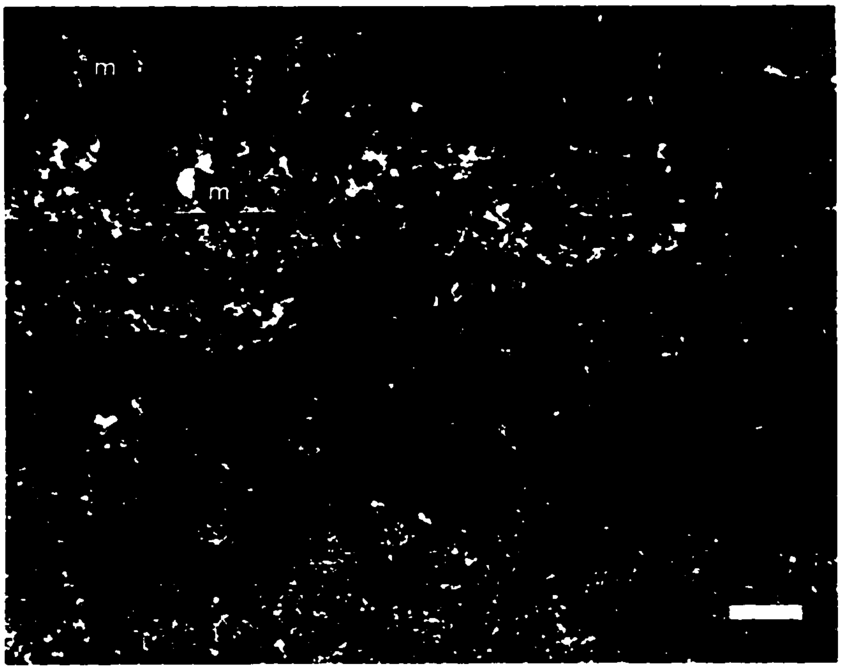
Description

Planar laminates, in field outcrops and slabs, are composed of alternating laminae of relatively uniform lime mud and of more discontinuous peloidal laminae (Fig. 11). These laminae weather to a light gray and medium gray color, respectively, and range from 1 mm to 3 mm thick. Between the laminae there are dolomitic stylotized seams which weather to a very pale orange. Planar laminates are generally unbioturbated although some horizons are disrupted.

The peloidal laminae, in acetate peel, are composed of generally well-sorted mud peloids and disseminated dolomite rhombs in a wackestone to packstone fabric. Many of these laminae are lenticular in shape and pinch out against the mud laminae. Many laminae contain stylolized bituminous seams (possibly algal mat remnants) along which the dolomite rhombs are concentrated. Where the dolomitic laminae become more dense they form laminae of mud peloids, dolomite rhombs and thin discontinuous bituminous films. Rare sheet cracks are associated with these laminae. The intraparticle spaces within the peloidal laminae are generally filled with calcite-spar or the stylotized dolomitic seams. These dolomitic seams are also seen at the top of mud laminae.

The mud laminae are more continuous laterally than the peloidal and are laminae isopachous. They consist of lime mud, disseminated dolomite rhombs, scattered, discontinuous, dolomitized, bituminous films and irregular to tubular fenestrae. The small irregular-shaped, spar-filled fenestrae resemble desiccation cracks. The very fine tubular-shaped fenestrae that are filled with microspar may represent algal filament molds. The tops of the mud laminae are generally sharp and are usually marked by dolomitic seams. Boundaries between the peloidal and mud laminae are more gradational and are not always separated by the dolomitic seams.

FIGURE 11. Photomicrographs of the New Market Limestone: Lithofacies I, planar laminate subfacies C. This subfacies consists of alternating laminae of relatively uniform lime mud (m) and more discontinuous peloidal laminae (p). Usually the mudstone laminae are capped by thin, stylolitized, dolomitic seams (dark horizontal layers). Scale bar: 1 mm.


m
m

Whole to fragmented ostracodes are the only observed fossils preserved in subfacies C. They are commonly associated with the dolomitic seams and display shelter geopetal features.

Interpretation

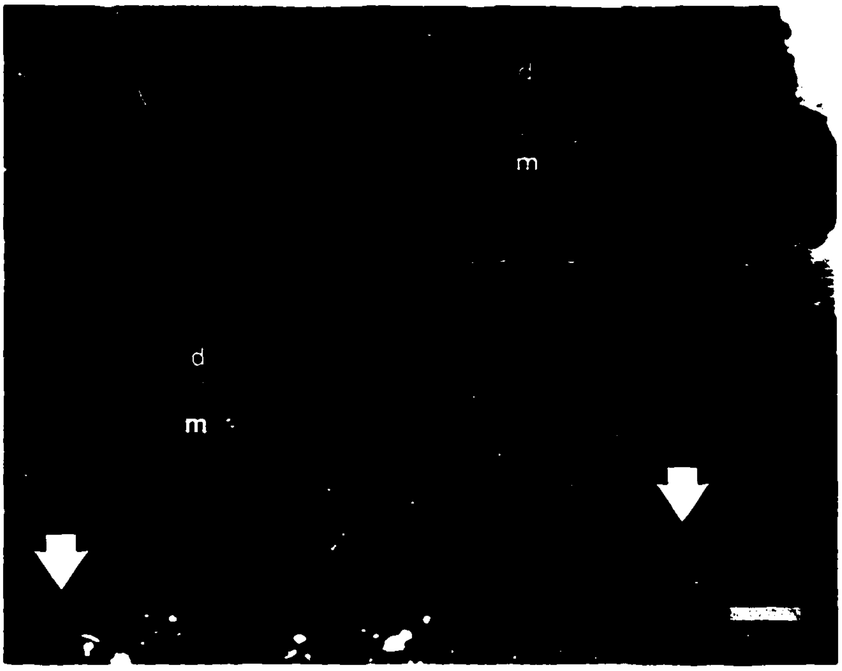
The absence of marine fauna and bioturbation indicates a very restricted environment. Irregular-shaped fenestrae which resemble desiccation cracks indicate that the planar laminates were subjected to periods of subaerial exposure. The planar laminates are interpreted to have formed in a tidal flat setting, under a restricted environment which was subjected to periods of subaerial exposure. Deposition in a tidal flat subenvironment is supported by the interbedding of the planar laminates with other disrupted laminates of similar, laterally contiguous subenvironments. Such uniform planar laminated sediments have been described by Mitchell (1982) in Facies II and IV of the St. Paul Group. Planar laminated sediments have been observed on the levee crest subenvironment of Andros Island by Hardie and Ginsburg (1977).

d. Disrupted Flat Laminates Subfacies D

Description

The disrupted flat laminated subfacies make-up only a small percentage of Lithofacies I. Laminae of this subfacies vary in thickness from a few millimeters up to 1 cm. The laminae consist of disrupted peloidal mudstones interlaminated with (or floating as intraclasts within) coarse dolomitic silt laminae (Fig. 12).

FIGURE 12. Photomicrographs of the New Market Limestone: Lithofacies I, disrupted flat laminates Subfacies D. This subfacies consists of disrupted peloidal mudstones (m, light colored) interlaminated with or floating as intraclasts in coarse dolomitic silt laminae (d, dark colored). The disrupted beds are believed to be due to burrowing organisms. A thin bed of intraformational flat-pebble breccia is located at the base (arrow). This disrupted bed is believed to have been produced by burrowing organisms, producing pseudobreccias. Scale bar: 6 mm.


d
m
d
m

The coarser laminae are composed of mud peloids, coarse dolomitic rhombs, thin bituminous films, and rare rounded quartz grains. These coarse laminae are generally continuous, but the coarse silt also fills in scours, mud-cracks, burrows and depressions in the mudstone laminae and act as a matrix to the peloidal mud intraclasts (Fig. 12). The peloidal mudstones are composed of very fine mud peloids and scattered fine dolomitic rhombs in a clotted mudstone to wackestone fabric. The mudstone laminae are usually capped by a more dense mudstone. These alternating laminae show a general progression from coarse laminae to a dense mudstone cap followed by a composite mudstone layer.

The mudstone laminae have a few very fine, spar-filled, tubular- to irregular-shaped fenestrae. Most fenestrae are subvertically oriented. Many of the mudstone laminae are disrupted by mud-cracks. The mud-cracks generally start along laminae indicating frequent exposure. Mud-cracks are filled with the same material which comprises the coarse dolomitic laminae and often contain small intraclasts of the mud laminae. Rarely, these mud-cracked laminae are ripped up forming intraformational flat pebble conglomerates with a coarse dolomitic silt matrix.

Some laminae are highly disrupted and give the unit a mottled and mixed appearance. These disruptions are believed to be the product of burrowing organisms. The burrows are filled with coarse dolomitic silt. Some disrupted laminae appear to be thin beds of intraformational flat pebble breccias (Fig. 12). These disrupted layers have flat bases and irregular tops and the intraclasts are horizontally oriented. Many of the mud intraclasts are oriented parallel to the layering and appear to be continuous with undisrupted layers. These intraclasts are floating in a coarse dolomitic silt matrix. Similar types of disrupted beds have been described by Mitchell (1982) for the Laminated Facies II and IV of the St. Paul Group. Mitchell suggested that these disrupted laminae are produced by horizontal mining invertebrates or may represent "pseudobreccias." These burrowing organisms follow the sediment layers rather than cross-cutting them. The preserved fossils in this subfacies are rare whole-bodied to fragmented ostracodes. These ostracodes often display geopetal fabrics and shelter features.

Interpretation

The two different types of laminae are thought to have formed in two distinct ways. The mudstone laminae are believed to be cryptalgal. This interpretation is supported by the very fine, tubular- to irregular-shaped, spar-filled fenestrae which may represent algal filament molds. Also, these isopachous continuous mudstone laminae are similar to the peloidal mudstones of the very thinly bedded subfacies which are believed to be controlled by algal growth.

The coarser dclomitic laminae are less continuous and are deposited in mud-cracks, burrows, and scours, and provide a matrix for the flat pebble conglomerates. These intraformational flat pebble conglomerates indicate that currents were periodically strong enough to rip-up the mudstone laminae. A few of the mudstone intraclasts appear curved. This curvature indicates that the mudstone laminae were flexible which supports a cryptalgal origin.

The mudstone laminae were deposited in an environment which was normally quiet, and were often subjected to subaerial exposure. These conditions alternated with short periods of current activity which deposited the coarse dolomitic laminae and formed the flat pebble conglomerates. These conditions have been found in the modern upper intertidal to supratidal environments of tidal flats.

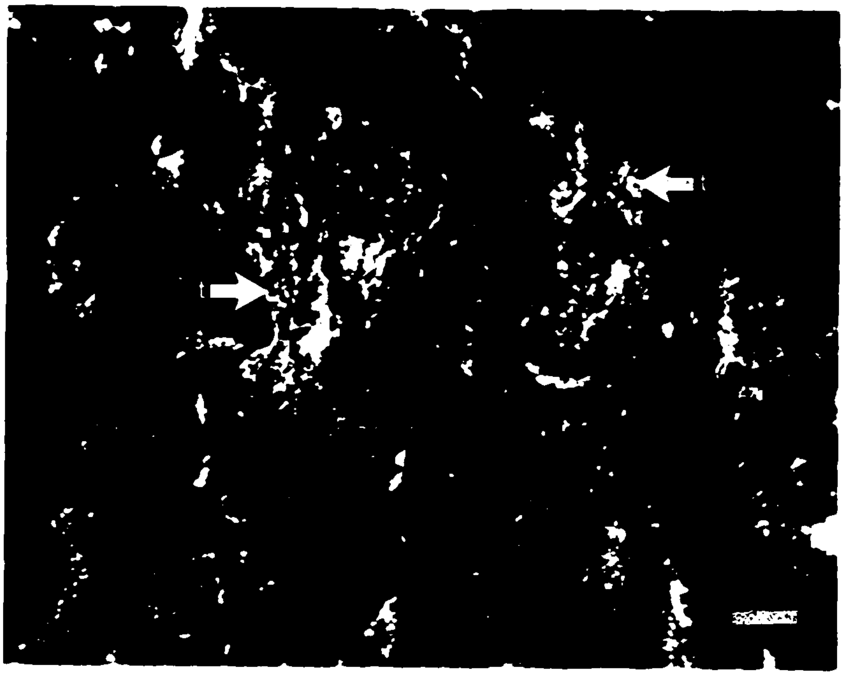
e. Disrupted Dololaminates Subfacies E

Description

The small-scale structures and fabric of the disrupted dololaminate subfacies are not readily visible due to recrystallization of the constituent particles. If the laminae are visible they are flat to wavy with apparent mud- and sheet-cracks that are visible in stained acetate peels. This subfacies is comprised mostly of abundant, very fine, anhedral to cryptocrystalline dolomite crystals, and euhedral dolomite rhombs, ranging from 0.01 to 0.12 mm.

Other minor constituents include mud peloids and thin bituminous films which anastomose around peloids and dolomite rhombs. Some samples contain a few sand-sized intraclasts of lime mudstone similar to the peloidal mudstones of the very thinly bedded subfacies which in some cases lies below subfacies E. The contact between these two subfacies (in samples collected) is marked by an "intraformational erosion surface" (Fig. 7C; Read and Grover, 1977). A few samples contain branching and anastomosing spar-filled fenestrae that contain abundant inclusions and dolomite rhombs (Fig. 13). These fenestrae may represent remnants of algal tufa. The only fossils preserved in this rock type are rare whole-bodied to fragmented ostracodes. In the

FIGURE 13. Photomicrographs of the New Market Limestone: Lithofacies I, disrupted dololaminates subfacies E. This disrupted dololaminate sample contains branching and anastomosing fenestrae that may represent algal tufa (t). These fenestrae are filled with calcite-spar or micrite. Scale bar: 0.4 mm.



field, exposures of this subfacies generally weather to a pale yellowish brown color but may also weather to a light- to medium light-gray. When the subfacie weathers to a gray color, it may be mistaken for a massive lime mudstone.

Interpretation

The disrupted dololaminates lack diagnostic environmental indicators. These laminates, however, are apparently mud-cracked and lack a normal marine fauna suggesting that they were deposited in a restricted intertidal to supratidal environment. The interbedding of Subfacies E with other disrupted laminates, thought to have formed on supratidal algal flats, suggests a similar origin for the disrupted dololaminates. Mitchell (1982) described a similar disrupted dololaminite subfacies of Facies II and IV of the St. Paul Group.

Bahamian Analog for the Laminated Subfacies of Lithofacies I

Layering similar to that of the New Market Limestone in northern Virginia is reportedly being formed on levees of the tidal flats of northwest Andros Island. The levees are part of the channeled belt system which lies between the shoreline and the inland algal marshes (Fig. 14). The subenvironments of the channel belt system include: (1) channel and pond (described earlier), (2) levee crest, (3) levee backslope, (4) high algal marsh, and (5) low algal marsh (Fig. 15). The subenvironments (excluding the pond subenvironment) are defined by the morphology of the algal mat covering the surface, disruption features and desiccation features. Each of these subenvironments contain algally laminated sediments with distinctive sedimentary

FIGURE 14. Schematic drawing of the environments on the northwest side of Andros Island. Shown are the marine, channelled belt (levee, algal marsh, and pond), inland algal marsh, and freshwater lake environments. From Hardie and Ginsburg (1977).

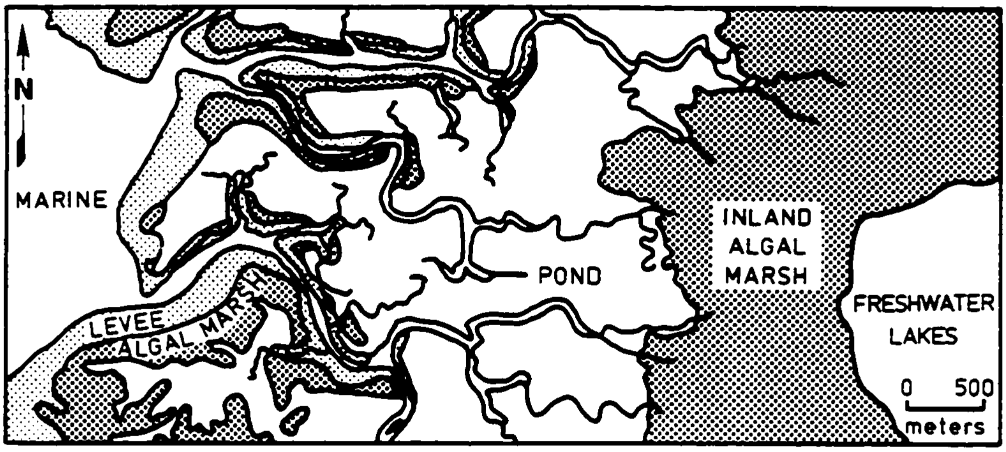
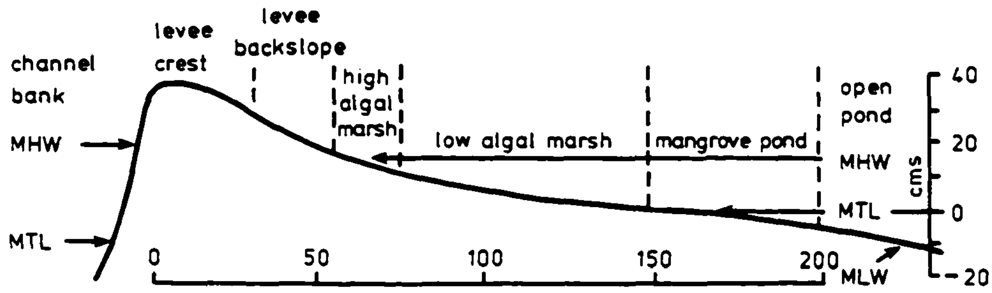
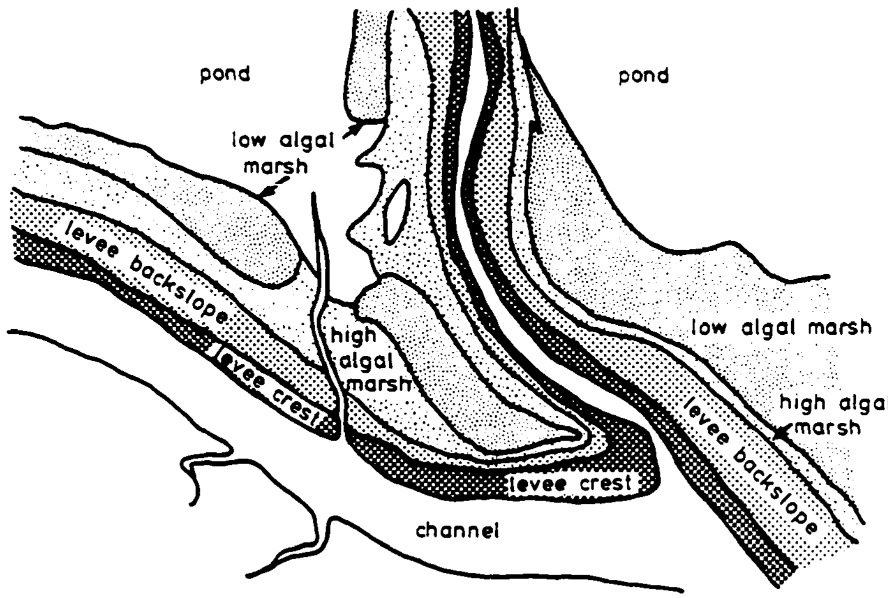

N
MARINE
LEVEE
ALGAL MARSH
POND
INLAND
ALGAL
MARSH
FRESHWATER
LAKES
0 500
meters

FIGURE 15A. Cross section through a levee of Andros Island, Bahamas, showing the characteristic distribution of the subenvironments. Vertical exaggeration 100. From Hardie and Ginsburg (1977).

B. Map of the subenvironments in a portion of the channeled belt of the tidal flats of northwest Andros Island. From Hardie and Ginsburg (1977).


levee
levee
backslope
channel
bank
crest
high
algal
marsh
open
pond
low algal marsh
mangrove pond
MHW
MHW
MTL
MTL
MLW
cms
40
20
0
-20
0
50
100
150
200
Meters

A.


pond
pond
low algal
marsh
levee backslope
levee crest
high
algal
marsh
levee crest
channel
low algal marsh
high algal
marsh
levee backslope

B.

structures and fabrics. The following descriptions of the algally layered sediments of the channeled belt system are taken from Shinn et al. (1969) and Hardie and Ginsburg (1977).

Smooth, flat laminations are found on the surfaces of levee crests and channel bar subenvironments of the Andros Island tidal flats (Hardie and Ginsburg 1977). The laminae, 0.1 to 2 mm thick, are characterized by laminae of mud alternating with laminae of peloidal sand. The peloidal laminae consist of well-sorted, silt- to fine-sand peloids with some abraded bioclasts. These laminae are discontinuous forming lenticular sand-filled depressions or starved ripples. The uniform mud laminae consist of mud and various amounts of suspended peloids and bioclasts. These laminae commonly contain filament molds in the form of tubular voids. The tops of the mud laminae are marked by a thin dense layer or "cap" of algal crust similar to those discussed under the disrupted flat laminated subfacies. The planar laminates are rarely mud-cracked. These alternating uniform mud and peloidal laminae may have formed by mechanical deposition of peloidal layers and by agglutination of mud-sediment to a sticky algal surface.

The smooth, flat laminated sediments of the levee crest and channel bar subenvironments of Andros Island tidal flats resemble the planar laminates of Lithofacies I in northern Virginia. Similar characteristics, including the sediment type, style of layering, disrupted features and the close association with other laminated sediments, support a cryptalgal origin of the planar laminates and deposition in a subenvironment similar to the levee crest of Andros Island.

The disrupted flat laminates from the levee backslope subenvironment of tidal flats of Andros Island (Hardie and Ginsburg, 1977) are similar to the disrupted flat laminated subfacies of the Middle Ordovician New Market Limestone. These disrupted flat laminates have the following characteristics in common: (1) the laminae alternate from discontinuous peloidal laminae to composite mud laminae with dense caps; (2) mud-cracking is common, which results in the concentration of mud intraclasts in pockets or as beds of flat pebble conglomerates; (3) deposition of the mud laminae is algally controlled; and (4) horizontal "mining" invertebrate disrupt laminae forming "pseudobreccias."

Basically, the blue-green algae Schizothrix inhabit the levee crest and levee backslopes. During storms these subenvironments are covered by muddy waters. The sticky algal mat formed by Schizothrix selectively traps the fine suspended sediments. Once the algal mat is choked with sediment, the mat is no longer able to trap sediment. As the storm continues, coarser sediments are washed over the levee crests and deposited as bed loads. These processes result in thin uniform mud laminae overlain by coarser peloidal laminae and lenses. No more fine mud sediments may be trapped until the algae have recolonized the surface, which can occur in 12 to 24 hours (Mitchell, 1982). The cohesiveness of the algal mats generally prohibits mud-cracking even though it is exposed 99 percent of the time (Hardie and Ginsburg, 1977).

In summary, the layering of the levees of the channeled belt system on Andros Island form during storm washover. The style of layering developed is dependent on the type of algae which inhabit the subenvironments. Because of the similarities between these modern laminated carbonates and the laminated subfacies of the New Market Limestone in northern Virginia, these older deposits most likely formed under similar conditions.

2. Lithofacies II: Unlayered Mudstones

Description

The unlayered mudstones consist of homogeneous, structureless, relatively pure limestone. These mudstones are generally massively bedded with no visible textural layering. An apparent bedding is suggested by abundant bedding parallel stylolites.

Lithofacies II consists of clotted lime mud, mud peloids and bioclasts with a mudstone, wackestone and, less commonly, packstone fabric (Fig. 16A). Whole to fragmented bioclasts are commonly numerous and relatively diverse. The bioclasts comprise up to 15 percent of the sediment.

The most common fossil is the schizocoral *Tetradium* sp. (Cooper and Cooper, 1946). Other bioclasts include: ostracodes, gastropods, brachiopods, trilobites, bryozoans and palmatazoans. Many bioclasts are preserved as calcite spar with and without preserved shell structure. Some samples contain large, subvertically or randomly oriented, tubular-shaped, spar-filled features that vary from 2 to 3 mm in diameter and 9 to 12 mm long. In cross section these features are tetragonal to subspherical, with well-rounded to irregular corners (Figs. 16A and 16B). These features are believed to be molds of the *Tetradium* corals. Original shell structure is rarely preserved. Few

FIGURE 16. Photomicrographs of the New Market Limestone: Lithofacies II, Unlayered Mudstone.

A. Lithofacies II consists of clotted lime mud (dark), peloids (p), and molds of bioclasts (white) in a wackestone fabric. The molds of bioclasts are the schizocoral *Tetradium* sp.. Shell-structure is partially preserved for a few bioclasts (s). Geopetal sediments floor several molds (g). The molds are filled with fine (f)- to coarse (c)-equant or two-generation equant and void-filling equant (v) cementation patterns. Scale bar: 0.67 mm.

B. Molds of bioclasts (b) that are believed to be the *Tetradium* sp. schizocoral are in some cases floored with geopetal crystal silt (g) and the remainder of the void and the other molds are filled with two generations of fine (f)- and coarse (c)-equant cements. Scale bar: 1 mm.

C. The unlayered mudstone at measured section No. 1 is a burrowed and bioturbated mudstone to wackestone. Scale bar: 1 mm.

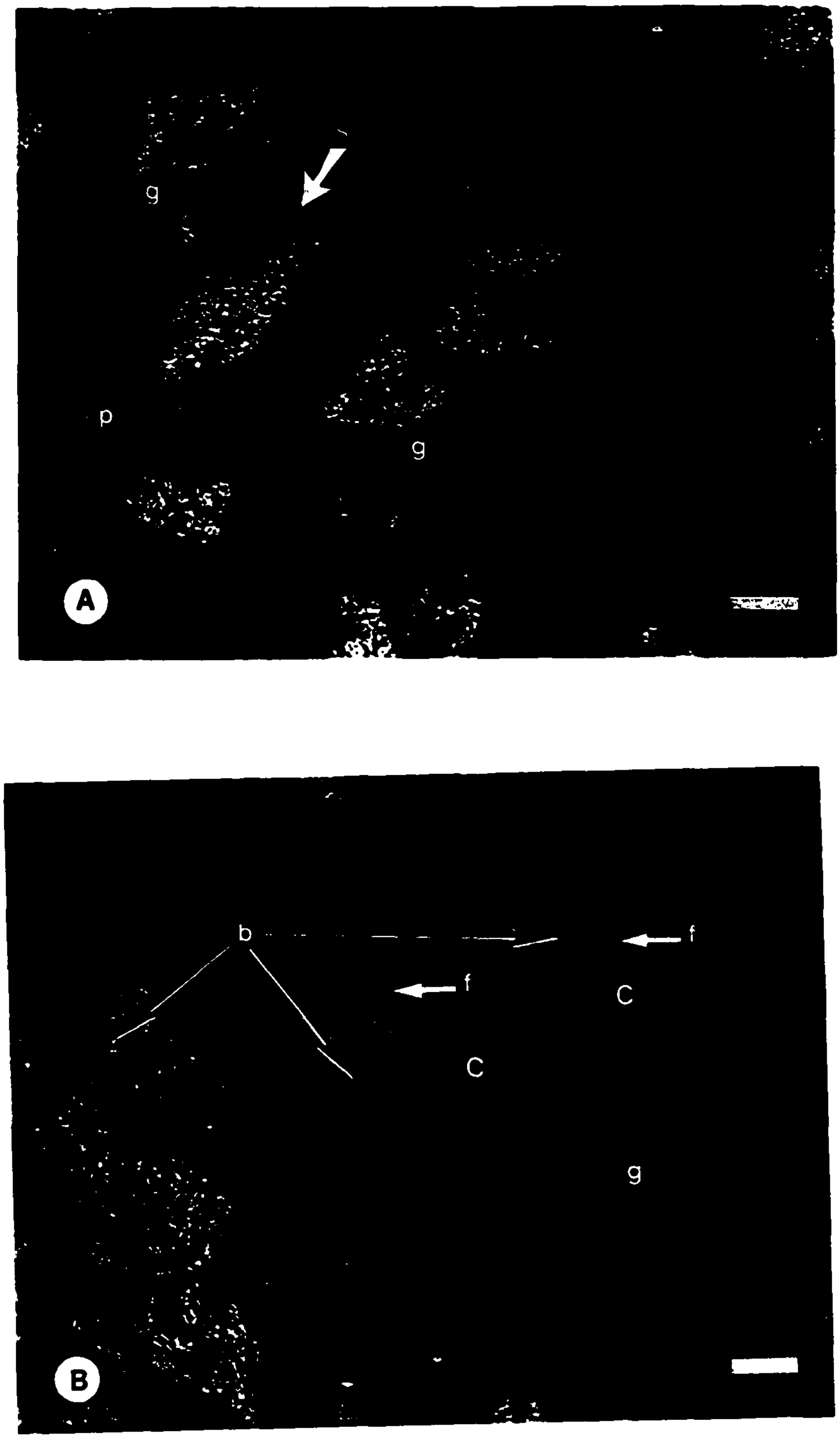
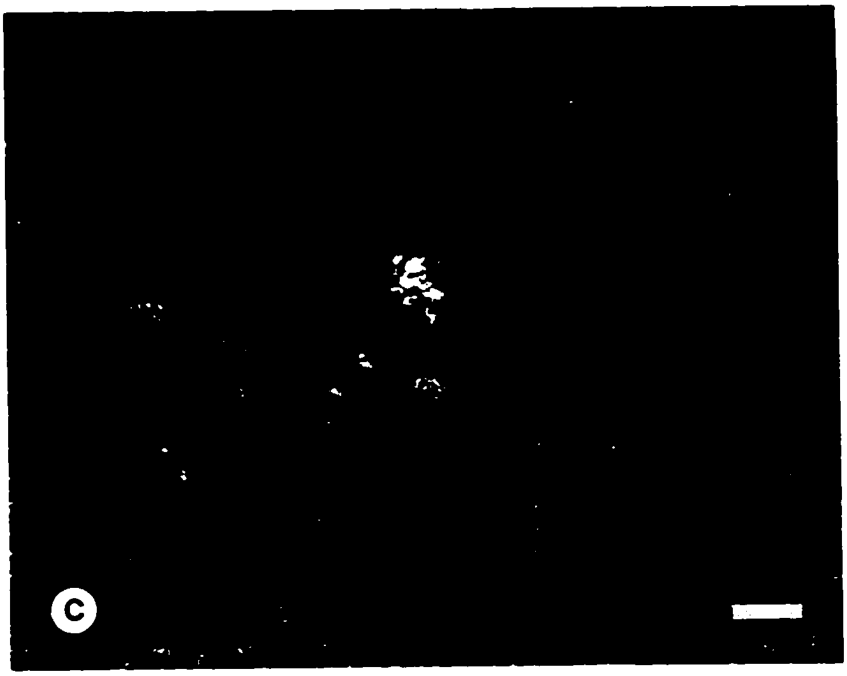
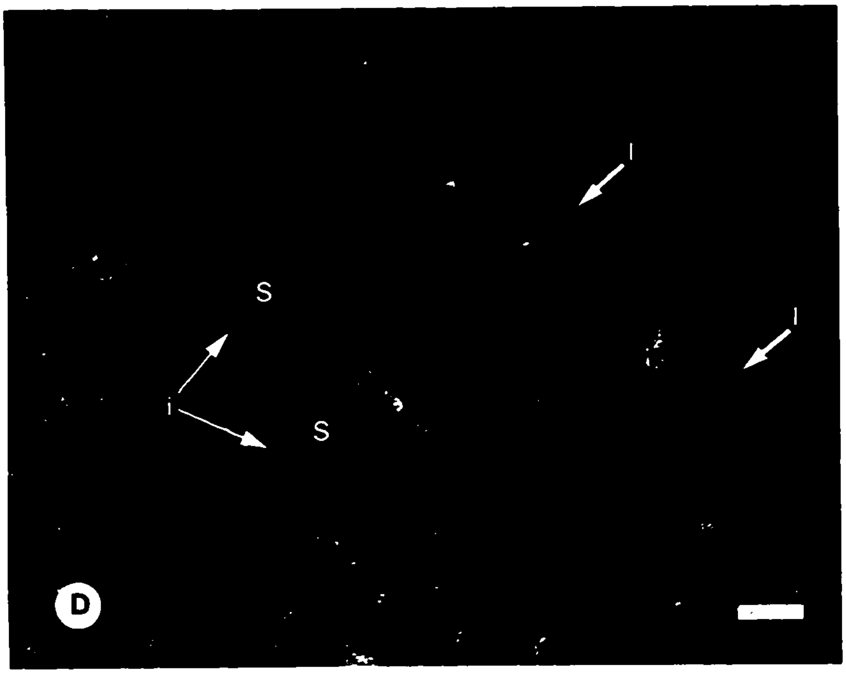

g
p
g
A
b
f
f
C
C
g
B

FIGURE 16 (continued)

D. Rare peloidal wackestone/packstone beds near the upper contact of Lithofacies II, at measured section No. 3, that contains numerous laminoid (l) and irregular (i) fenestrae. The laminoid fenestrae produce an apparent layering. The irregular fenestrae are filled with equant cements (white) and crystal silt (s). The laminoid fenestrae are filled with equant cements. Scale bar: 1 mm.

E. Fenestrae in the unlayered mudstone lithofacies that has pendant equant cement (p) that predates or is contemporaneous with the crystal silt (s) which fills the remainder of this feature. The pendant equant crystal faces abut the crystal silt. Scale bar: 1 mm.


C


I
S
I
i
S
D


S
P
S
E

molds of this coral display geopetal fabric (Figs. 16A and 16B). These molds are floored with crystal silt overlain by void-filling calcite spar.

Samples which lack bioclasts contain large tubular to irregular shaped, spar-filled fenestrae. These structures may be oriented subvertically, horizontally, or randomly. They are usually filled with calcite spar but may contain crystal silt, peloids and/or intraclasts.

The Unlayered Mudstone Lithofacies at measured section No. 1 (Fig. 1) differ sedimentologically from the mudstones at the other measured sections. In outcrop, these mudstones are light- to medium dark-gray, bioturbated peloidal lime mudstones to wackestones with thin, medium dark gray argillaceous partings. The unlayered mudstones at the other locations are a light gray homogenous mudstone to bioclastic wackestone.

In acetate peels and slabs, the unlayered mudstones (at Section No. 1) consist of mud peloids, mud intraclasts, lime mud and bioclasts in a peloidal mudstone to wackestone fabric (Fig. 16C). The dark argillaceous material is seen in mottles and burrows within these mudstones. Bedding parallel stylolites which concentrate the dark argillaceous material are common, especially along bedding planes. These mudstones contain fragmented bioclasts of a similar relatively diverse fauna but lack the Tetradium corals which are common in the other unlayered mudstones.

Near the upper contact of Lithofacies II in the measured section No. 3 (Fig. 1), there are rare peloidal packstone beds which contain numerous laminoid and irregular fenestrae (Figs. 16D and 16E). These fenestrae are probably formed by desiccation and produce an apparent layering. They are commonly filled with geopetal crystal silt, peloids, and/or calcite spar. This is the only occurrence of layering found in the Unlayered Mudstones of Lithofacies II.

Lithofacies II has a sharp planar to scalloped contact with the overlying Lincolnshire Formation (either Lithofacies III or IV). This contact is observed at measured sections No. 2 and No. 3 (Fig. 1). At measured section No. 2, the interformational erosional surface is between light gray, New Market mudstones of Lithofacies II and medium dark gray, Lincolnshire bioclastic-peloid wackestones of Lithofacies III (Figs. 17A and 17B). At this location, the erosional contact is planar to scalloped with a topographic relief of up to 0.15 meters.

The erosional contact at measured section No. 3 lies between the unlayered New Market mudstones of Lithofacies II and the Lincolnshire bioclastic wackestones of Lithofacies IV (Fig. 18). Interbedding of Lithofacies (I and II) of the New Market Limestone and Lithofacies (III, IV, and V) of the Lincolnshire Formation is never observed.

At measured section No. 1, the formational contact is between bioturbated peloidal mudstones of Lithofacies II and the overlying bioclastic-peloid wackestones/packstones of Lithofacies III. The formational contact, at other locations, is either covered or poorly exposed. Similar interformational erosional contacts are reported between the fenestral micrites of the New Market Limestone and the overlying skeletal Lincolnshire Formation of southwest Virginia (Read and Grover, 1977). Mitchell (1982) reported an erosion contact between Facies I and Facies IA of the Middle Ordovician St. Paul Group in Pennsylvania. This section is located on the eastern limb of the Massanutten Synclinorium.

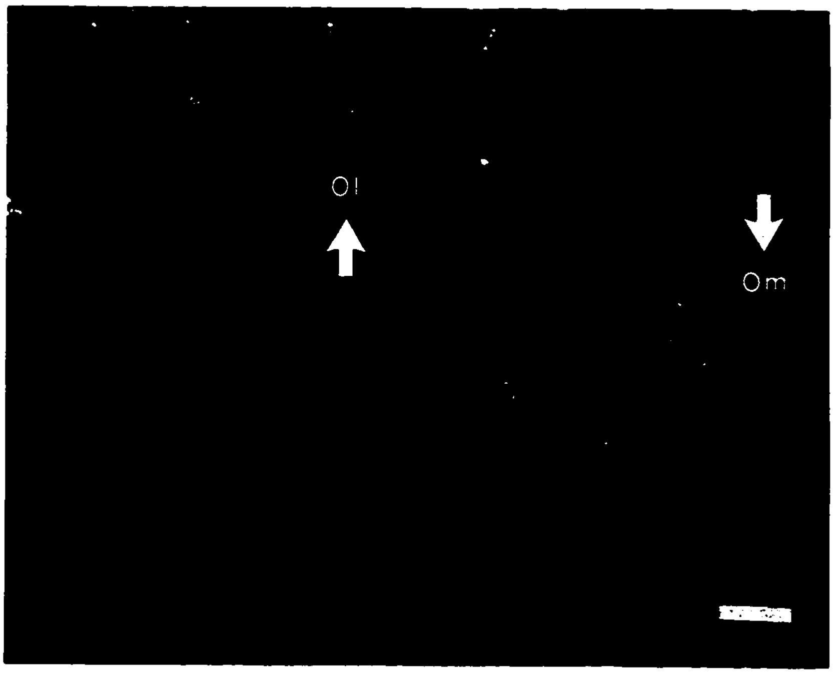
FIGURE 17A. The contact between the New Market Limestone (left) and the Lincolnshire Formation (right) at the measured section No. 2.

B. Close-up of 17a showing the planar to scalloped nature of this interformational contact (arrow). The eroded contact has a topographic relief of up to 0.15 meters.


A


B

FIGURE 18. Photomicrograph of the contact (arrow) between the New Market Limestone (Om, bottom) and the Lincolnshire Formation (Ol, top) at measured section No. 3. This interformational erosional surface truncates the sediments, fabric, and cements of the New Market Limestone. The large spar-filled fenestra (f) in the New Market Limestone, at the contact, may have formed by dissolution. Scale bar: 1 mm.


Ol
Om

Interpretation

The unlayered mudstones contain numerous tubular-shaped, spar-filled structures. Many of these structures are interpreted to be burrows because of their shape and occurrence in structureless mudstones (Grover and Read, 1978). Several horizons contain tubular features which are attributed to molds of Tetradium sp. corals (Figs. 16A and 16B). These structures are always associated with other features (such as tetragonal, spar-filled "molds" which are cross-sections of the corals and the presence of other bioclasts) which supports a fossil related origin. The faunal assemblage is a relatively diverse marine fauna.

Lithofacies II lacks structures indicative of subaerial exposure, such as desiccation fenestrae, mud-cracks, and solution features that were found in Lithofacies I. The presence of the anomolous layered units in Lithofacies II which contains desiccation features (at section No. 3), are important because they indicate that the depositional environment of Lithofacies I is not far from the intertidal zone (Figs. 16D, 18).

The unlayered mudstones is interpreted to have been deposited in the shallow subtidal depositional environment. The unlayered homogeneous nature of these rocks indicates that the rate of bioturbation exceeded the rate of mechanical reworking suggesting relatively low energy environment. The relatively diverse fauna implies a circulation of normal or near-normal marine waters. The depositional environment was less restricted than that of the Laminated Lithofacies I.

Scalloped to planar interformational erosional surfaces are developed at the top of the New Market Limestones in northern Virginia (Figs. 17A, 17B and 18). The erosional contact is marked by an abrupt lithologic change from the underlying, light gray, homogeneous New Market mudstones to the dark gray, bioclastic wackestones/packstones of the Lincolnshire Formation. Sediment and cements (filling fenestrae and intraparticle space) are truncated by these erosive surfaces indicating early lithification prior to deposition of the overlying Lincolnshire unit.

Similar interformational erosional surfaces are described by Read and Grover (1977) in southwest Virginia. These surfaces are believed to have developed by solution and early lithification under subaerial conditions followed by intertidal erosion during subsequent marine submergence. Since erosional surfaces are developed within and on top of the New Market Limestone in Virginia, Read (1980) suggested that these events may be related to short lived shoaling to near sea-level. Possible shoaling was observed at measured section No. 3 (Fig. 1) where an anomalous layered fenestrae unit displayed evidence of emergence such as laminoid and irregular desiccation fenestrae (Figs. 16D, 18). Also, rare solutional features were observed in the fenestral mudstones below the interformational surface at measured section No. 2 (Read and Grover, 1977). Repetition of these erosional surfaces within and on top of the New Market Limestone of northern Virginia and features indicative of early lithification and emergence in the underlying unit suggests that shoaling occurred, due either to deposition out-pacing subsidence, or to minor regressive phases of sea-level followed by further marine transgression. The final erosion surface at the top of the New Market Limestone is followed by a transgressive event.

The sedimentologic characteristics and the faunal assemblage of the Unlayered Mudstones, Lithofacies II, resembles Mitchell's (1982) Upper Structureless Micrites of Facies V. Mitchell suggested that Facies V represents the transgression of marine water over his peritidal Laminated Facies IV.

In southwest Virginia, the New Market Limestone is described by Grover and Read (1978) as a fenestral, pellet-intraclast packstone/ wackestone, lime mudstone and locally a skeletal limestone. The sediment type and structures are similar, in part, to Facies I and V of the St. Paul Group according to Mitchell (1982). These rocks may have been deposited under similar environmental conditions; however, they are not believed to be laterally equivalent. An explanation for the relationship of the New Market Limestones in Virginia and the St. Paul Group in Maryland and adjacent states is outlined by Read (1980). He suggests that the New Market beds, of southwest Virginia, were unconformably deposited on Knox-Beekmantown beds during a northward transgression of the southern subbasin. This is supported biostratigraphically by a decrease in the age of New Market beds to the north. Deposition of the New Market beds in northern Virginia, however, may have been deposited with little or no erosion (Anita Harris, A, personal commun., 1986). Neuman (1951) suggested that the New Market beds in northern Virginia may have been deposited by overlap as the northern basin advanced southward into northern Virginia. This southward transgression is supported by a similarity in the sediment type, sedimentary structures and the faunal assemblages of the New Market beds in northern Virginia and the St. Paul Group. The great thickening and development of more marine facies of the St. Paul Group in Pennsylvania also supports a southward transgression (Neuman, 1951). The differences in lithofacies and age relationships suggests that the New Market beds of southwest Virginia and the St. Paul Group including the New Market beds in northern Virginia were deposited in two initially separate sedimentary subbasins associated with depocenters in Tennessee and Pennsylvania. Eventually these subbasins became connected as the Knox-Beekmantown beds in Virginia were submerged.

Modern Bahamian Analog

The bioturbated sediments of the "mud-pellet mud" and the "oolitic-grapestone" lithofacies of the Bahamian Bank are considered to be the modern analog for the Unlayered Mudstones of Lithofacies II. The "mud and pellet mud" lithofacies (Bathurst, 1971), located west of Andros Island on the Bahamian Bank, contains a very restricted faunal community of Didenmum candidum and locally Cerithidea costata. The remainder of the bank is composed primarily of the "oolitic and grapestone" lithofacies with a relatively diverse Strombus costatus community that consists of pelecypod, gastropods, echinoderms, corals, bryozoan, algae, sponges, grasses and crabs (Bathurst, 1971). These lithofacies contain up to 89 percent of nonskeletal material consisting of fecal pellets, peloids, intraclasts, grapestones, cryptocrystalline grains (irregularly shaped brown peloids), mud and ooids. The rate of bioturbation exceeds the rate of mechanical reworking of these sediments by currents and waves. These sediments were deposited at a depth which varies from 1.5 to 8 meters. Both modern and ancient lithofacies contain similar sediment types and a relatively diverse marine fauna. The Bahamian Bank lithofacies are interpreted to have been deposited in a low energy, shallow water environment with little evidence of exposure (Bathurst, 1971). A similar setting is suggested for the subtidal sediments of Lithofacies II.

C. LINCOLNSHIRE FORMATION

The Middle Ordovician Lincolnshire Formation contains three lithofacies. Lithofacies III, a local basal unit, crops out at measured section No. 1 (Fig. 1) as a unit that is 22.5m (74 feet) thick. This unit thins southward at measured section No. 2 (Fig. 2) where it is approximately 3m (10 feet) thick. Lithofacies III is not present at measured sections No. 3, 4, 5, or 6. This lithofacies is distinctly different from the underlying New Market Limestones and the overlying Lithofacies IV and V of the Lincolnshire Formation. Lithofacies III consists mainly of bioclastic-peloidal-oncoidal wackestones/packstones.

Lithofacies III is overlain by cherty, thin bedded, bioclastic wackestone/packstones and argillaceous mudstones/packstones of Lithofacies IV and V, respectively. Lithofacies IV and V have been arbitrarily divided based on an increase in the argillaceous content and a decrease in the bioclasts. All three lithofacies contain a diverse normal marine fauna suggesting an open shallow marine depositional setting.

1. Lithofacies III: Bioclastic-Peloidal-Oncoidal Packstone

Description

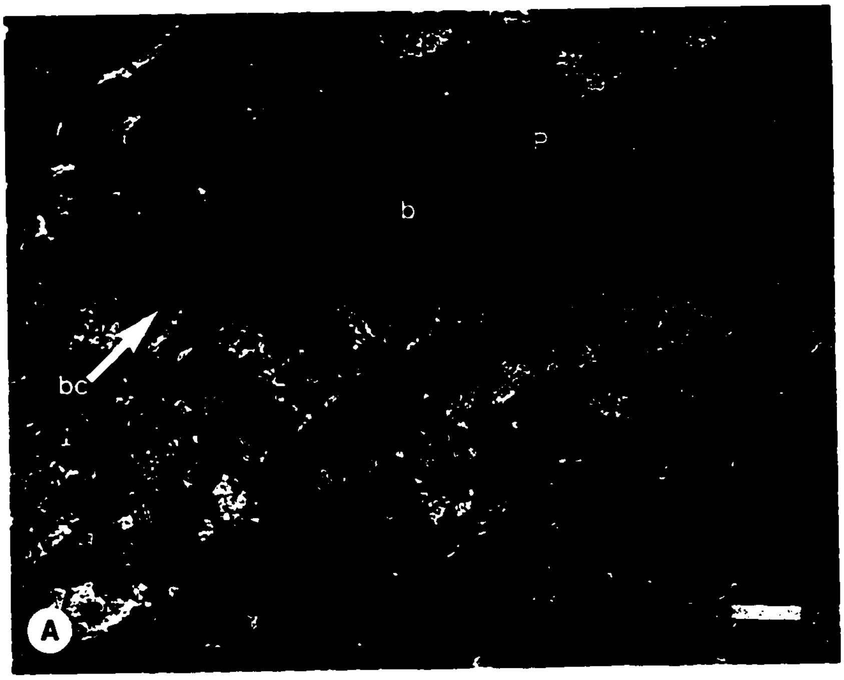
Lithofacies III consists of bioclastic-peloidal wackestones/packstones (Fig. 19A), bioclastic-peloidal-oncoidal packstones/grainstones (Figs. 19B and 19C), and less commonly, a peloidal wackestone/packstone (Figs. 19D and 19E) subfacies. These subfacies are composed of a normal marine faunal assemblage, abraded

FIGURE 19. Photomicrographs of the Lincolnshire Formation: Lithofacies III: Bioclastic-Peloidal-Oncoidal Wackestone/Packstone.

A. Bioclastic-peloidal wackestone/packstone with an elongate bioclast (b) oriented parallel to bedding. The bioclast display shelter porosity space that is filled with pendant bladed cement (bc), syntaxial rim cement (s) fringing palmatazoan grains, and fine- to coarse-equant (e) cements. The intraparticle spaces are filled with syntaxial rim and equant cements (white). The peloids (p) and bioclasts (b) have been micritized and some display dark micrite coats. Scale bar: 1 mm.

B. Bioclastic-oncoidal-peloidal wackestone/packstone. The cores of the oncoids are comprised of bioclasts (b), intraclasts (arrow) and peloids (p). Cements include syntaxial rim (s) and fine- to coarse-equant (e) cements. Scale bar: 2.8 mm.

C. Bioclastic (b)-peloidal (p)-oncoidal (not shown) packstone. Some polycrystalline bioclasts are fringed with bladed cements (bc). Pelmatazoans are fringed with syntaxial rim cements (s) and often only a shadow of the original bioclast remains (b). Other cements include fine- to coarse-equant (e) cement fabrics. Scale bar: 1 mm.


b
bc
A

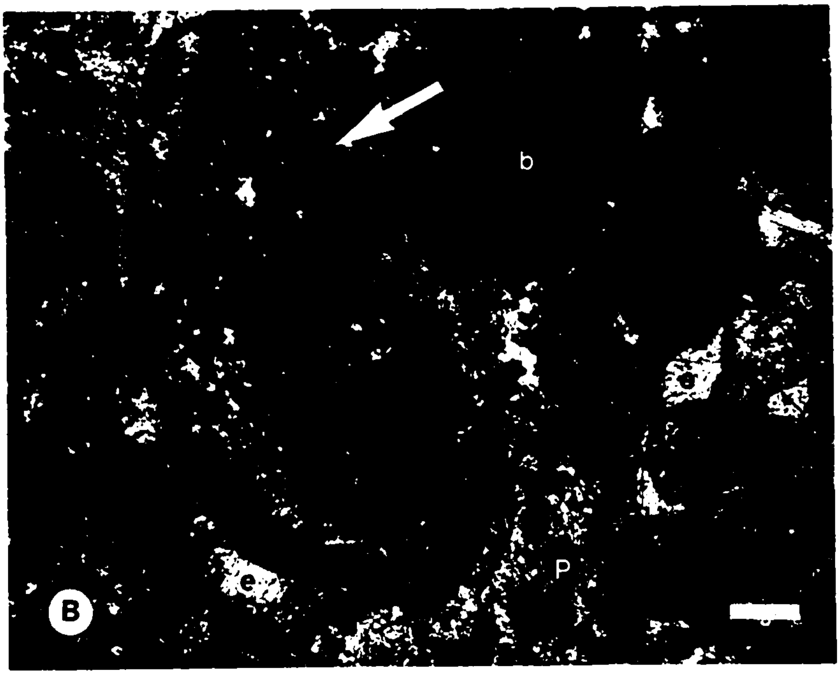
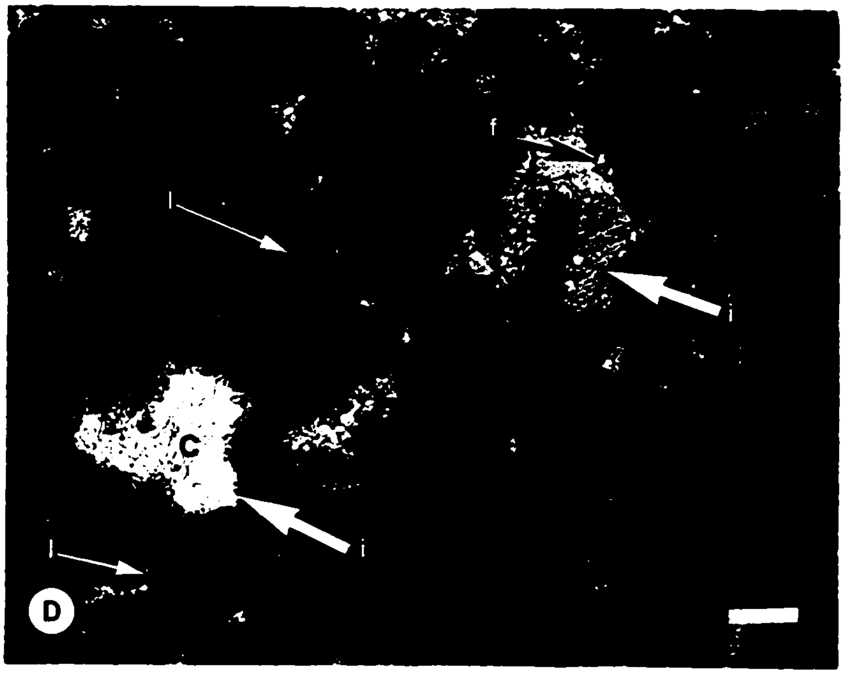

b
P
B

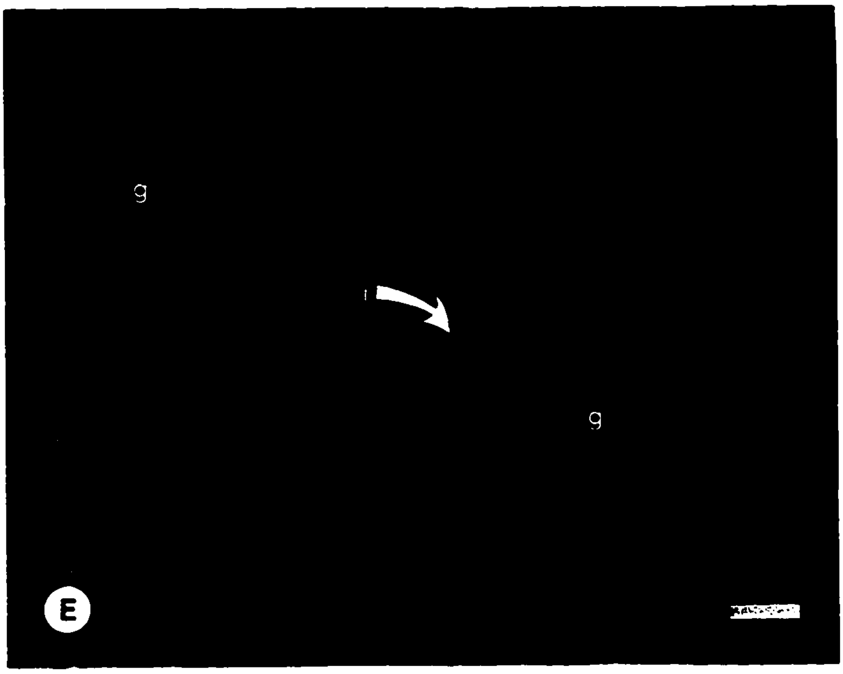
FIGURE 19 (continued)

D. Peloidal wackestone containing laminoid (l) and irregular (i), spar-filled fenestrae that are believed to be produced by desiccation. The large irregular fenestrae are fringed with isopachous, fine-equant (f) cement and are filled with coarse equant (c) cement or a single equant crystal. The peloids have dark micrite coats. Scale bar: 0.8 mm.

E. Peloidal wackestone/packstone that contains large irregular fenestrae (i) which display geopetal fabric. The geopetal sediments (g) are diagenetically replaced with dolomite rhombs. Cements include fine- and coarse-equant cements (white). Scale bar: 0.8 mm.


bc
b
C
P


f
l
i
c
i
l
D


g
g
E

and micritized bioclasts, peloids, and oncoids, abundant syntaxial rim and fine- to coarse-equant cement, and generally lack textural layering and desiccation features.

The faunal assemblage is very diverse, consisting of ostracodes, gastropods, brachiopods, trilobites, bryozoans, pelmatazoans, pelecypods, codiacian and dasycaladacean chlorophyte algae and Girvanella. Elongate fossil fragments that are oriented parallel to layering often display bridging and shelter porosity where grains are caught above flat fragments or pore space is sheltered below grains and becomes filled with calcite spar (Fig. 19A; Wilson, 1975). The fauna of Lithofacies III, is similar to the basal oncolitic unit of the Lincolnshire Formation of southwest Virginia (Read and Grover, 1977; Read, 1980) and to Mitchell's (1982) Facies IA of the St. Paul Group to the north.

Many units of this lithofacies contain abundant partially micritized sediment particles and bioclasts with dark micrite coats or envelopes (Figs. 19A, 19B, and 19D; Bathurst, 1971). Micritization of these grains is the work of boring algae, fungus, and sponges. If the micritization process goes to completion, the original micro-structures of the bioclasts may be totally obliterated. Complete micritization of bioclasts produce micritic peloids.

Bioclasts, peloids, and intraclasts comprise the cores of oncoids (Fig. 19B). These oncoids have a roughly concentric or randomly coated nucleus, or an unlayered micritic cortex. These coatings may be relatively thin and difficult to distinguish from the micritized grains or they may be up to 3 mm thick. Many oncoids are partially recrystallized to microspar or spar and are rarely partially replaced with dolomite. The oncoids often contain inclusions of dolomite, silica, and pyrite. Some oncoids display intertwined, micron-sized tubes that are filled with microspar (Fig. 19B). These tubes may be the preserved remains of the endolithic algae, such as those described for the recent lime sands in the Bimini Lagoon, Bahamas (Bathurst, 1971).

Contacts between subfacies of Lithofacies III are commonly gradational or may be sharp and irregular. The sharp contacts are generally marked by a bedding parallel stylolite which truncates sediment particles and cements. Dark argillaceous silt is commonly concentrated along these stylolites. The bedding parallel stylolites suggest an apparent bedding.

The peloidal wackestone subfacies rarely contains fenestrae other than the intraparticle cement-filled spaces. The fenestrae are laminoid- to irregular-shaped and are believed to be due to desiccation (Figs. 19D and 19E). Irregular fenestrae (3 to 4 mm in diameter) display geopetal fabrics of micritized peloidal, internal sediments. In some cases the internal sediments are diagenetically replaced with dolomite rhombs (Fig. 19E). Rare, larger (up to 0.8 x 1.7 cm) irregular "fenestrae" are bordered by stylolites and are filled with syntaxial rim cement. These irregular "fenestrae" are believed to have formed during later diagenesis and are not related to the desiccation features. Bioclasts are not as abundant in this subfacies. Rare geopetal fabrics, containing micritized peloidal sediment similar to the surrounding unit, are observed within rare whole fossils (ostracodes and gastropods). In some cases, these internal sediments are partially replaced with dolomite rhombs.

Interpretation

The association of a marine faunal assemblage and oncolites indicates that Lithofacies III was deposited in a relatively shallcw subtidal to low-intertidal environment. Deposition of this lithofacies above the underlying erosional surface (discussed previously under Lithofacies II) suggests a renewal of the transgression seen during the deposition of the New Market Limestone. These packstones lack features which indicate exposure with the exception of a rare peloidal packstone subfacies found near the base of Lithofacies III at measured section No. 1. These peloidal packstones contain laminoid and irregular shaped fenestrae (Fig. 19D and 19E) which are interpreted to be formed by subaerial exposure and desiccation (Shinn, 1968; Ginsburg et al., 1977; Grover and Read, 1978). This anomolous unit indicates that this continuation of the marine transgression following deposition and erosion of the New Market Limestone was interrupted by shoaling or minor regressive phases.

The lack of layering in this lithofacies suggests that the rate of bioturbation exceeded the rate of mechanical reworking. Rare bioclastic grainstones display large horizontal burrows which are filled with a dark argillaceous bioclastic wackestone. Some bioclastic-peloidal wackestones show mottles of bioturbated dark argillaceous silt. Mechanical laying is suggested in rare samples of bioclastic-peloid packstones which contain elongate bioclasts (Fig. 19A).

The sedimentary particles comprising this lithofacies were reworked by currents and/or waves. Reworking is indicated by: 1) oncoids which need to be rolled about in order to form, 2) the abraded and fragmented nature of the bioclasts, and 3) the concentration of bioclasts in lenses or pods above some stylolitized bedding planes. The presence of oncoids indicate that deposition was within the photic zone. The limited distribution of Lithofacies III (at measured sections Nos. 1 and 2 only) indicated that deposition was more localized than that of the previous Lithofacies I and II of the New Market Limestone.

Lithofacies III is interpreted to have been deposited on a lithified tidal flat deposit as a nearshore transgressive shoal deposit. Deposition in a localized, shallow subtidal to low-intertidal environment is indicated by the numerous oncolites of Girvanella. Ginsburg (1964) has shown that the formation of oncolites (algally coated grains) is largely restricted to the subtidal environment of Florida Bay. Modern occurrences of oncolites are restricted to water depths of 0-6 meters (0-20 feet) according to Logan et al. (1964).

Similar depositional conditions were suggested by Markello et al. (1979) for the basal oncolitic grainstones of the Lincolnshire Formation in southwest Virginia. Facies IA, the skeletal packstones of the St. Paul Group (Mitchell, 1982), also resembles Lithofacies III. These packstones crop out in the eastern belt (eastern limb of the Massanutten Synclinorium) and may have acted as a barrier to the time-equivalent, more restricted tidal flat Facies I and II in the western belt (western limb of the Massanutten Synclinorium; Mitchell, 1982).

Modern Bahamian Analog

Similarities in the faunal diversity, sedimentary structures and early diagenetic features of Lithofacies III and the skeletal sands of the Great Bahama Banks suggests analogous depositional environments. The distribution of Lithofacies III suggests an aerially restricted depositional environment similar to the skeletal sand deposits which rim the Bahama Platform edge.

These sands are composed of a mixture of bioclasts, pellets, grapestones and ooids (Bathurst, 1971). The skeletal fragments of the Strombus samba and Plexaurid communities include: calcareous algae, pelecypods, gastropods, echinoids, forminifera, sponges, red and brown algae, corals and bryozoans. Studies of cores into these fringing sand shoals of the Great Bahama Banks show that the sediment below the mechanically reworked surface has been reworked by burrowers (Mitchell, 1982). The bioturbated sediments are composed of poorly sorted bioclasts-peloids-ooid packstones and wackestones. The peloids may originate as faecal pellets, inorganic accretions or as skeletal grains micritized by boring algae (Bathurst, 1971).

2. Lithofacies IV: Bioclastic Wackestone and Packstone

Description

Lithofacies IV is comprised of thinly bedded, medium- to medium dark gray, cherty, fine-grained bioclastic wackestones, fine- to coarse-grained bioclastic packstones and mudstones with burrow mottles and stylolitic seems of black, dolomitic argillaceous silt (Fig. 20A). Dark gray to black dolomitic argillaceous shale forms partings to thin laminations between the beds (Fig. 20B). The bedding is generally uneven (or wavy), being unequal in thickness and laterally variable in thickness but continuous (Pettijohn, 1975).

The bioclastic packstones are found as interbeds or as pods and lenses along bedding planes (Fig. 20C). They consist of abundant fine- to coarse-grained bioclasts and minor intraclasts in carbonate cement and/or lime mud. The cements include syntaxial rim cement on palmatazoans and fine to coarse equant cements. These packstones contain similar dark argillaceous burrow-fills, mottles and stylotized seams.

The bioclasts represent a normal marine faunal assemblage including: ostracodes, gastropods, brachiopods, trilobites, bryozoans, pelmatazoans, pelecypods, dasycladacean algae and sponges. Bioclasts that are broken during compaction are healed by later calcite cements (Fig. 20D). There are some thin beds of bioclastic-oncolitic wackestones/ packstones which indicates deposition within the photic zone.

FIGURE 20. Lincolnshire Formation: Lithofacies IV, Bioclastic Wackestone/Packstone.

A. Bioclastic wackestone, seems of black dolomitic, argillaceous silt along bedding planes. Chert forms as bedding parallel nodules (c). Tectonic fractures (white) cross-cut these nodules indicating that the chert formation pre-dates the emplacement of the tectonic fractures. The tectonic fractures are filled with late white calcite cement.

B. Photomicrograph of the Lincolnshire bioclastic wackestone lithofacies (IV) that consists of fine lime mud, fine bioclastic debris (d), stylolitic seams (arrow), and burrow mottles (black). Scale bar: 4 mm.

C. Bioclastic packstone are found along bedding planes. They consist of fine- to coarse-grained bioclasts (b) and minor intraclasts in equant (e) and syntaxial rim (s) cements. Chert (c) has partially replaced some bioclasts. The underlying bed is a bioclastic wackestone (w). The irregular contact (arrow) may be due to scouring by currents prior to deposition of the overlying packstone unit. Scale bar: 0.6 mm.

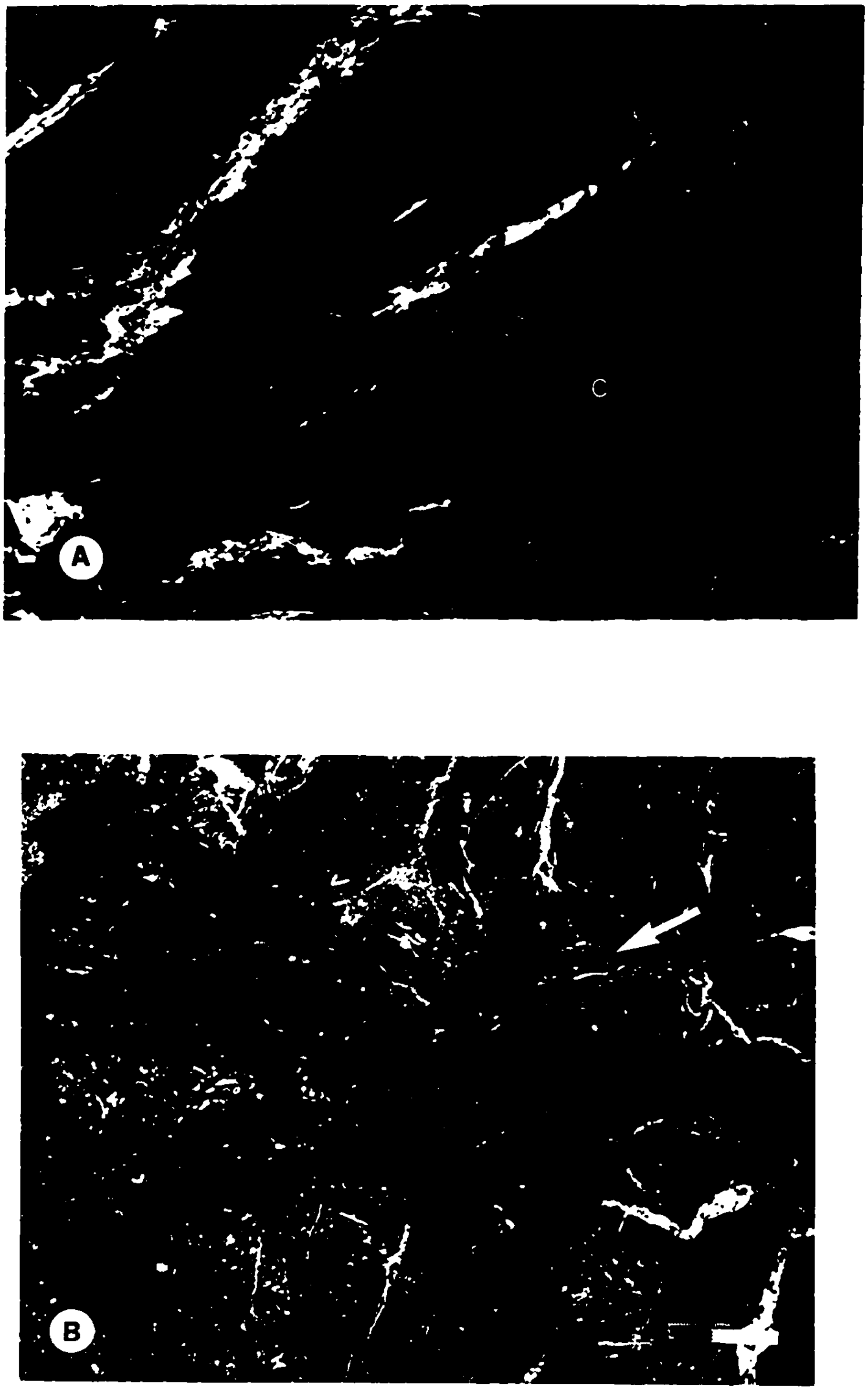
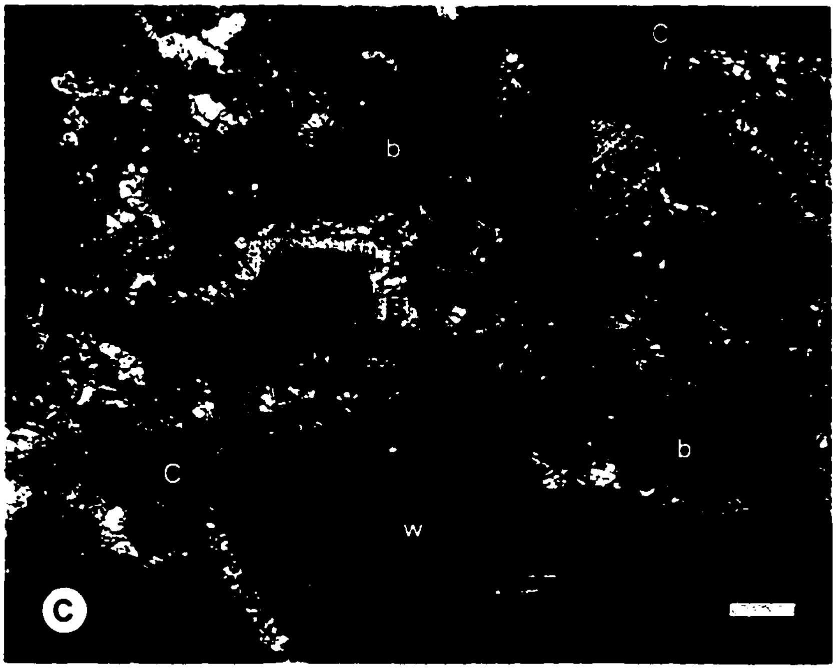
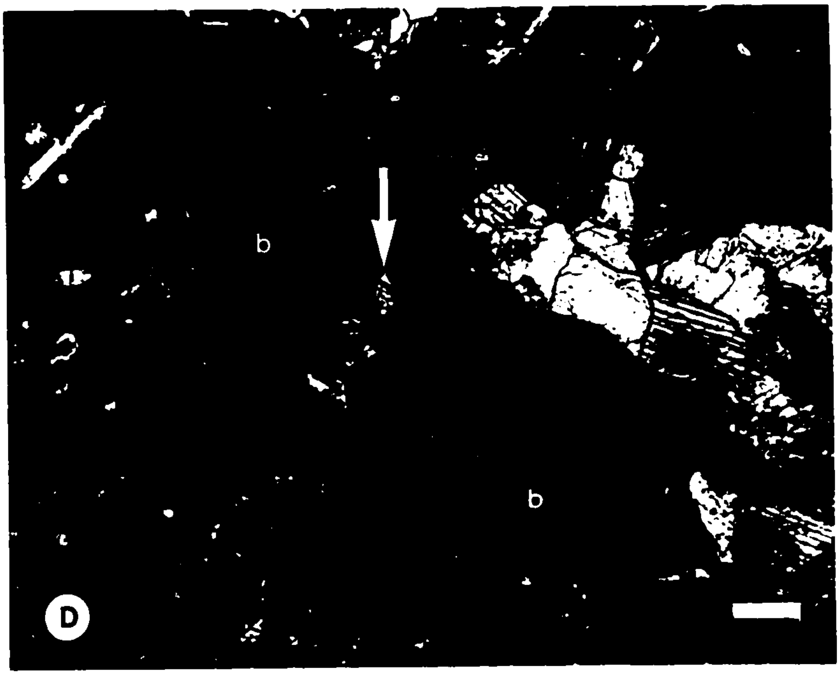

A
C
B

FIGURE 20 (continued)

D. Bioclastic wackestone/packstone with bioclasts (b) that have been broken (arrow) during the compactional phase and are healed by later equant cements (white). Scale bar: 0.4 mm.

E. Bioclastic wackestone has been partially replaced with chert (c). The chert contains remnants of bioclasts (b), argillaceous silt (s), and calcite spar (white). The bioclasts in the limestone bed surrounding the chert are preferentially replaced with chert. Scale bar: 1 mm.


C
b
b
C
w
C


b
b
D

C
S
C
b
E

Chert forms irregular nodules and lenses (Fig. 20A) to continuous beds that are parallel to bedding. The chert is generally dark gray and may have a brownish, coarser rim. The chert nodules rarely contain remnant bioclasts, patches of lime mud, argillaceous silt, large ferroan dolomite rhombs (Grover and Read, 1983), calcite spar, and disseminated crystals of pyrite/hematite (Fig. 20E). These features indicate that the chert formed after shallow burial and partial lithification due to diagenesis. Bioclasts in the beds surrounding the chert formation are often preferentially replaced with chert. Chert nodules and beds are usually bounded by dark argillaceous stylolitic seams. Tectonic fractures cut across beds and chert and are filled with late calcite cement (Fig. 20A).

Interpretation

The high percentage of lime mud and the abundant normal marine fauna suggests that Lithofacies IV is a low-energy, shallow subtidal, ramp facies. This lithofacies is formed in the subtidal ramp environment located, generally, below wave-base between and landward of the outer-ramp skeletal sheets and mounds (Read, 1985). Carbonate ramps have relatively uniform, gentle slopes (slope is less than 1° or approxomately 1 m/km) on which shallow shoaling facies of the near shore zone pass downslope (without a break in slope) to deeper water deposits (Ahr, 1973). Skeletal buildups, described by Read (1980) in southwest Virginia, include: the shallow ramp buildups (Rockwell/Ward Cove Formations) which overlie the skeletal Lincolnshire Formation and interfinger with and are overlain by the deep ramp Benbolt Formation and the downslope buildups (Effna/Murat Formations) that interfinger with or are overlain by the skeletal Botetourt and basinal Liberty Hall Formation. These buildups thin laterally into skeletal sheets. Mitchell (1982) has also described sediments (Facies IA of the St. Paul Group in Pennsylvania) located in the eastern belt (east of the Massanutten Synclinorium) which may have acted as a barrier to facies being deposited in the western belt.

The shallow ramp is relatively restricted with normal marine salinity and circulation being very moderate (Wilson, 1975). The somewhat restricted subtidal environment may be due in part to the outer-ramp buildups and skeletal sheets which may have acted as a barrier. Conversely, this restricted environment might have resulted from its location well onto shallow ramp and some distance from deeper shelf waters with vigorous currents. The dark argillaceous silt and shale found in these sediments may be windblown dust, or material carried to the ramp from the adjacent argillaceous basin. The lithofacies has been burrowed resulting mottling of the dark argillaceous sediment in the carbonate sediments.

Depositional Model

The "homoclinal ramp model with isolated shallow ramp and downslope buildups" proposed by Read (1985) is the suggested depositional model for Lithofacies IV. The facies belts include: 1) tidal-supratidal complex, 2) lagoonal, 3) shallow ramp banks and local patch reefs, separated laterally by intermound, fine carbonates and 4) deep ramp and basin slope with isolated downslope buildups and basin facies. The buildups are mainly skeletal banks and sand sheets with reefal rims on the western side. Continued growth of these banks may produce a barrier-bank complex. Lithofacies IV represents the shallow subtidal lagoon deposits located landward and between the shallow ramp buildups or skeletal sands, and is believed to have been deposited in a temperate climate similar to Lithofacies I, II and III. This lithofacies is similar to the Lincolnshire Formation located in southwest Virginia (Read and Grover, 1978; Read, 1980). To the north, the Lincolnshire Formation is faulted out near the Virginia-West Virginia border (Neuman, 1951). This lithofacies is similar to Wilson's (1975) Belt 7 the Open Marine Platform Facies. A modern analog of the homoclinal ramp model is the Persian Gulf (Read, 1985); however, the Persian Gulf represents arid climatic conditions.

3. Lithofacies V: Argillaceous Mudstone/Wackestone

Description

Lithofacies V is thinly-bedded, medium dark-to dark-gray, cherty, mudstone, fine-grained bioclastic wackestone/packstone. Dark gray to black dolomitic-argillaceous silt is seen: as burrow mottles (Fig. 21A); along stylolites (Fig. 21B); bioturbated throughout the thin beds (Fig. 21C); and as thicker, dolomitic-argillaceous, shale partings to thin beds between the carbonate beds. The argillaceous material is more abundant and the shale partings are in general thicker than that of Lithofacies IV. Bedding is uneven to wavy and often appears nodular on weathered surfaces.

The constituent particles are lime mud, dolomitic-argillaceous silt, dark peloids, fine-bioclastic debris, and minor recognizable bioclasts (Fig. 21B). Bioclasts are: bryozoans, brachiopods,

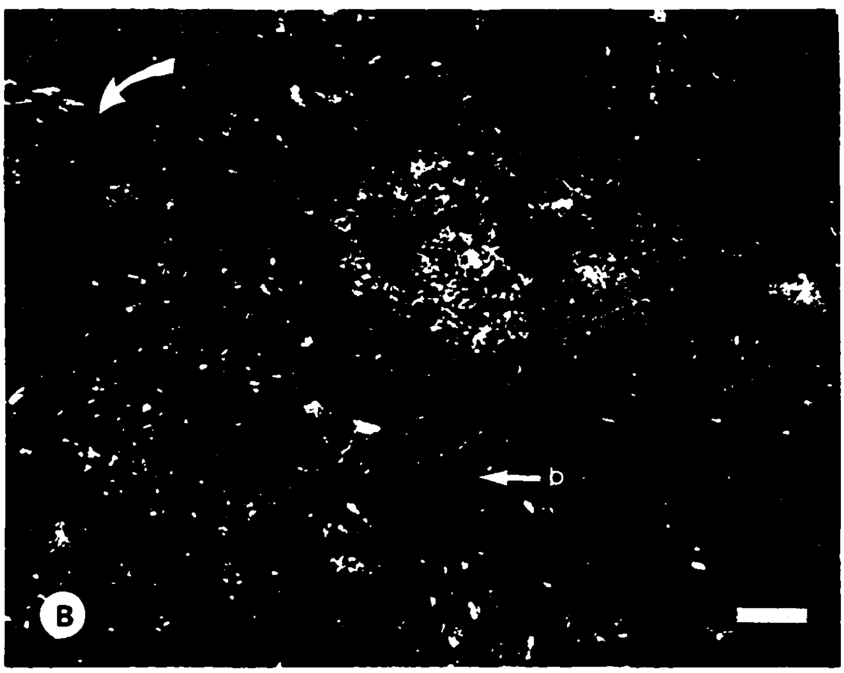
FIGURE 21. Photomicrographs of the Lincolnshire Formation: Lithofacies V, Argillaceous Mudstone/Wackestone.

A. Argillaceous mudstone with dark gray to black dolomitic-argillaceous silt (black) seen as burrow mottles in the mudstone layers adjacent to the bedding planes. Scale bar: 3.7 mm.

B. The argillaceous wackestones are composed of lime mud, dolomitic argillaceous silt (black), fine-bioclastic debris (b), and minor recognizable bioclasts. The dolomitic argillaceous silt is concentrated along the stylolitic seams (arrow). Scale bar: 1.4 mm.

C. Argillaceous mudstone with the dark argillaceous silt bioturbated throughout (black). The spar-filled features (white) may be replaced bioclasts. Minor bioclastic debris (arrows). Scale bar: 1.7 mm.


A


b
B

trilobites, pelmatazoans, ostracodes, dasyclacean algae, and mollusks. The faunal assemblage is similar to that described for Lithofacies IV, however the bioclasts tend to be finer-grained. These bioclasts indicate relatively normal marine conditions. The unit has been extensively bioturbated. No oncolitic units were observed. Some bioclastic packstone units consist of bioclasts, lime mud and abundant microspar with inclusions of dolomite, pyrite, and abundant dark argillaceous material. This microspar is probably recrystallized lime mud. The chert resembles the chert nodules and beds described in Lithofacies IV. Late tectonic fractures cut across beds and chert of this Lithofacies similar to those in Lithofacies IV. They are filled with late calcite cement.

Interpretation

Lithofacies IV and V have been arbitrarily divided based on an increase in the dolomitic-argillaceous content of Lithofacies V, an increase in the relative amount of bioturbation of the argillaceous material in the carbonate unit (some samples of Lithofacies V are approximately 95 percent argillaceous material), and by a lack of oncolites in Lithofacies V. Lithofacies V contains abundant lime mud and a normal marine faunal assemblage similar to Lithofacies IV suggesting a similar environment of deposition in a low energy, subtidal-ramp environment. The bioclasts are, in general, fine-grained transported debris.

Lithofacies V represents an increase in the amount of argillaceous silt reaching the subtidal ramp. This Lithofacies is gradationally overlain by a deep ramp facies (Edinburg Formation) indicating continued subsidence and more deep water argillaceous deposits (Read, 1980). This supports a gradually deeper subtidal ramp environment to the southeast for the deposition of Lithofacies V. The source of the basinal clastics is believed to be the tectonic highlands along the eastern margin of the basin (Read, 1980).

Depositional Model

The "homoclinal" ramp model with isolated shallow ramp and downslope buildups (Read, 1985) is the suggested depositional model for Lithofacies V. This same model was suggested for Lithofacies IV and was originally based on the Lincolnshire Formation located in southwest Virginia (Read and Grover, 1978; Read, 1980). However, the Lincolnshire Formation located in Southwest Virginia has not been divided into two lithofacies.

The "homocinal" ramp model consists of the following facies: 1) tidal-supratidal complex, 2) lagoonal, 3) shallow ramp banks and local patch reefs, separated laterally by intermound, fine carbonates and 4) deep ramp and basin slope with isolated downslope buildups and basin facies. The buildups are mainly skeletal sheets and sand sheets with reefal rims on the western side. Continued growth of these banks may produce a barrier-bank complex. The argillaceous mudstones/ wackestones of Lithofacies IV and V are interpreted to have been deposited in quiet waters of slightly deeper subtidal ramp environment located between and landward of the shallow ramp buildups.

D. DISCUSSION OF DEPOSITIONAL ENVIRONMENTS

The subfacies of the New Market Limestone and Lithofacies III of the Lincolnshire Formation in northern Virginia are strikingly similar to the modern deposits of the tidal flat, algal marsh, and subtidal environments of Andros Island and the Great Bahama Banks (Table 2). Lithofacies I, II, and III are believed to have been deposited in environments similar the modern environments of the Bahamas. Lithofacies I is believed to have been deposited in an environment which includes the channeled belt complex and the freshwater algal marsh subenvironment; Facies II in a semi-restricted subtidal environment; and Lithofacies III in a transgressive shoal environment under normal marine conditions.

Lithofacies IV and V of the Lincolnshire Formation do not have analogs on the modern Bahama platform due to the geomorphologic differences between the subtidal environment of the Great Bahama Banks and the ancient carbonate ramp of the Middle Ordovician carbonates in Virginia. These lithofacies are believed to have been deposited in a "homoclinal" shallow subtidal-ramp between and landward of isolated shallow ramp buildups and downslope buildups (Table 2; Read, 1985). A modern example of this depositional model is the Persian Gulf (Purser, 1973). However, the climatic parameters under which the Lincolnshire lithofacies (IV and V) were deposited are believed to be analogous to the modern Bahamas since there is no evidence of a change to an arid climate such as exists in the Persian Gulf.

TABLE 2. CORRELATION OF THE LITHOFACIES WITH ANALOGOUS DEPOSITIONAL EVIRONMENTS

LITHOFACIES	SUBFACIES	DEPOSITIONAL ANALOG
LITHOFACIES I	PLANAR LAMINATES DISRUPTED FLAT LAMINATES DISRUPTED DOLOLAMINATES UNLAYERED MUDSTONES VERY THIN BEDS	LEVEE CREST LEVEE BACKSLOPE LEVEE BACKSLOPE (?) TIDAL PONDS INLAND FRESHWATER MARSH
LITHOFACIES II	UNLAYERED MUDSTONES	SHALLOW, SEMI-RESTRICTED SUBTIDAL
LITHOFACIES III	BIOCLASTIC-PELOIDAL PACKSTONE BIOCLASTIC-PELOIDAL-ONCOIDAL PACKSTONE/GRAINSTONE	NORMAL MARINE SUBTIDAL AND SHOAL
LITHOFACIES IV	BIOCLASTIC WACKESTONE/ PACKSTONES	NORMAL MARINE, SHALLOW SUBTIDAL
LITHOFACIES V	ARGILLACEOUS WACKESTONE/MUDSTONE	NORMAL MARINE, DEEPER SUBTIDAL

The Middle Ordovician carbonates of northern Virginia are believed to have been deposited in a temperate, sub-tropical to tropical climate. Factors which support these climatic conditions are: (1) deposition of modern shallow-water carbonates only occurs below latitudes of 30 degrees where a tropical to sub-tropical climate and clear, warm waters exist (Wilson, 1975); (2) the lack of evaporite minerals, molds, casts and disruption features suggests a non-arid climate; (3) erosion surfaces are the result of dissolution by meteoric waters of soluble carbonate phases; and (4) the existence of freshwater algal marshes of Lithofacies I.

The salinity of restricted waters is probably controlled by the climate of the marginal marine area (Mitchell, 1982). The tidal flat and adjacent subtidal lithofacies (I and II, respectively) of the New Market Limestone have abundant freshwater features including: dissolution features and Karst surfaces, freshwater algal marshes and cryptalgal laminates. On Andros Island today, the runoff from coastal freshwater environments tends to dilute the tidal flat and adjacent subtidal area during rainy periods (Bathurst, 1971). A similar scenario is suggested for the New Market Limestone in northern Virginia. On the other hand, the presence of abundant normal marine fauna of the relatively restricted, shallow subtidal, ramp-lithofacies (III, IV and V) of the Lincolnshire Formation is suggestive of more normal open marine salinity.

Burrowing is the major disruptive feature in the lower intertidal to subtidal environment. In the semi-restricted shallow subtidal environment, the rate of bioturbation exceeded the rate of sedimentation. This resulted in the relatively homogenous, unlayered mudstones of Lithofacies II. Lithofacies III, the bioclastic-peloid-oncoid packstone shoal deposits also generally lack layering. In rare instances, packstones contain elongate bioclasts oriented parallel to bedding suggesting some possible layering. The subtidal-ramp, Lithofacies IV and V are bedded but contain abundant burrows and mottling. The distribution of whole fossils or shell debris and the variations in faunal diversity from one lithofacies (or subfacies) to another helps to differentiate and interpret the subenvironments. This is especially true for the bioturbated skeletal packstones of Lithofacies III which contain open marine platform/ramp fauna and for the unbioturbated, unfossiliferous cryptalgal laminates and very thin bedded-algal marsh deposits of Lithofacies I which indicate a freshwater environment.

The different styles of layering of the cryptalgal laminates in Lithofacies I is attributed to different types of algae and their control on deposition. This is analogous to levee deposits of Andros Island where different styles of cryptalgal laminae occur in different positions on the levee due to algal zonation (Hardie and Ginsburg, 1977). The algal zonation is basically controlled by the ratio of Schizothrix-type mats to the percentage of Scytonema-type mats. Scytonema-dominated mats are restricted to the inland algal marsh and to a narrow zone fringing the ponds in the channel belt (Hardie, 1977). At the upper edge of the high algal marsh zone, the Scytonema mats grade into the Schizothrix-dominated levee backslope subenvironment where the Scytonema mat is patchy and discontinous.

The levee backslope grades into the Schizothrix-dominated levee crest subenvironment. A similar algal zonation is inferred for the laminated subfacies of the New Market Limestone.

The sediments of the New Market and Lincolnshire Formations are essentially carbonates consisting of a mixture of low magnesium calcite and dolomite. The dominant carbonate sedimentary particles are micritic peloids that probably originated as feacal pellets and intraclasts of cohesive sediments. Skeletal fragments and whole fossils generally comprise a relatively small percentage (less than 10%) of the sediments (the tidal flat sediments of Lithofacies I) but may comprise a large percentage of the constituent sediments of individual beds (bioclastic packstones of Lithofacies III and IV).

Carbonate mud is abundant. Its origin is unknown but may include the following: micritization of particles by endolithic algae and bacteria, precipitation of micrite around algal filaments, direct precipitation in the water column and a breakdown of algal tissues (Mitchell, 1982). All of the above sediments are intrabasinal in origin. This indicates that the depositional environments of the Middle Ordovician carbonates were, in general, isolated from a siliciclastic sediment source. The exception to this rule is the shallow subtidal-ramp lithofacies (IV and V) which contain variable amounts of dolomitic argillaceous silt and mud that was probably derived from a distal terrestrial source to the east (tectonic highlands within the basin).

Hardie and Ginsburg (1977), report that flooding by storms (meteorological tides) were more important than the day-to-day tidal currents in controlling deposition of sediments in the Bahama platform environments. Episodic deposition by currents is indicated by the very thin beds of peloid-intraclast wackestones and packstones deposited in the freshwater algal marsh subenvironments of Lithofacies I. These deposits are believed to be storm deposits because they occur within a subfacies which is predominately unfossiliferous and very fine-grained. The disrupted and planar laminates of the upper intertidal to supratidal deposits are interpreted to have formed during periods of storm washover. Analogous laminates are reported on the modern Bahama levee system (Hardie and Ginsburg, 1977). Conversely, the relatively low velocity tidal current of Lithofacies III, IV, and V is indicated by the lack of sedimentary structures in the subtidal sediments. This suggests that the rate of bioturbation exceeded the rate of sedimentation and/or reworking of the sediments by currents.

The subfacies of Lithofacies I are not arranged in a cyclic sequence. Hardie and Ginsburg (1977) suggest that the accumulation mechanism for the channeled belt of Andros Island is vertical accretion behind a barrier of some kind. Infilling behind this barrier would result in a complex packaging of subfacies including channels, channel bars, levees, ponds and marshes with no predictable vertical succession. The large number of closely associated subenvironments make recognition of a typical cycle in the channeled belt very difficult. A typical cycle would be deposited if sedimentation continues and the main channels become plugged, isolating the depressions. These depressions would then become freshwater algal marshes or lakes which will slowly fill with a more typical pattern of marsh-lake, levee backslope and levee crest deposits. When filling of the marshy lakes with sediment is complete the coastal plain would become a beach-ridge washover crest. These cycles are observed in the inland freshwater lake facies (Facies III) of the St. Paul Group in Maryland and Pennsylvania (Mitchell, 1982).

To the north, in Maryland and Pennsylvania, rocks which may be litho- and chrono-stratigraphically equivalent to the New Market Limestone in northern Virginia occur as the thicker St. Paul Group (Mitchell, 1982). The St. Paul Group consists of: Facies I, shallow restricted bank and subtidal pond; Facies IA, normal marine subtidal shoals; Facies II, freshwater algal marsh-levee and pond sediments; Facies III, inland freshwater lakes; Facies IV, same as Facies II; and Facies V, semi-restricted, shallow subtidal deposits. These facies thin southward into northern Virginia where the Laminated Lithofacies I (this paper) is analogous to Mitchell's (1982) Facies II and IV and the Unlayered Mudstone Lithofacies II (this paper) is analogous to Mitchell's (1982) Facies V. In southwest Virginia, the New Market Limestone is a fine-grained subtidal deposit which is similar to but probably not time-correlative to the Lithofacies II in northern Virginia and to Facies I and V in Maryland and Pennsylvania (Mitchell, 1982). No laminated freshwater facies are seen in southwest Virginia.

The Lincolnshire Formation in northern Virginia consists of a basal bioclastic-peloidal-oncoidal packstone overlain by bioclastic wackestones, packstones and mudstones with increasing argillaceous content (Lithofacies III, IV, and V; this paper). Similar deposits (but not necessarily time-correlative deposits) have been described for the Lincolnshire Formation in southwest Virginia (Read and Grover, 1977; Read, 1980). The Lincolnshire Formation crops out as far north as the Virginia-West Virginia border (Neuman, 1951). No Lincolnshire facies are observed in the Maryland and Pennsylvania; however, Lithofacies III in northern Virginia resembles Mitchell's (1982) Facies IA suggesting similar depositional and environmental conditions for the facies in both areas.

E. DEPOSITIONAL HISTORY OF THE MIDDLE ORDOVICIAN CARBONATES IN NORTHERN VIRGINA AND ADJACENT STATES

Stage 1

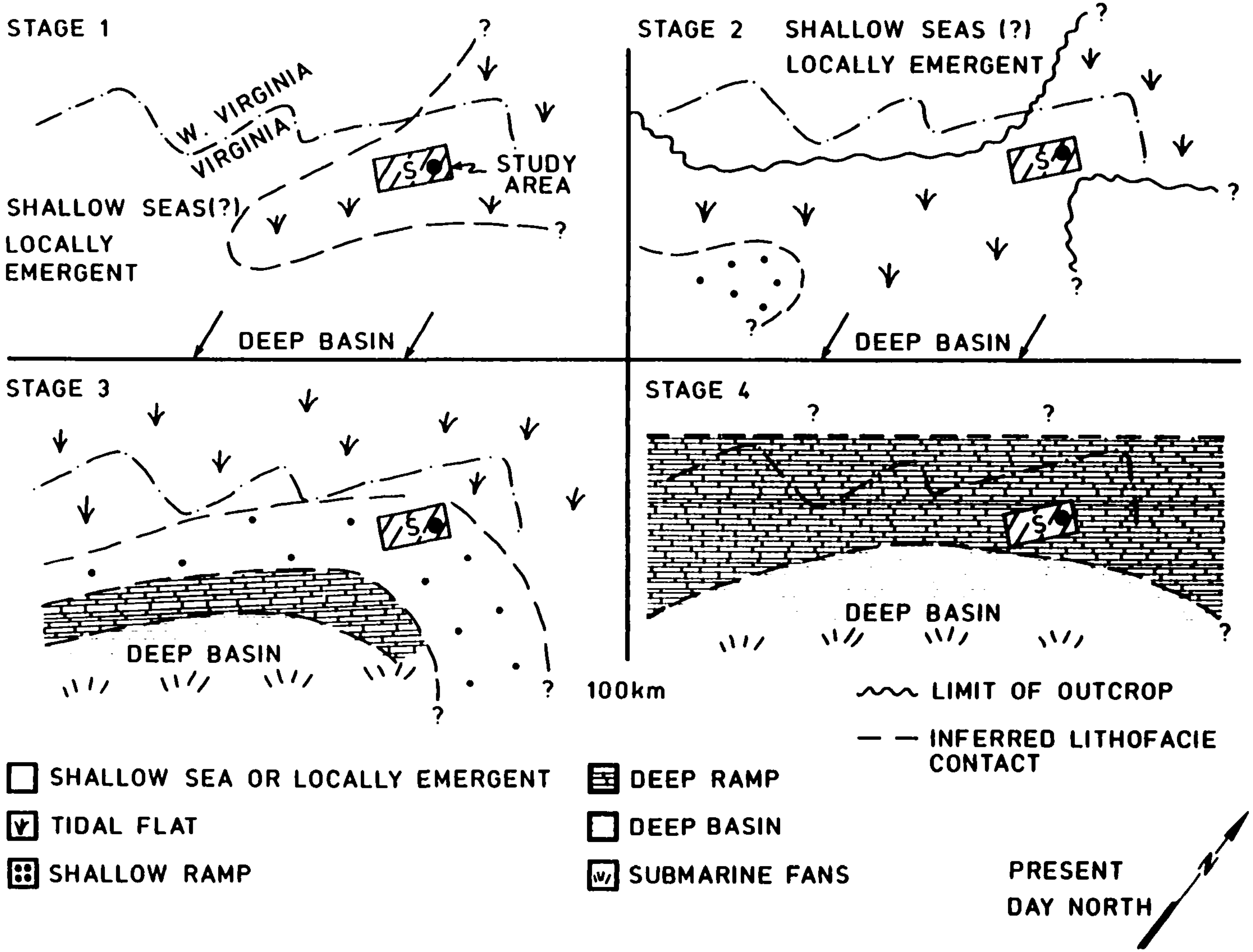
Deposition of the Laminated Lithofacies I of the New Market Limestone in northern Virginia began on an unconformable surface of Lower to Middle Ordovician Beekmantown beds (Fig. 22, Mussman and Read, 1986). The determination of this unconformity is based on the low relief, karst surface; however no break is evident based on paleontologic data. Periodic shoaling to sea-level during the deposition of Lithofacies I, is shown by the intraformational erosion surfaces which truncate sediments, cements, and the sedimentary fabrics. These erosional surfaces suggest early lithification prior to burial and subaerial exposure.

Similar facies (but not necessarily time-correlative) are reported to the north in Maryland and Pennsylvania (Mitchell, 1982). Deposition of thicker more normal marine deposits to the northeast suggests that the seas transgressed from that direction. McBride (1962) states that the deepest part of the northern subbasin during deposition of the overlying Martinsburg Shale was located near the Pennsylvania-New Jersey border. The transgression of Lithofacies I must have come from this direction. Areas to the south were covered by shallow seas or were locally emergent.

Stage 2

The initiation of ramp submergence begun in Stage 1 and continued over most of northern Virginia in Stage 2. It is also highly probable

FIGURE 22. Paleogeographic maps showing the distribution of environments during the successive stages of deposition of the Middle Ordovician limestones in northern Virginia. (Modified after Read, 1980).


STAGE 1
W. VIRGINIA
VIRGINIA
STUDY AREA
SHALLOW SEAS(?)
LOCALLY EMERGENT
DEEP BASIN
STAGE 2
SHALLOW SEAS (?)
LOCALLY EMERGENT
DEEP BASIN
STAGE 3
DEEP BASIN
STAGE 4
DEEP BASIN
100km
LIMIT OF OUTCROP
INFERRED LITHOFACIE CONTACT
SHALLOW SEA OR LOCALLY EMERGENT
TIDAL FLAT
SHALLOW RAMP
DEEP RAMP
DEEP BASIN
SUBMARINE FANS
PRESENT DAY NORTH
N

that this submergence corresponded to a submergence immediately to the north as evidenced by the thick tidal flat and semi-restricted shallow subtidal deposits in Maryland and Pennsylvania (Fig. 22; Facies IV and V of Mitchell, 1982).

Downwarping and the associated marine transgression of the southern depocenter (or subbasin) as it migrated northward over the erosional Knox Group caused widespread flooding of Virgina (Read, 1980). The deposition of a thin transgressive (Mosheim-Lenoir) unit, consisting of lithofacies similar to the New Market Limestone (tidal flat) and the Lincolnshire Formation (shallow ramp) of northern Virginia but not time-correlative to these limestones, indicates that the Post Knox-Beekmantown deposition may have been initiated in two separate sedimentary subbasins. Deposition in two separate sedimentary subbasins was also suggested by Neuman (1951) and Read (1980). These two separate subbasins were probably connected during this stage.

Stage 3

Widespread downwarping in the southeast continued into northern Virginia during Stage 3 where the New Market tidal flat lithofacies were progressively overlain by the shallow ramp Lincolnshire beds consisting of Lithofacies III, IV, and V. Benedict and Walker (1978) suggested that the basin was deepest in Tennessee and became shallower to the southwest and to the northeast. In southwest Virginia, a thick sequence of submarine-fan clastics derived from the tectonic highlands to the southeast were deposited along the eastern basin margin. These clastics graded from deep basinal shales to deep ramp carbonate facies.

Evidence of the initial influx of these clastics into the study area is the bioturbated argillaceous material within limestone beds and the argillaceous shale partings between limestone beds of Lithofacies IV and V (Lincolnshire Formation). This argillaceous material is very fine-grained indicating that it represents the very distal portion of the submarine fans.

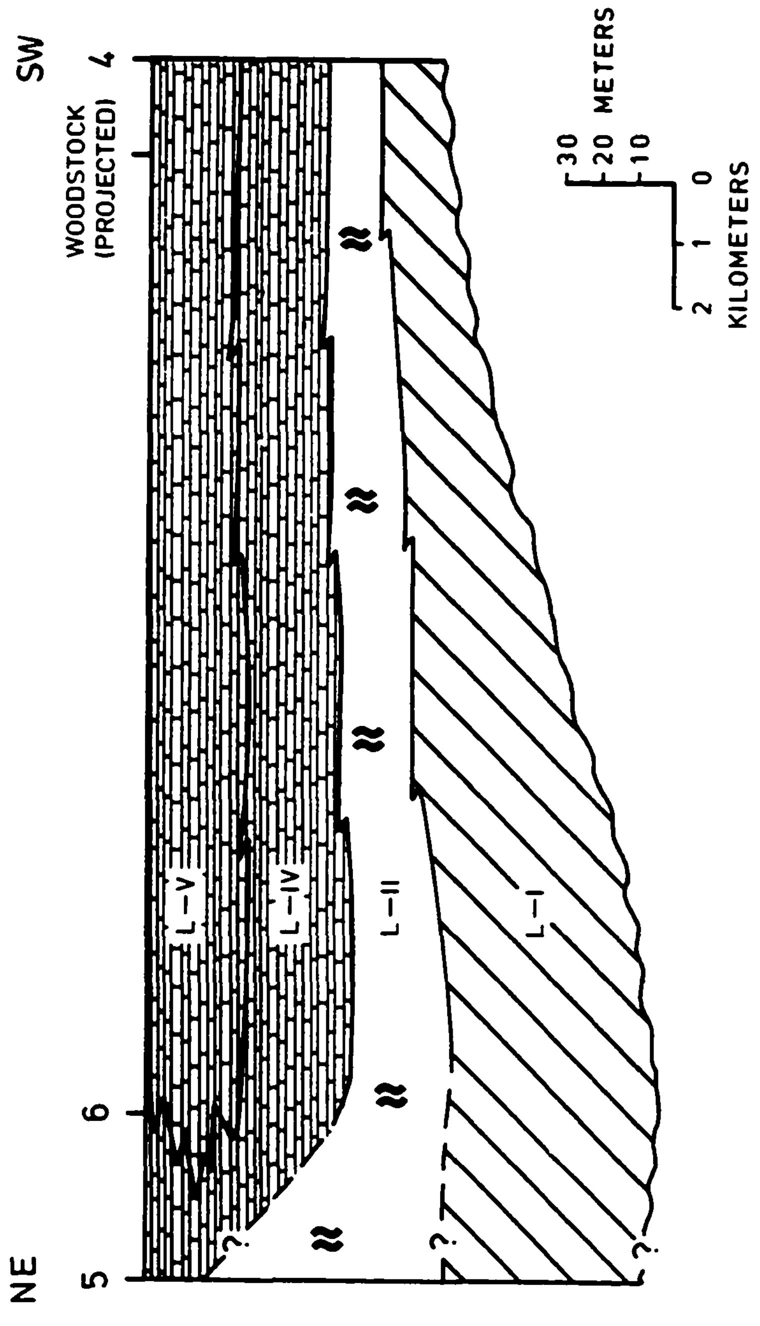
The north and east margin of the basin was bordered by the shallow ramp Lincolnshire lithofacies which tended to close the basin in northern Virginia (Fig. 22; Read, 1980). Hence, Lincolnshire beds were not deposited much further north of the Virginia-West Virginia border. Throughout this area the Lincolnshire Formation graded eastward into into tidal flat facies. Stage 3 represents the final stage of New Market and Lincolnshire deposition in the study area.

Stage 4

Beds overlying the Middle Ordovician New Market and Lincolnshire Formations sugggest that the submergence continued in Stage 4 with the deposition of the deep ramp facies of the Edinburg Formation in northern Virginia and the equivalent units in adjacent area (Read, 1980). These deep ramp facies passed southeastward and eastward into the deep basinal shales and the clastic submarine fans. Facies to the northwest are unknown.

A cross section which is drawn perpendicular to the strike of the beds shows the lithofacies variation in the study area from the northwest to the southeast (Fig. 23). The New Market Limestone, Lithofacies I and II, were deposited as a thick sequence in the northwest (at measured section No. 6) and thinned southeastward

FIGURE 23. Northwest to southeast cross section, drawn perpendicular to the strike of the beds, shows the lithofacies variation in the study area. This cross section was constructed through measure sections 4, 5 and 6. The horizontal distance represents a palinspastic reconstruction (Eugene Rader; personal commun., 1987). Lithofacies (L) in northern Virginia include: L-I, L-II, L-IV and L-V. Lithofacies III does not crop out in this part of the study area.


SW
4
WOODSTOCK
(PROJECTED)
6
NE
5
L-V
L-IV
L-II
L-I
?
30
20
10
0
METERS
2
1
0
KILOMETERS

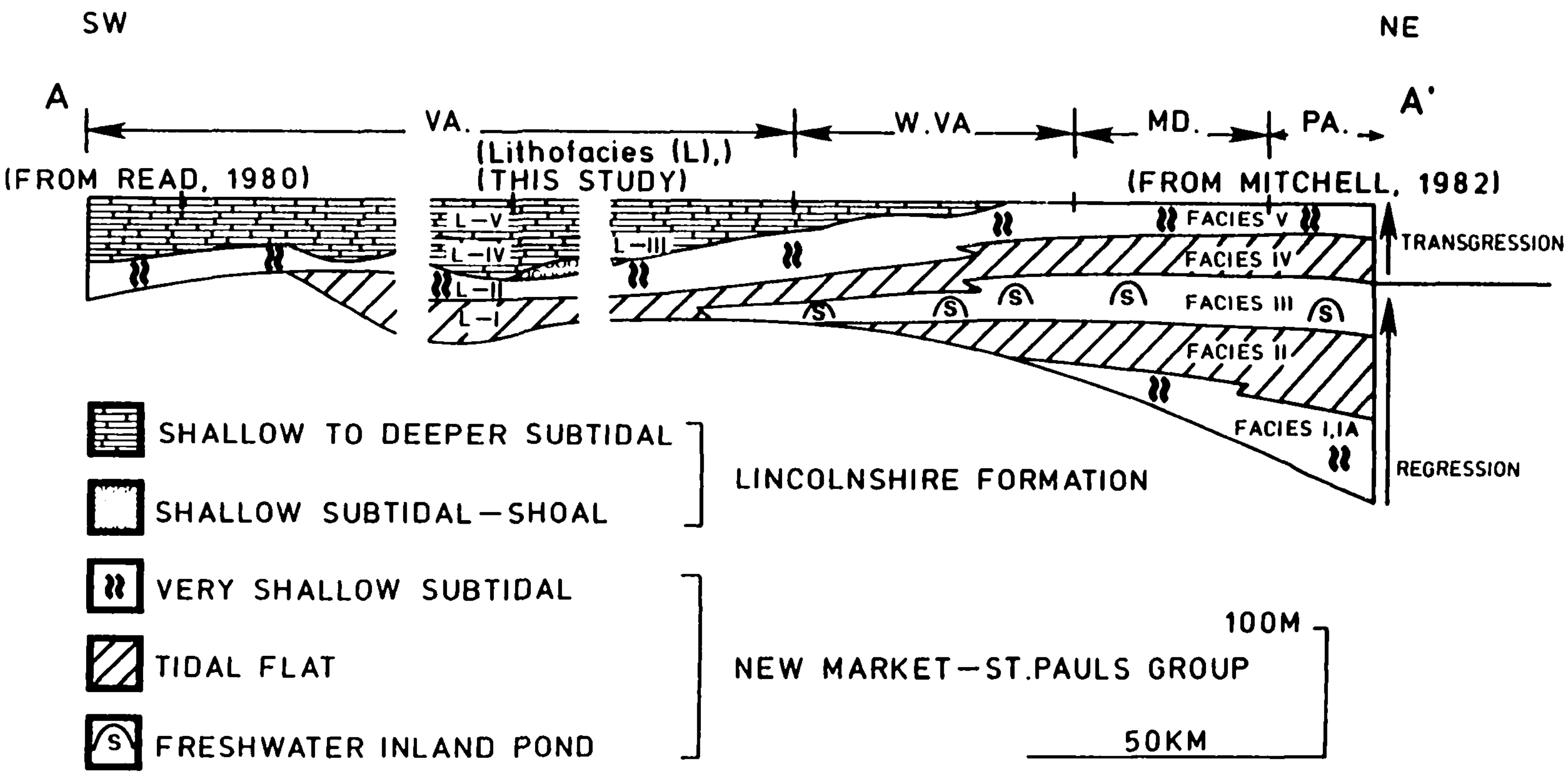
(at measured section No. 4). This indicates that as the seas transgressed into the northwest, still-stand conditions may have prevailed which allowed the thicker tidal flat and then the semi-restricted subtidal lithofacies, I and II respectively, to be deposited on the carbonate ramp. These still-stand conditions probably reflect a balance between sedimentation and submergence. Lithofacies III did not crop out at any of the measured sections in this portion of the study area. The shallow ramp Lithofacies IV and V of the Lincolnshire Formation crop out as a thin unit in the northwest and they thicken to the southeast (or basinward). However, Lithofacies V which is believed to represent deeper "shallow ramp" conditions, was not observed at measured section No. 5 (Fig. 23). This indicates that the basin deepened to the southeast. This deepening is also suggested by the increase in the argillaceous material in Lithofacies V and in the overlying beds of the Edinburg Formation. The deposition of these shallow to deeper "shallow ramp" lithofacies, IV and V respectively, indicates that the carbonate ramp was submerged probably due to the increase in the rate of subsidence over the entire ramp.

F. REGIONAL LITHOFACIES RELATIONSHIPS

The cross section (Fig. 24), drawn parallel to the strike of the Middle Ordovician beds shows the lithofacies variation from the northeast to the southwest. Initially, a relatively stable platform may have existed in northern Virginia. Sedimentary subbasins were forming on the platform in areas to the north and south. The initial subsidence in the northern subbasin deposited Mitchell's (1982) shallow shelf Facies I and IA. The regressive facies (Facies II and III) prograded over these shallow shelf deposits in Maryland and Pennsylvania (Mitchell, 1982). The onset of continued subsidence in the northern subbasin, caused the seas to transgress southward into northern Virginia and deposited the laminated tidal flat Facies IV (Mitchell, 1982) in Maryland and Pennsylvania and the Laminated Lithofacies I in northern Virginia. Subsidence in the southern subbasin, on the other hand, caused the seas to transgress northward depositing a New Market unit similar to but probably not time-correlative to Facies V (Mitchell, 1982). Near the end of New Market deposition the entire platform was submerged connecting the two sedimentary subbasins (Stage 3).

Rapid downwarping in the southeast extending as far as northern Virginia resulted in the deposition of the Lincolnshire Formation in southwestern Virginia and the Lincolnshire Lithofacies III, IV and V in northern Virginia. Submergence of the entire ramp continued causing widespread deposition of deep ramp and basin facies (Stage 4).

FIGURE 24. Cross-section showing the facies variation of the Middle Ordovician Carbonates from northern Virginia and adjacent states. Lithofacies (L) in northern Virginia include: L-I, L-II, L-III, L-IV, and L-V. The facies in Maryland and Pennyslvania, as defined by Mitchell (1982) include: Facies I, IA; Facies II; Facies III; Facies IV; and Facies V. The cross-section is drawn parallel to the Middle Ordovician Shoreline as defined by Read (1980).


SW
NE
A
A'
VA.
W.VA
MD.
PA.
(Lithofacies (L),)
(THIS STUDY)
(FROM READ, 1980)
(FROM MITCHELL, 1982)
L-V
L-IV
L-III
L-II
L-I
FACIES V
FACIES IV
FACIES III
FACIES II
FACIES I,IA
TRANSGRESSION
REGRESSION
SHALLOW TO DEEPER SUBTIDAL
SHALLOW SUBTIDAL-SHOAL
LINCOLNSHIRE FORMATION
VERY SHALLOW SUBTIDAL
TIDAL FLAT
FRESHWATER INLAND POND
NEW MARKET-ST.PAULS GROUP
100M
50KM

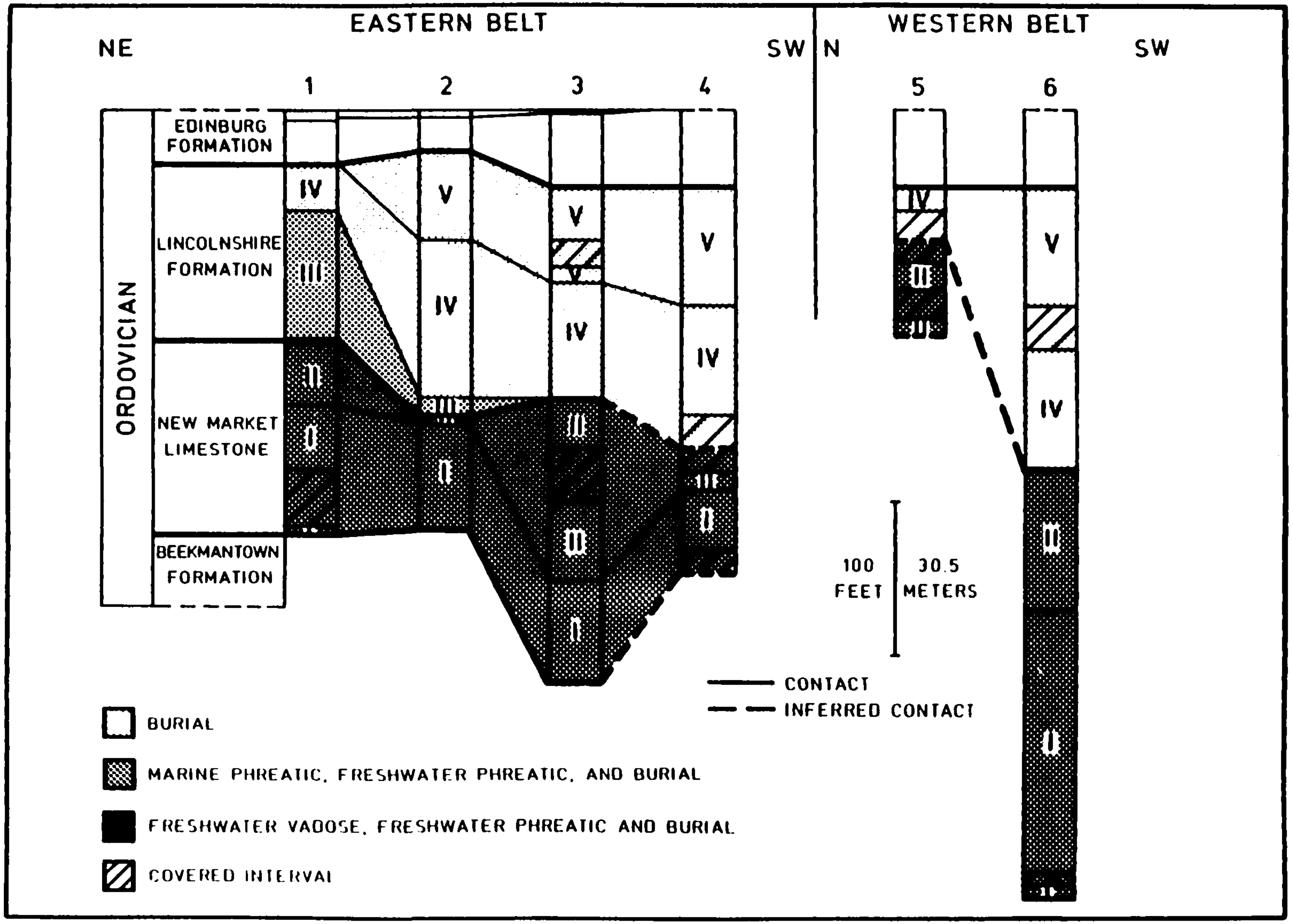
CHAPTER V. DIAGENETIC HISTORY

The Middle Ordovician carbonates have been affected by both shallow subsurface (Longman, 1980) and/or burial diagenetic environments. The diagenetic setting is initially inherited from the depositional setting but is believed to be continually modified during burial (Harris et al., 1985). Our knowledge of shallow carbonate cementation is based in part on studies of carbonates undergoing near-surface (vadose- to shallow-phreatic) diagenesis on small Pleistocene islands (Bathurst, 1971; Bricker, 1971; Matthews, 1974; Longman, 1980). These islands have undergone a complex diagenetic history due to rapid changes in sea-level, and their depositional setting, hydrology, and geologic history may differ from most ancient carbonate platforms that underwent relatively continuous sedimentation and deep burial (Moore and Druckman, 1981). The differences in the depositional parameters and geologic history make it difficult to assess the relevance of such modern diagenetic studies to ancient deposits. The diagenetic environments described in this paper are inferred from both modern and ancient studies of carbonates.

Grover and Read (1978) have documented the fenestral and associated diagenetic fabrics in the peritidal New Market Limestone, located in southwest Virginia which provides a paleoenvironmental interpretation of the Middle Ordovician carbonates in Virginia. Regional cementation patterns of the Middle Ordovician carbonates in Virginia, based on cathodoluminescent patterns, are documented by Grover (1981) and Grover and Read (1983). Such a regional study is beyond the scope of this paper but their work provides information on the regional tectonic uplift during foreland basin development, burial history, depositional environments, climatic setting, cement fabrics, cementation patterns, and the proximity of tectonic highlands. This information is useful to the interpretation of the carbonates in this study. The diagenetic model formulated for the Middle Ordovician carbonates in northern Virginia will be compared to the model suggested for the Middle Ordovician carbonates of southwest Virginia (Grover and Read, 1978) in order to determine the similarities and differences in the paleoenvironmental conditions laterally along depositional strike during the Middle Ordovician.

Three diagenetic zones have been recognized in these carbonates which are associated with the depositional environments (Fig. 25). These are: (1) the tidal flat zone (Lithofacies I and II) where early diagenesis in the shallow, freshwater vadose to phreatic, and burial diagenetic zones occurred; (2) the shoaling, subtidal zone (Lithofacies III) where marine phreatic, freshwater phreatic, and/or burial diagenesis occurred; and (3) the normal marine subtidal zone (Lithofacies IV and V) where mainly burial diagenesis occurred.

FIGURE 25. Diagenetic zones of the Middle Ordovician Limestones in northern Virginia. Three diagenetic zones are recognized: Diagenetic Zone 1, the New Market Lithofacies I and II; Diagenetic Zone 2, the Lincolnshire Lithofacies III; and Diagenetic Zone 3, which consists of the Lincolnshire Lithorfacies IV and V.


EASTERN BELT
NE
SW
WESTERN BELT
N
SW
1
2
3
4
5
6
EDINBURG FORMATION
LINCOLNSHIRE FORMATION
NEW MARKET LIMESTONE
BEEKMANTOWN FORMATION
ORDOVICIAN
I
II
III
IV
V
100 FEET
30.5 METERS
CONTACT
INFERRED CONTACT
BURIAL
MARINE PHREATIC, FRESHWATER PHREATIC, AND BURIAL
FRESHWATER VADOSE, FRESHWATER PHREATIC AND BURIAL
COVERED INTERVAL

A. DIAGENETIC ZONE 1

Lithofacies I and II of the New Market Limestone were deposited in a tidal flat setting and are believed to have been lithified early under freshwater vadose to shallow phreatic conditions. Porosity occlusion may have occurred under burial conditions.

Diagenetic fabrics which occur in the New Market Limestone include: 1) fenestral fabrics, 2) geopetal internal sediments (crystal silt) in fenestrae, and other diagenetic spaces, 3) molds of shells, 4) dissolution or erosional surfaces, 5) common pendant equant and fine- to coarse-equant cements, and 6) dolomitization.

Tidal flat facies typically undergo early, near-surface diagenesis (Friedman, 1964). Diagenetic modifications include cementation, internal sedimentation, and the formation of vadose features (Dunham, 1969). Early diagenetic fabrics are influenced by factors that characterize the depositional environment (Logan, 1974). Such factors are: climate, salinity of tidal and groundwater, freshwater influx, submergence, and emergence. Fenestral fabrics also provide important sedimentologic and environmental information because they result from physicochemical and biological processes (Logan et al., 1974; Logan, 1974). Fenestrae form during or slightly after deposition by processes acting within the depositional environment (Logan, 1974). Therefore, studies of the diagenetic modifications and the fenestral fabrics of the New Market Limestone should provide a better understanding of environmental conditions during and following deposition.

Fenestral Fabric

There are three distinct types of fenestrae found in the New Market Limestone of northern Virginia. These fenestrae are similar in type and in part to the origin of fenestrae described by Grover and Read (1978) for the New Market Limestone of southwest Virginia. Similar types of fenestrae and their origins have been described by other authors (Tebbut et al., 1965; Logan, 1974; Hardie and Ginsburg, 1977).

The fenestral types and their associated origins are as follows:

(1) Tubular fenestrae, formed by burrowing organisms, are generally found in the homogeneous, unlayered mudstones but rarely occur in laminated subfacies where they form homogenized patches (Fig. 8A, Tebbut et al., 1965; Logan, 1974; Grover and Read, 1978). Modern structureless carbonate muds located below mean tide level are homogenized by burrowing organisms (Hardie and Garrett, 1977).

(2) Irregular fenestrae are believed to have formed mainly due to desiccation (Figs. 7B, 8B; Tebbut et al., 1965; Logan, 1974; Hardie and Ginsburg, 1977). These fenestrae commonly occur between grain boundaries and as expansions of intraparticle void spaces in grain-supported rocks suggesting that some packstones were diagenetically formed from mud-supported sediments during fenestral formation (Fig. 9A). Where irregular fenestrae are found in the cryptalgal sediment, they may also have formed by volume increase with precipitation of cements, and possibly by growth and decay of algal mats (Fig. 9B; Logan et al., 1974).

(3) Laminoid fenestrae with matching sides form by "pull-apart" due to desiccation of laminated sediment (Tebbut et al., 1965; Shinn,

1968). Laminoid fenestrae with unmatching sides may also form from desiccation of homogeneous muds (Shinn, 1968). This type of laminoid fenestrae is often associated with erosional surfaces and a unit which lacks marine fossils suggesting that these fenestrae formed mainly due to desiccation during frequent exposure. With increasing formation of laminoid fenestrae, the peloidal mudstones may form diagenetic packstones (Grover and Read, 1978). Laminoid fenestrae commonly form by decay of algal material in modern cryptalgal sediments or occur at interlaminar boundaries that were formerly occupied by algal films (Logan, 1974; Hardie and Ginsburg, 1977). These fenestrae formed by oxidation of algal mats (Logan, 1974) or by desiccation along bedding planes (Hardie and Ginsburg, 1977). It is likely that the laminoid fenestrae of the New Market Limestone formed by desiccation (Figs. 16D., 18) and/or by the growth and decay of algal material (Fig. 8C).

In general, the tubular fenestrae are more common in the unlayered mudstones of the pond and shallow subtidal environments where marine burrowers and browsers rework the sediments. They rarely occur in the laminated subfacies in patches of disrupted homogenized mud. The laminated subfacies of modern supratidal levee deposits remain relatively unbioturbated because the dryness excludes most marine infaunal burrowing organisms (Hardie and Ginsburg, 1977). Likewise, the inland marsh layering is preserved because the low salinity of these freshwater "ponds" keep out the burrowing and browsing marine organisms. The unlayered muds contain desiccation fenestrae (laminoid or irregular fenestrae) where they are associated with erosional surfaces indicating emergence. Laminated subfacies generally contain abundant laminoid and irregular fenestrae which form by desiccation or by algal growth and decay. Some samples contain all three types of fenestrae.

Grover and Read (1978) determined that the fenestral fabrics of the New Market Limestone in southwest Virginia are noncyclic, lack a distinctive vertical sequence, and that all three fenestrae types occur together forming complex fabrics. They suggest that a small fluctuation in the frequency of wetting or emergence of the tidal flat sediments would cause an overprinting of the fenestral types. The overprinting of these fabrics, therefore reflect subtle environmental changes and superimposed diagenetic environments as the tidal flat sediments maintained a near sea-level depositional surface. The New Market Limestone of southwest Virginia does not contain the cryptalgal laminated sediments or the thinly bedded sediments of Lithofacies I indicating that upper intertidal and supratidal algal flat deposits were not deposited or were not preserved in southwest Virginia. The presence of laminoid and irregular fenestrae in the New Market Limestones of southwest Virginia suggest that, in general, algal mat deposition plays a lesser role in the formation of these type of fenestrae. Grover and Read (1978) hypothesize instead that these fenestrae formed mainly due to desiccation and lithification.

Crystal Silt

Mechanically deposited crystal silt is composed of silt-sized carbonate particles (Dunham, 1969) which form the geopetal fabric flooring both primary and secondary void spaces. Several beds in the Laminated Lithofacies I of the New Market Limestone contain geopetal fabrics. Geopetal fabrics generally occur in the intraparticle void spaces of whole ostracodes (Fig. 7A) and less commonly gastropods. These internal sediments may resemble the sediment substrate suggesting that they infiltrated the whole bioclasts upon or soon after deposition and do not represent crystal silts. Few beds, containing abundant fenestrae, have geopetal crystal silt flooring the fenestrae void spaces (Fig. 9B). In general, crystal silt is relatively rare in Lithofacies I, perhaps due to the lack of extensive development of fenestrae and solutional features. The Unlayered Mudstone, Lithofacies II, contains horizons which have geopetal internal sediments (crystal silt). These geopetal sediments are found in molds of bioclasts (Figs. 16A and 16B) and in rare beds which contain abundant fenestrae (Figs. 16D and 16E). The beds containing geopetal sediments are located within the upper 9 meters of the upper contact of the New Market Limestone and near to interformational erosional surfaces suggesting emergence.

The crystal silt consists of a mosaic of calcite crystals and rare peloids. The deposits are massive and unlaminated and the upper surface is typically near horizontal. This silt generally floors but may also completely fill the molds of shells and fenestrae. The silt commonly rests directly on the substrate but may also lie on the fine- to coarse-equant cements which line fenestrae or molds of fossils in Lithofacies II. In rare samples of this lithofacies, fine- to coarse-equant cements predate or are contemporaneous with the crystal silt (Fig. 16E). This is indicated by silt abutting equant cements that line walls of voids and by rare crystal terminations between pendant equant crystals and crystal silt.

Crystal silt which floors or completely fills fenestrae and solutional features is characteristic of vadose diagenesis (Dunham, 1969). This vadose-crystal silt results from the internal erosion of host sediments and cements in the vadose zone and mechanical deposition by percolating meteoric waters (Dunham, 1969). The abundant crystal silt in some beds and lack of silt in others indicate that vadose diagenesis occurred several times during the deposition of the New Market Limestone.

Moore et al. (1976) advised caution in the use of crystal silt as an indicator of vadose diagenesis because it resembles the internal sediments that may be formed by boring sponges in subtidal environments. The crystal silt found in the New Market Limestone is believed to be vadose because it is: restricted to peritidal facies; truncated by erosion surfaces; occurs within solutional features; and is associated with pendant (vadose) cement fabrics. Similar crystal silt was described by Grover and Read (1978) for the New Market of southwest Virginia.

Dissolution Features

Several types of solution features are present in the New Market Limestone including: molds of shells, rare solution enlarged molds of shells, and possible solutional vugs. The molds of shells in Lithofacies I are mainly whole to fragmented gastropods and ostracods (Figs. 10A and 10B). The *Tetradium* corals typically form molds in Lithofacies II where shell structure is only rarely preserved (Figs. 16A and 16B). Rare molds appear to be modified to form subspherically-shaped, solution-enlarged molds of possible gastropod shells in which the original shape is somewhat recognizable. Some voids have irregular outlines that show little to no evidence of a skeletal host. These may represent rare solutional vugs (Fig. 18). These solutional features are filled with fine- to coarse-equant cements and may be floored by crystal silt.

The solutional features (including molds of shell and possible solution-enlarged molds and solution vugs) in the New Market Limestone indicate selective dissolution of metastable carbonate phases. Holocene carbonate sediments are mainly composed of metastable aragonite and high-magnesium calcite. Little dissolution of these minerals occurs by marine waters that are saturated with respect to calcium carbonate and contain free Mg^{+2} (Bathurst, 1971). Dissolution of these phases may occur in the marginal marine environment where waters are undersaturated with respect to calcium carbonate due to an influx of meteoric water; however, it may also occur in the freshwater vadose and phreatic diagenetic environments. The association of solutional features with vadose crystal silt suggest periodic movement of freshwaters (meteroic) through the sediments and dissolution in the vadose zone (Grover and Read, 1978). On the other hand, where molds of shells (such as the Tetradium corals) are filled with equant cements, dissolution may have occurred in the freshwater, shallow phreatic diagenetic zone (Longman, 1980).

Erosional Surfaces

Erosional surfaces occur within Laminated Lithofacies I (Fig. 7C) and on top of Lithofacies II (Figs. 17A, 17B and 18) of the New Market Limestone. The intraformational erosional surfaces are marked by a planar to slightly irregular contact between carbonate units of laterally contiguous subenvironments of the tidal flat, Lithofacies I. These erosional surfaces indicate early lithification because they truncate the sediments and cements in the underlying carbonate unit and the overlying unit typically contains reworked clasts of the underlying cemented sediments in a coarse, dolomite silt. The intraformational erosional surfaces probably resulted from emergence, early lithification, mud-cracking, and desiccation of the peritidal sediments followed by limited erosion and deposition of overlying sediments during storm washovers. Similar sediments and contacts have been observed in modern Bahama Andros Island tidal flats (Hardie and Ginsburg, 1977).

Interformational erosional surfaces occur at the top of the New Market Limestone and are marked by an abrupt lithologic change from Lithofacies II to Lithofacies III - Bioclastic-peloid packstones or Lithofacies IV - dark gray, bioclastic wackestones. These interformational surfaces are described by Read and Grover (1977). The surfaces have a scalloped to planar outline and are scoured into the underlying New Market Mudstones by up to 0.2 meters. The sediment, cements, and fenestral fabrics are truncated by the erosional surface.

These interformational erosional surfaces indicate early lithification because they truncate the sediments and cements of the underlying unit (Read and Grover, 1977). These surfaces are believed to have developed by solution and early lithification under subaerial conditions followed by intertidal erosion during subsequent marine submergence. Erosional surfaces which indicate subaerial exposure or emergence, also support early lithification in the freshwater vadose to shallow phreatic diagenetic environments.

Equant Cements

The New Market Limestone in northern Virginia is cemented by fine- to coarse- and pendant-equant cements (blocky and drusy cements). They are composed of clear euhedral to subhedral crystals that have straight, curved to irregular crystal interfaces. The crystals are generally in sharp contact with the substrate and geopetal internal sediments. Most equant cements occur as a mosaic of calcite crystals commonly displaying a void-filling fabric where crystals show a gradual increase in size towards the center of the void or normal to the initial substrate (Figs. 8C and 16A; Bathurst, 1971). Some fenestrae are filled by a single equant crystal (Fig. 9B).

Many fenestrae or molds of bioclasts show two generations of equant cements (Figs. 16A and 16B). A first generation of fine-equant crystals may form a thin continuous fringe lining the void (isopachous rim cement, Fig. 16A) or a discontinuous fringe on the roof of voids (pendant-equant cement). A later generation of fine- or coarse-equant cement or rarely a single equant crystal generally occupies the remaining pore space. Some samples have internal sediments (crystal silt) that floor or fill the remainder of the void (Fig. 16D). In the examples which are floored by crystal silt, the remainder of the pore space is filled by void-filling or two-generations of fine- and coarse-equant cements (Figs. 7A, 9B, 16A and 16B). Rare samples have pendant-equant cement with euhedral crystal terminations abutting crystal silt (Fig. 16E).

Early cementation features include: truncation of cements by the erosional surfaces, vadose crystal silt resting directly on cement-lined fenestrae or molds of shells, solutional features which show no evidence of compaction, pendant equant cement, and pendant equant cements which abutt vadose-crystal silt.

The New Market Limestone is cemented by equant cements. These cements frequently have a pendant morphology indicating precipitation from freshwaters in the vadose zone (Muller, 1971). This diagenetic environment is supported by its association with other vadose features such as crystal silt and solutional features. Pendant equant cements ("gravitational cements" of Muller, 1971) form by a two-phase system, air-water, where water has drained out of the pores and/or evaporated leaving a thicker water film (drop) of calcium-carbonate rich waters on the undersides of grains due to surface tension and precipitate as pendant equant cements (Purser, 1969; Logan, 1974).

Equant cements in limestone sequences are generally believed to be burial cements related to pressure-solution (Oldershaw, 1971). However, the initial equant cements in the New Market Limestone are believed to have been precipitated early. Evidence suggesting early precipitation includes: the association with vadose-crystal silt which rest on equant cements and pendant-equant cements which show crystal terminations at the cement-crystal silt boundary indicating that the cements predated or formed contemporaneously with the crystal silt. Furthermore, the equant cements are truncated by erosional surfaces. The equant cements which line voids predating vadose-crystal silt may have formed in the freshwater phreatic zone. This indicates that the carbonate sediments may have fluctuated between the freshwater vadose and shallow phreatic diagenetic zones. Subsequent cementation may have taken place in the shallow to deeper burial environment.

Grover (1981), based on cathodoluminescent cement patterns, suggested that cementation of the laterally equivalent New Market Limestone, in southwest Virginia, continued under increasingly more reducing conditions of pore waters. He found that early cements formed under oxygenated vadose to shallow phreatic waters. Subsequent reducing conditions may be due to oxidation of organic matter, stagnation of pore waters and/or by low permeability of fine-grained beds and by aggradation of tidal deposits under gradually transgressive conditions (Grover, 1981). Porosity occlusion of the New Market Limestone in northern Virginia may have occurred under similar increasingly reducing conditions.

Early Dolomitization

Dolomite is found in most subfacies of the Laminated Lithofacies I. The subfacies which generally contain dolomite are: Planar Laminates (Fig. 11), Disrupted Flat Laminates (Fig. 12), Disrupted Dololaminates (Figs. 7C and 13) and the Very Thin Bedded subfacies (Figs. 7, 8, and 9) of the levee and algal marsh subenvironments. The unlayered mudstone subfacies of the tidal pond subenvironment did not contain dolomite. The dolomite occurs as fine to coarse dolomite rhombs which are desiminated throughout the sediments as cryptocrystalline dolomite surrounding peloids (Fig. 9A) and filling intraparticle spaces or as a dolomitic "silt." Rare samples which are believed to represent algal tufa, also contain dolomite surrounding calcite spar-filled, branching tubular features believed to represent algal filament molds (Fig. 13).

In the modern Bahama Andros Island tidal flat deposits, Hardie (1977) describes cemented crusts (a few centimenters thick) which occur above the mean tide level. These crusts were found to contain very high magnesium calcite or protodolomite. They occur as surface crusts on the backsides of levees, on high algal marsh fringing the tidal ponds and on isolated highs along the seaward edge of the inland algal marsh. In the subsurface, these crusts were found beneath levees, beneath the upper pond sediments, and they are characteristic of all cores of the inland algal marsh sediments. Agal tufa is also believed to be produced in the subsurface of the inland marsh (Hardie, 1977). The absence of subsurface production of tufa in the channeled belt may be explained by the increased bioturbation and bacterial reduction in the seawater setting of the channeled belt system (Hardie, 1977).

The actual processes of cementation of these dolomitic crusts have not been entirely resolved. Hardie (1977) suggests possible mechanisms by which these crusts are being formed.

Two types of crusts are described: the algal tufa of inland marshes and the cemented sediment crusts of the channelled belt. The algal tufa of Andros Island is composed of pure calcite to magnesium calcite which is precipitated around algal filaments (Hardie, 1977). The algal tufa precipitation may be induced by the evaporation and/or photosynthesis of groundwaters drawn up as capillary films around Scytonema filaments. At Three Creeks, Andros Island the inland marsh tufas have higher $MgCO_3$ concentration at the seaward edge due to seawater contamination than in the freshwater inland lakes.

The non-tufa crusts occur in the seawater-dominated channelled belt. These crusts form by inorganic precipitation from supersaturated interstitial vadose waters which are formed by evaporative capillary action or by dissolution of aragonitic sediments. Cement crusts in the channel belt environment is more pervasive because seawater is very close to critical supersaturation with respect to Mg-calcite, so that only a small amount of evaporation would be effective in promoting nucleation.

Dolomite found in tne New Market peritidal subfacies, of the Laminated Lithofacies I, may have formed under similar processes as the "dolomitic" crusts of the Bahama Andros Island. In the New Market limestone, the presence of dolomite would indicate early lithification at the surface or with whallow burial in the vadose to shallow phreatic environments. The waters which percolated through these Middle Ordovician limestones must have been contaminated with seawater to provide the Mg^{+2} ions necessary to produce dolomite.

Evidence for Vadose to Shallow Phreatic Diagenesis

The association of crystal silt, pendant equant cements, dolomitization, and erosional surfaces that truncate sediments and clear cements indicate early lithification of the New Market peritidal beds, under vadose to shallow phreatic conditions (Dunham, 1969; Muller, 1971; Logan, 1974; Read and Grover, 1977; Grover and Read, 1978).

Vadose alternating with phreatic diagenetic zones may be caused by vertical water table fluctuations due to tidal, seasonal, or longer term changes (Taylor and Illing, 1969; Matthews, 1971). The interstitial waters are also affected by these fluctuations, possibly due to lateral migration of the freshwater phreatic lens and the brackish waters of the mixing zone (Longman, 1980). During the wet periods, an extensive freshwater phreatic lens would develop and the vadose zone would be absent or poorly developed. The interstitial waters would be freshwater (meteoric waters) which would result in the dissolution of metastable carbonates and precipitation of low magnesium carbonate cements with equant fabrics.

During relatively dry periods, the vadose zone might be well developed. Interstitial pores may be filled with air and water. Meteoric water is important in early modification and lithification of carbonate sediments under vadose conditions (Friedman, 1964). In this environment, carbonates may be dissolved and removed by groundwaters or reprecipitated as low magnesium calcite cements (Harris and Matthews, 1968). Cements include pendant equant or fine-equant cements. The general lack of porosity and the early lithification of the New Market Limestone might be due to the reprecipitation of the dissolved carbonates as cements in the vadose and/or phreatic diagenetic zones. Crystal silt, formed by internal erosion of sediments and cements, may also be deposited by percolating freshwater in the vadose zone (Dunham, 1969).

The vadose-freshwater lens may be contaminated with seawater during marine flooding. Dolomitization might occur by evaporation and/or photosynthesis of brackish waters drawn up around algal filaments or by inorganic precipitation from supersaturated waters in the vadose zone (Hardie and Ginsburg, 1977). The freshwater phreatic lens may be displaced landward, during dryer periods, resulting in contamination of the groundwater with the more brackish waters of the mixing zone (Longman, 1980). The important diagenetic process in the mixing zone is dolomitization (Badiozamani, 1973; Land, 1973; Longman, 1980). Minor dolomitization of the New Market Limestone in northern Virginia might have occurred under vadose to shallow phreatic conditions, similar to the Bahama Andros Island, indicating early dolomitization of the sediments. It is likely that the diagenetic processes of the New Market Limestone resulted from periodic seasonal or long-term fluctuations in the groundwater level (or composition) in the tidal flats and/or from minor fluctuations in sealevel.

Another criterion which supports vadose to shallow phreatic diagenesis is the absence of subtidal marine deposits in the New Market carbonates. This suggests that a depositional surface in the tidal/supratidal zone may have been maintained for long periods, supporting early lithification of the New Market Limestone. The New Market sequence in northern Virginia varies from 18 meters to a maximum of 76 meters thick and may have taken 40-250 Ka to accumulate, given that sedimentation rates of similar Holocene tidal flat sediments are about 30 to 50 $cm/10^3$ yrs. (Logan, 1974). This is believed to have been ample time for intense lithification under vadose to shallow phreatic conditions (Logan, 1974). Pleistocene limestones that are 80-140 Ka old (Gavish and Friedman, 1969) have been cemented in a humid climatic setting similar to that interpreted for the Middle Ordovician in northern Virginia. A climate of high rainfall relative to evaporation is suggested by the abundant vadose-crystal silt, pendant-equant cements, solutional features and by the absence of evaporites or their pseudomorphs which are common in tidal deposits from arid to semiarid climates. A humid climatic setting is suggested for the Andros Islands depositional environments (Hardie, 1977) which are used as modern analogs for the New Market Limestone lithofacies of northern Virginia. Grover and Read (1978) suggest a similar diagenetic setting for the New Market Limestone of southwest Virginia. The similarity in the diagenesis of the New Market Limestone, laterally along strike, indicates that the paleoclimate was similar throughout the New Market depositional area.

B. DIAGENETIC ZONE 2

Lithofacies III of the Middle Ordovician Lincolnshire Formation was deposited in a normal marine subtidal and current washed shoal depositional environment. These carbonates are believed to have undergone diagenesis in the marine phreatic environment, followed by the freshwater phreatic environment and/or shallow to deeper burial zone. Rare samples contain features which indicate possible vadose diagenesis; these features predate the "freshwater" phreatic and/or burial diagenetic features.

Diagenetic features of the bioclastic-peloidal-oncoidal packstones of Lithofacies III suggest that these sediments were initially modified in the marine phreatic environment. Such features include micritized grains and bioclasts and possibly bladed cement fabrics. Bladed cements may occur in the marine or freshwater phreatic environments (Longman, 1980). Freshwater phreatic diagenesis and/or burial diagenesis is suggested by the abundant equant and syntaxial rim cement types.

Most carbonates that are deposited in a marine setting begin their diagenetic history in the marine phreatic environment (Longman, 1980). This diagenetic environment is characterized by micritization which generally occurs under more stagnant conditions and slower depositional rates compared to marine cementation which occurs with active circulation of seawater through the sediments. Vadose conditions are suggested in rare peloidal wackestones which contain desiccation fenestrae. The vadose diagenetic environment was described in detail in the previous section (Diagenetic Zone 1). The freshwater phreatic diagenetic environment is characterized by rapid and extensive cementation (Longman, 1980). Cement fabrics include equant cements and syntaxial rim cements. These cements also form in the subsurface making it difficult to distinguish the phreatic zone diagenesis from burial diagenesis (Wilson, 1975).

Micritization

Lithofacies III, contains abundant micritized grains and grains with dark micritic coating. These grains include peloids, bioclasts and oncoids (Figs. 19A, 19B and 19C). Some possible bioclasts have been dissolved out and partially replaced with equant calcite spar that is post-dated by chert which fills the remaining pore space. Their original shapes are preserved by the micrite envelopes and micritized oncolitic coating. The chert was probably emplaced during a later stage of burial diagenesis. Some oncoids display intertwined, micron-sized tubes that are filled with microspar. These tubes may be preserved remains of the boring algae Girvanella problematica (Fig. 19B; Barthurst, 1971).

Boring algae, fungus, and sponges may produce micrite envelopes on carbonate grains and bioclasts (Bathurst, 1971). The order of events by which these envelopes are produced are: (1) boring and colonization by algae, (2) death of algae and vacation of the algal tubes, and (3) emplacement of micritic aragonite or high-magnesium calcite in the tube by an unknown processes to make micritic rods (Bathurst, 1971). By repeating this process, the carbonate grains are gradually and centripetally replaced by micrite. This process has been referred to as micritization (Bathurst, 1971). Complete micritization of grains or bioclasts produces silt-to sand-sized crytocrystalline or micritic peloids.

Initially, the micrite envelopes are composed of aragonite or high-magnesium calcite with a high content of organic matter (Bathurst, 1971). In ancient limestones, these envelopes (or micritized grains) are composed of low-magnesium calcite and if the envelope has formed around an aragonitic grain then the aragonite core has normally been replaced by calcite-spar. This suggests that during freshwater phreatic diagenesis the grain, if aragonitic, was dissolved-out leaving the organic matter as a mold before precipitation of low-magnesium calcite cements (Bathurst, 1971). If the grain or bioclast was composed of high-magnesium calcite it would simply lose the Mg^{+2} as in Lands' Stage III diagenesis (Bathurst, 1971).

Bladed Cements

Bladed cements consist of elongate crystals with planar intercrystalline boundaries and well-defined crystal terminations. The individual crystals are oriented normal to the surface of the bioclasts and their size increase toward the center of the pore space. Their outward increase in crystal size is a product of competitive crystal growth (Bathurst, 1971). The bladed cements do not completely fill the void space. They occur as isopachous rim cements around bioclasts (Fig. 19C) or as pendant bladed cements (Figs. 19A and 19C) forming on the undersides of elongate bioclasts in the shelter porosity spaces. The bladed cements appear to be substrate controlled, i.e., they grow preferentially on bioclasts. The elongate bioclasts display bridging and shelter porosity fabric, exemplified by grains caught above flat fragments or flat fragments acting as protectors to underlying pore space which becomes filled with cements (Wilson, 1975). The accumulation of peloids on top of some elongate bioclasts (bridging effect) appears to prohibit the growth of isopachous bladed cement fabric restricting instead to the underlying sheltered pore space.

Because the formation of pendant fabric of bladed cements appears to be substrate controlled, these cements are interpreted to have been formed in the phreatic environment instead of a vadose environment as described for other pendant cements in the New Market Limestone. Acicular cements consisting of aragonite and high magnesium calcite occur in Quaternary sea-floor cemented sediments (Shinn, 1971; Purser, 1969) and beach rocks (Schmalz, 1971). These unstable mineralogies alter to bladed calcite cements (columnar or fibrous cements) in ancient carbonates (Purser, 1969). The bladed calcite cements may form under hypersaline and aragonite- precipitational fields characterized by marine brines (Logan, 1974). Bladed cements may also develop in a mixed marine-freshwater phreatic environment (Schmalz, 1971). Cementation occurs mainly during the influx of meteoric waters when intertitial waters are brackish rather than hypersaline (Schmalz).

Well developed bladed cements in Lithofacies III are rare, suggesting precepitation in beachrock or in the submarine environment under mixed marine-freshwater phreatic conditions. These cements occur in a few bioclastic-peloidal packstones which contain abundant bioclasts of mainly elongate brachiopods, bryozoans and crinoid fragments. These samples are from the measured section No. 1.

Equant and Syntaxial Rim Cements

Clear equant and syntaxial rim cements overlie the host sediments or abut the bladed cements. Equant cements occur on polycrystalline grains and within intraparticle spaces of fossils (Figs. 19A and 19C). Commonly, the cement consists of fine equant crystals which coat grains or fill intraparticle and interparticle spaces. Most crystal are equidimensional with flat to rounded crystal interfaces. These fine equant crystals may be in contact with syntaxial rim cements, or they may be post dated by a mosaic of coarse equant crystals. Coarse equant crystals are subhedral to anhedral with straight, curved and irregular crystal faces. Some spaces are filled entirely by coarse equant cements. Equant cements may also show the typical void filling fabric where crystal size increases towards the center of the pore space.

Syntaxial rim cement coats palmatozoan grains (Figs. 19A, 19B, and 19C). The host is usually a crinoid columnal that is constructed of a single crystal and the rim cement or overgrowth retains crystallographic continuity with the original grain. The core is often recognized by its inclusions or outer rim of impurities as a ghost structure. The outer boundaries of the rim cements are in contact with other rim cements, equant cements, bladed cements, or detrital grains. Rim cements also enclose adjacent polycrystalline grains (mainly bryozoans and peloids). In cases where the syntaxial rim cement abuts micrite, the cement may have formed by grain growth or replacement (Chilingar et al., 1979). The crystal interfaces are generally planar and most crystals tend to be equidimensional.

Equant and syntaxial rim cements are the most abundant cement types of Lithofacies III. These cements are also similar to those found in packstones of Lithofacies IV and V of the Lincolnshire Formation. Such cement fabrics may form in the freshwater phreatic and/or shallow to deep burial diagenetic environments (Wilson, 1975; Longman, 1980).

Evidence of Marine Phreatic, Freshwater Phreatic and/or Burial Diagenesis

Diagenetic features in Lithofacies III, of the Lincolnshire Formation, do not show evidence of early lithification in the vadose to shallow phreatic environments. Features associated with these environments (pendant cements, crystal silt, solutional spaces and erosional surfaces) are absent. Instead, the sediment particles have been micritized by boring algae and initially cemented by bladed cement in the marine phreatic environment during or soon after deposition. The bladed cement types may indicate precipitation of cements under hypersaline- and aragonite-precipitation fields (Logan, 1974) or from mixed meteoric-marine waters (Schmalz, 1971). An arid climate is characterized by an aragonite precipitation field and the development of supratidal evaporite minerals (Logan, 1974). The lack of evidence for such a climate in Lithofacies III and the rarity of bladed cement horizons suggests dilution of interstitial marine waters with meteoric waters. This is probably due to the influx of freshwaters or continental waters as a result of high rainfall relative to evaporation. There may have been periodic development of ephemeral brines (hypersaline tidal/groundwaters which would allow the development of bladed cements. Extensive dilution of interstitial marine waters with freshwater would also inhibit the development of bladed cements from mixed marine-meteoric waters (Schmalz, 1971).

Development of a marine vadose zone is suggested by rare samples which contain micritized grains, micrite envelopes, and desiccation fenestrae (lamininoid and irregular) but lack features which characterize the freshwater vadose environment (such as solutional features, erosional surfaces, and pendant equant cements).

Syntaxial rim and equant cements are volumetrically the most important cement types in Lithofacies III. These cements may form in the freshwater phreatic or shallow to deep burial environments. Grover (1981) has shown that the subtidal facies of similar Middle Ordovician carbonates south of the study area are dominated by dull cements which are burial in origin. However Lithofacies III, in northern Virginia, generally lack intense grain-to-grain pressure solution fabrics and/or extensive breakage of shells. Such fabrics would be expected where cementation occurred during or after the burial compaction phase of diagenesis (Moore and Druckman, 1981). This suggests that the competence of these rocks had been enhanced by cementation under shallow burial conditions. These beds were not affected by the paleoaquifer which carried oxidized meteoric waters from the recharge area of the tectonic highlands to the southeast as was the case for the subtidal lithofacies in southwest Virginia

(Grover, 1981). Oxidizing waters may have been incapable of reaching these sediments due to their distance from the uplands and because ground water undergoes a decrease in redox potential as it migrates downslope from upland recharge areas to more distant discharge areas (Grover, 1981). The Lincolnshire Formation of southwest Virginia is thought to have been cemented mainly under shallow to deeper burial conditions (Grover, 1981; Grover and Read, 1983). These burial cements overlie minor marine cements. No micrite envelopes have been described for the Lincolnshire Formation in southwest Virginia.

Because the Lincolnshire Formation in southwestern Virginia and northern Virginia are lithostratigraphically similar and possibly time-transgressive, a similar diagenetic history may be inferred. A shallow to deeper burial diagenetic history of these rocks is supported by similar diagenetic features, such as the lack of extensive compaction which suggests that the integrity of these rocks was enhanced under shallow burial conditions and by the presence of abundant equant and syntaxial rim cements which may form under shallow to deeper burial conditions. Furthermore, these rocks are believed to have undergone a similar geologic history of progressive burial of these beds by 3,000 m of Middle Ordovician through Mississippian sediments followed by Pennsylvanian-Permian overthrusting (Grover, 1981).

C. DIAGENTIC ZONE 3

Lithofacies IV and V of the Lincolnshire Formation were deposited in a normal marine, shallow subtidal environment. These carbonates are believed to have undergone mainly shallow to deeper burial diagenesis. Cements included rare bladed cements and common syntaxial rim and equant cements. These cements are similar to the cement types described for Lithofacies III in Diagenetic Zone 2. Other diagenetic features include abundant bioclasts broken during compaction and healed by later ferroan calcite cements (Grover, 1981), dolomite, chert nodules, and late tectonic fractures which are filled with late calcite cement.

Bladed Cements

Bladed cements resemble those described for Lithofacies III (Diagenetic Zone 2). These rare cements occur as thin isopachous fringes around bioclasts or beneath bioclasts in the bioclastic packstones/grainstones (Fig. 20C). The bladed cements abut syntaxial rim and equant cements. These cements may suggest minor cementation under a mixed marine-freshwater phreatic environment similar to Lithofacies III. These lithofacies lack the dark micrite coats and micritized grains common in Lithofacies III.

Equant and Syntaxial Rim Cements

The equant and syntaxial rim cements are also coincident to those described for Lithofacies III (Diagenetic Zone 2). Syntaxial rim cements occur on pelmatazoan grains and commonly abut or enclose polycrystalline grains, or abut other syntaxial rim, equant, or rarely bladed cements (Fig. 20C). Equant cements occur on polycrystalline grains and as intraparticle and interparticle cements (Figs. 20C and 20D). They generally form void-filling fabric where the crystal size increases toward the center. Some spaces are filled entirely by coarse equant cements. Most equant cement crystals have curved to rounded crystal interfaces.

Evidence for Burial Diagenesis

The Lincolnshire Lithofacies IV and V are believed to have been cemented mainly under burial conditions. The cements do not show evidence of early lithification in the vadose to shallow phreatic environments. Features associated with these environments (pendant cement fabrics, solutional features and erosional surfaces) are absent from these lithofacies. Instead, the cements of Diagenetic Zone 3 are isopachous or substrate controlled. Also, these lithfacies are subtidal in origin and probably not influenced by vadose/shallow phreatic diagenesis during deposition.

Cementation under shallow to deeper burial conditions is supported by ferroan dolomite (Grover, 1981), the presence of abundant grains broken during the compactional phase which are healed by later clear equant cements (Fig. 20D) and by the widespread occurrance of tectonic fractures which are filled by late clear equant cements (Fig. 20A). These tectonic fractures are believed to have formed prior to or during major Late Paleozoic deformation (Grover, 1981). Such features were used elsewhere as evidence of burial cementation (Moore and Druckman, 1981; Grover, 1981). The spar-filled tectonic fractures cut across the chert beds and nodules indicating that they formed after the chert formation. Ferroan dolomite rhombs (Grover, 1981) occur in the dark argillaceous silt partings and burrow mottles and also within the chert.

The chert nodules are formed by silica replacement under shallow to deeper burial conditions. A replacement origin with reducing conditions due to burial is supported by the preservation of bioclasts, patches of lime mud clasts, dark "organic" material, large ferroan dolomite rhombs, calcite-spar, and disseminated crystals of pyrite and hematite as remnants in the chert nodules (Fig. 20E). These nodules generally form along the bedding planes which suggests that the source of the silica may be the argillaceous shale interbeds. Some cementation prior to silica replacement is evident by the preservation of calcite-spar and dolomite as cements in the chert.

A burial diagenetic history is also supported by the geologic history of the Paleozoic sequence in Virginia. The geologic history indicates that these Middle Ordovician limestones were progressively buried by 3,000 m (10,000 feet) of Middle Ordovician through Mississippian sediments followed by tectonic thickening of the sequence by Pennsylvanian-Permian overthrusting (Grover, 1981; Grover and Read, 1983).

Studies of regional cementation patterns by Grover using cathodoluminescence, show that the Lincolnshire beds in the northwestern belts of Virginia (including the study area of this paper) are dominated by dull burial cements. Lincolnshire beds (Lithofacies IV and V) lack intensive grain-to-grain pressure solution fabrics and extensive breakage of shells. These features would be common if cementation had occurred during or after the burial compaction phase (Moore and Druckman, 1981). This suggests that the competence of these rocks had been enhanced by cementation under shallow burial conditions. A later cementation phase during or after compaction is indicated by the abundant fractured bioclasts which are healed by late clear calcite cements and the widespread occurrence of tectonic fractures which are filled by clear calcite cements. This cement probably formed under deeper burial conditions and is the last cement precipitated.

D. DISCUSSION OF THE DIAGNETIC HISTORY

The diagenetic history appears to have been strongly influenced by the conditions which prevailed in the depositonal environment and/or by the burial history of the Middle Ordovician carbonates. Diagenetic Zone 1 comprises Lithofacies I and II of the New Market Limestone. These lithofacies have been deposited in a peritidal environment and have undergone early lithification and other diagenetic modifications in the vadose to shallow phreatic environments. The diagenetic fabrics were strongly influenced by the factors that characterized the depositional environment (Logan, 1974). The diagenetic features include: the development of fenestral fabrics, crystal silt, solutional features, erosional surfaces, early dolomitization, and cementation by pendant equant and equant cements. These features indicate that the New Market beds had maintained a depostional surface in the tidal and supratidal zones for long periods. This is supported by the lack of subtidal marine sediments and the slow sedimentation rate inferred by analogy to recent carbonate sediment accumulation.

Lithofacies III which encompasses Diagenetic Zone 2 was deposited in a normal marine and current washed shoal environment. Diagenesis was intitiated in the marine phreatic environment with the development of micrite envelopes, complete micritization of grains, and partial cementation by bladed cements. The bladed cements are believed to have been precipitated in a mixed marine-freshwater phreatic environment (Schmalz, 1971). The pore space in Lithofacies III is occluded by syntaxial rim and equant cements. These cements are believed to have been formed under shallow to deeper burial conditions. The lack of intensive grain-to-grain pressure solution fabrics and abundant broken grains indicates that the competence of the rocks was enhanced by further cementation during shallow burial.

Lithofacies IV and V, contained in Diagenetic Zone 3, were deposited in a normal marine, shallow subtidal environment. The cementation of interbedded packstones is by minor bladed and common syntaxial rim and equant cements under shallow to deeper burial conditions, similar to Lithofacies III above. However, these lithofacies show evidence of some late cementation following the compactional phase. This late cementation is indicated by broken grains which have been healed by calcite cement and by the widespread occurrance of tectonic fractures that are filled with late calcite cements.

The diagenetic history suggested for the Middle Ordovician carbonates in northwest Virginia agrees with the diagenetic model proposed for the similar carbonate deposits in southwest Virginia (Read and Grover, 1977; Grover and Read, 1978; Grover, 1981; Grover and Read, 1983). This indicates that the environmental conditions and burial histories were similar.

Grover (1981) documented the differences in the regional cathodoluminescent patterns of the cements of the Middle Ordovician carbonates in Virginia. These differences have been related to the proximity of the tectonic highlands which acted as a major area of meteoric recharge for paleoaquifers. A sequence of zoned cements were formed in areas proximal to the upland-source and dull, non-zoned cements were formed in the distal areas. The sequence of precipitated cements relates to increasing reducing conditions of pore waters in the distal parts of the regional paleoaquifer system. Groundwater apparently undergoes a decrease in the redox potential as it migrates from an upland recharge area to more distal discharge areas (Grover and Read, 1983). The oxidizing meteoric waters may have been incapable of reaching the subtidal lithofacies in northern Virginia because of their distance to the upland source (50 to 150 km.; Grover and Read, 1983). Thus zoned cements did not form in northern Virginia because the pore waters were reducing from the onset of burial. Reducing conditions are also supported by the pyrite and hematite crystals and the ferroan dolomite rhombs that are preserved in the chert.

CHAPTER VI. CONCLUSIONS

Five main lithofacies have been recognized for the Middle Ordovician carbonates. Lithofacies I and II occur in the New Market Limestone and Lithofacies III, IV and V occur in the Lincolnshire Formation. These lithofacies are the Laminated Facies (I), the Unlayered Mudstones (II), the Bioclastic-Peloidal-Oncoidal Packstones (III), the Bioclastic Wackestone/Packstone (IV), and the Argillaceous Mudstone/Wackestone (V). Lithofacies I, II, and III are interpreted to have been deposited under depositional environments akin to the tidal flat and semi-restricted shallow subtidal environments on Andros Island and the Great Bahama Bank. Lithofacies IV and V were deposited in a normal marine, shallow subtidal, ramp environment, generally below wave base. The Middle Ordovician carbonates, in northern Virginia were deposited in a temperate, subtropical to tropical climate under relatively low energy and salinity conditions similar to the climate of the Bahamas.

These carbonates represent an overall transgressive sequence. The transgression was not uniform but paused several times to allow carbonate deposition to reach sea-level. These minor shoaling phases, occurred wtihin the New Market Lithofacies I and II. Associated diagenetic features which indicate early lithification and vadose meteroic diagensis during these emergent intervals are: geopetal crystal silt, pendant-equant cements, equant cements which predates the crystal silt, molds of shells and possibly solution-enlarged molds of shells. The intraformational and interformational erosion surfaces which truncate the sediments and the cements are further evidence of early lithification, hence emergence.

The depositional model proposed in this study is in agreement with models for similar middle Ordovician carbonates from adjacent states. The only exceptions are: 1) the relatively thinner sequence found in northern Virginia compared to the adjacent subbasins to the north and south, 2) the greater importance of the algal tidal flat environment in northern Virginia, Maryland and Pennsylvania and the general absence of this environment in southwestern Virginia, and 3) the thick inland freshwater lake sequence in Maryland and Pennsylvania and its absence in Virginia. Thus, similar depositional environmental and climatic conditions existed laterally along strike during the Middle Ordovician from Pennsylvania to Tennessee, although sedimentation rates and sedimentation patterns differed. This site was nearly parallel with the Middle Ordovician equator (Dott and Batten, 1981) thus the similar climate interpreted for these deposits along strike from Tennessee to northern Virginia would be in agreement with the genral paleogeographic and paleomagnetic data of this time.

Deposition in northern Virginia was influenced by the development of the two shelf-depocenters that evolved into subsiding sedimentary subbasins to the north and south of the study area. These subbasins controlled the direction of marine transgression and sedimentation patterns during the Middle Ordovician.

The New Market Lithofacies I and II show evidence of freshwater vadose to shallow phreatic diagenesis, indicating early lithification prior to the deposition of the overlying Lincolnshire beds, although porosity occlusion may have taken place under shallow burial conditions. The Lincolnshire Lithofacies III shows evidence of marine phreatic diagenesis followed by freshwater phreatic and/or shallow burial diagenesis. Lithofacies IV and V of the Lincolnshire Formation show evidence of shallow to deeper burial diagenesis. The diagenetic models suggested in this study agree with the models proposed for similar Middle Ordovician limestones in southwest Virginia except for the general distribution of fenestral types and the abundance of diagenetic features. No diagenetic model is available for equivalent rocks to the north. Thus, a similar tectonic regime and burial history exists for the Middle Ordovician carbonates in Virginia, mainly progressive burial beneath 3,000 m of Middle Ordovician through Mississippian sediments followed by tectonic thickening of the sequence by Pennsylvanian-Permian overthrusting (Grover, 1983).

REFERENCES

Ahr, W. M., 1985, Limestone depositional sequence on shelves and ramps: modern and ancient. Geology Today, v. 1, no. 3, p. 84-89.

Aitken, J. D., 1967, Classification and environmental significance of limestones and dolomites, with illustrations from the Cambrian and Ordovician of Southwestern Alberta: Jour. Sed. Petrology, v. 37, p. 1163-1178.

Badiozamani, K., 1973, The Dorag dolomitization model-application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrology, v. 43, p. 965-984.

Bathurst, R. G. C., 1971, Carbonate Sediments and Their Diagenesis: Amsterdam, Elsevier Pub. Co., 620 p.

Benedict, G. L., III, and Walker, K. R., 1978, Paleobathymetric analysis in Paleozoic sequences and its geodynamic significance: Am. Jour. Sci., v. 278, p. 579-607.

Bricker, O. P. (ed.) 1971, Carbonate cements: Baltimore, Johns Hopkins University Studies in Geology, no. 19, 376 p.

Chilingar, G. V., Bissel, H. J., and Wolf, K. H., 1979, Diagenesis of carbonate sediments and epigenesis (or catagenesis) of limestones: IN Larson, G. and Chilingar, G. V. (eds.), Developments in Sedimentology 25A: Amsterdam, Elsevier Pub. Co., p. 249-422.

Colton, G. W., 1970, The Appalachian basin-its depostional sequences and their geologic relationships: IN Fisher, G. W. et al. (eds.), Studies of Appalachian Geology: Central to Southern: Wiley and Sons, Inc., New York.

Cooper, B. N. and Cooper, G. A., 1946, Lower and Middle Ordovician Stratigraphy of the Shenandoah Valley, Virginia: Geol. Soc. America Bull., v. 57, p. 35-113.

Dott, R.H. Jr. and Batten R.L., 1981, Evolution of the Earth: New York, McGraw-Hill Book Company, 113 p.

Dunham, R. J., 1969, Early vadose silt in Townsend mound (reef), New Mexico: In Friedman, G. M. (ed.), Deposional Environments in Carbonate Rocks: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 14, p. 139-181.

Flugel, Erik, 1982, Microfacies analysis of limestones: New York, Springer-Verlag, 633 p. DM148 (translation by Karen Christenson).

Friedman, G. M., 1964, Early diagenesis and lithification in carbonate sediments: Jour. Sed. Petrology, v. 34, p. 777-813.

Friedman, G, M., and Johnson, 1982, Exercises in Sedimentology: New York, John Wiley and Sons, 208 p.

Garrett, P., 1977, Biological communities and their sedimentary record: In Hardie, L. A. (ed.), Sedimentation of the modern tidal flats of northwest Andros Island, Bahamas: Baltimore, Johns Hopkins University Press, p. 124-158.

Gavish, E., and Friedman, G. M., 1969, Progressive diagenes in Quaternary to Tertiary carbonate sediments: sequence and time scale: Jour. of Sed. Petrology, v. 39, p. 49-69.

Ginsburg, R. N., 1964, South Florida carbonate sediments: Guidebook for Field Trip No. 1, Geological Society of America Convention 1964: Geological Society of America, New York, 72 p.

Ginsburg, R. N., 1974, Introduction to comparative sedimentology: Am. Assoc. of Petroleum Geologists, v. 58, p. 781-786.

Ginsburg, R. N., Hardie, L. A., Owen, O. P., Garrett, P., and Wanless, H. R., 1977, Exposure index: A quantitative approach to defining position within the tidal zone: In Hardie, L. A. (ed.), Sedimentation of the modern carbonate tidal flats of northwest Andros Island, Bahamas: Baltimore, Johns Hopkins University Press, p. 7-11.

Grover, G. A., Jr., 1981, Cement types and cementation patterns in Middle Ordovician ramp-to-basin carbonates, Virginia: Dissertation, Virginia Polytechnic Institute and State University, Univ. Microfilms, 299 p.

Grover, G., Jr. and Read, J. F., 1978, Fenestral and associated vadose diagenetic fabrics of tidal flat carbonates, Middle Ordovician, New Market Limestone, S. W. Virginia: Jour. Sed. Petrology, v. 48, p. 453-473.

Grover, G., Jr., and Read, J. F., 1983, Paleoaquifer and deep burial related cements defined by regional cathodoluminescent patterns, Middle Ordovician carbonates, Virginia: Am. Assoc. Petroleum Geologists Bull., v. 67, no. 8, p. 1275-1303.

Hack, J. T., 1965, Geomorphology of the Shenandoah Valley Virginia and West Virginia and origin of the residual ore deposits: U.S. Geologic Survey Professional Paper 484, 84 p.

Hardie, L. A., 1977, Algal structures in cemented crusts and their environmental significance: In Hardie, L. A. (ed.), Sedimentation on the modern carbonate tidal flats of northwest Andros Island, Bahamas: Baltimore, Johns Hopkins University Press, p. 159-177.

Hardie, L. A., and Garrett, P., 1977, General environmental setting: In Hardie, L. A. (ed.), Sedimentation of the modern carbonate tidal flats of northwest Andros Island, Bahamas: Baltimore, Johns Hopkins University Press, p. 12-49.

Hardie, L. A., and Ginsburg, R. N., 1977, Layering: The origin and environmental significance of lamination and thin bedding: In Hardie, L. A. (ed.), Sedimentation of the modern carbonate tidal flats of northwest Andros Island, Bahamas: Baltimore, Johns Hopkins University Press, p. 50-123.

Harris, P. M., Kendall, C. G., St. C., Lerche, I., 1985, Carbonate sedimentation-A brief review: In Schneidermann, N., et al. (eds.), Carbonate cements: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 36, p. 79-95.

Harris, W. H., and Matthews, R. K., 1968, Subaerial diagenesis of carbonate sediments: Efficiency of the solution-precipitation process: Science, v. 60, p. 77-79.

Kay, M. G., 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

Land, L. S., 1971, Holocene meteroic dolomitization of Pleistocene limestones, North Jamaica: Sedimentology, v. 20, p. 187-200.

Logan, B., 1961, Cryptozoon and associated stromatolites from the Recent, Shark Bay, Western Australia: Jour. of Geology, v. 69, p. 517-533.

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: Am. Assoc. Petroleum Geologists Memoir 22, p. 195-249.

Logan, B., Rezak, R., and Ginsburg, R. N., 1964, Classification and environmental significance of algal stromatolites: Jour. of Geology, v. 72, p. 68-83.

Logan, B. W., Hoffman, P., and Gebelein, C. D., 1974, Algal mats, cryptalgal fabrics, and structures, Hamlin Pool, Western Australia: In Logan, B. W., (ed.), Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia: Am. Assoc. Petroleum Geologists Memoir 22, p. 140-194.

Longman, M. W., 1980, Carbonate diagenetic textures from nearsurface diagnetic environments: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 461-487.

Markello, J. R., Tillman, C. G., and Read, J. F., 1979, Lithofacies and biostratigraphy of Cambrian and Ordovician platform and basin facies carbonates and clastics, southwest Virginia: Geol. Soc. America Southeast Sec., Guides to Field Trips 1-3, p. 42-86.

Matthews, R. K., 1971, Diagenetic environments of possible importance to the explanation of cementation fabric in subaerially exposed carbonate sediments: In Bricker, O. P. (ed.), Carbonate cements: Baltimore, Johns Hopkins University Press, p. 127-132.

Matthews, R. K., 1974, A process approach to diagenesis of reefs and reef associated limestones: In Reefs in time and space; selected examples from the Recent and ancient: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 18, p. 234-256.

McBride, E. F., 1962, Flysch and associated beds of the Martinsburg Formation (Ordovician), central Appalachians: Jour. Sed. Petrology, v. 32, p. 39-91.

Mitchell, R. W., 1982, Day 1: Middle Ordovician St. Paul Group: In Lyttle, P. T. (ed.), Central Appalachian Geology. NE-SE GSA 82 Field Trip Guide Books: American Geologic Institute, VA., p. 171-266.

Monty, C. L. V., 1976, The origin and development of cryptalgal fabrics: In Walter, M. R. (ed.), Stromatolites, Developments in Sedimentology, 20: Elsevier Pub. Co., p 193-249.

Monty, C. L. V., and Hardie, L. A., 1976, The geologic significance of the freshwater blue-green algal calcareous marsh: In Walter, M. R. (ed.), Stromatolites, Developments in sedimentology, 20, Elsevier Pub. Co., p. 421-433.

Moore, C. H. and Druckman, Y., 1981, Burial diagenesis and porosity evolution, Upper Jurassic Smackover, Arkansas and Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 65, p. 597-628.

Moore, C. H., Graham, E. A., and Land, L. S., 1976, Sediment transport and dispersal across the deep fore-reef and island slope (55m to -305m), Discovery Bay, Jamaica: Jour. of Sed. Petrology, v. 46, p. 174-187.

Muller, G., 1971, "Gravitational" cement: An indicator for the vadose zone of the subaerial diagenetic environment: In Bricker, O. P. (ed.), Carbonate cements: Baltimore, Johns Hopkins University Press, p. 301-302.

Mussman, W. J. and Read, J. F., 1986, Sedimentology and development of passive- to convergent-margin unconformity: Middle Ordovician Knox unconformity, Virginia Appalachians: Geol. Soc. American Bull., v. 97, p. 282-295.

Neuman, R. B., 1951, St. Paul Group: A revision of the "Stone River" Group of Maryland and adjacent states: Geol. Soc. America Bull., v. 62, p. 267-324.

Oldershaw, A. E., 1971, The significance of ferroan and non-ferroan calcite cements in the Halkin and Wenlock limestone (Great Britain): In Bricker, O. P. (ed.), Carbonate cements: Baltimore, Johns Hopkins University Press, p. 225-232.

Pettijohn, F. J., 1975, Sedimentary Rocks (Third Edition): New York, Harper and Row Pub., Inc., 628p.

Purser, B.H., 1969, Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris Basin: Sedimentology, v. 12, p. 205-230.

Purser, B. H., 1973, The Persian Gulf: New York, Springer-Verlag, 471 p.

Rader, E. K., and Biggs, T. H., 1976, Geology of the Strasburg-Tom Brook Quandrangles, Virginia: Virginia Division of Mineral Resources, Report of Investigations 45.

Rader, E.K., and Henika, W. S., 1978, Ordovician Shelf-to-basin transition, Shenandoah Valley, Virginia: Virginia Division of Mineral Resources, pulb. no. 7 (Contributions to Virginia Geology, III), p. 51-65.

Read, J. F., 1980, Carbonate ramp to basin transition and foreland basin evolution, Middle Ordovician, Virginia Appalachians: Am. Assoc. Petroleum Geologist Bull., v. 64, p. 1575-1612.

Read, J. F., 1985, Carbonate Platform facies models: Am. Assoc. Petroleum Geologists Bull., v. 69, no. 1, p. 1-21.

Read, J. F. and Grover, G., Jr., 1977, Scalloped and planar erosional surfaces, Middle Ordovician limestones, Virginia: Analogues of Holocene exposed Karst or tidal rock platform: Jour. Sed. Petrology, v. 47, p. 956-972.

Rock-Color Chart, 1980, Distributed by the Geological Society of America, Printed in The Netherlands by Huyskes-Enschede.

Rodgers, J., 1971, The Taconic orogeny: Geol. Soc. America Bull., v. 82, p. 1141-1178.

Schmalz, R. F., 1971, Formation of beachrock at Eniwetok Atoll: In Bricker, O. P. (ed.), Carbonate cements: Baltimore, Johns Hopkins University Press, p. 17-24.

Shinn, E. A., 1968, Practical significance of birdseye structures in carbonate rocks: Jour. Sed. Petrology, v. 38, p. 215-223.

Shinn, E. A., 1971, Holocene submarine cementation in the Persian Gulf: In Bricker, O. P. (ed.), Carbonate cements: Baltimore, Johns Hopkins University Press, p. 63-65.

Shinn, E. A., 1983, Tidal Flat: In Scholle, P. A., Bebout, C. G., and Moore, C. H. (eds.), Carbonate Depositional Environments: Am. Assoc. of Petroleum Geologists Memoir 33, Tulsa, Oklahoma.

Shinn, E. A., Lloyd, R. M., and Ginsburg, R. N., 1969, Anatomy of a modern carbonate tidal-flat, Andros Island: Jour. Sed. Petrology, v. 39, p. 1202-1228.

Taylor, J. M. C., and Illing, L. V., 1969, Holocene inter-tidal calcium carbonate cementation, Qatar Persian Gulf: Sedimentoloy, v. 12, p. 69-107.

Tebbutt, G. E., Conley, C. D., and Boyd, D. W., 1965, Lithogenesis of distinctive carbonate rock fabric: Contributions to Geology: University Wyoming, v. 4, p. 1-13.

Williams, H., 1978, Tectonic lithofacies map of the Appalachian orogen: Memorial University of Newfoundland, Map no. 1a, 1978, scale 1: 2,000,000.

Wilson, J. L., 1975, Carbonate facies in geologic history: New York, Springer-Verlog, 471 p.

Wolf, K. H., Easton, A. J., Warne, S., 1967, Techniques of examining and analyzing carbonate skeletons, minerals and rocks: In Chilingar, G. V., Bissell, H. J., and Fairbridge, R. W. (eds.), Carbonate Rocks, Developments in Sedimentology 9B: Amsterdam, Elsevier Pub. Co., p. 253-341.

Young, R. W., and Rader, E. K., 1974, Geology of Woodstock, Wolf Gap, Conicville and Edinburg Quandrangles, Virginia: Virginia Division of Mineral Resources, Report of Investigations 35.

APPENDIX A

Measured Stratigraphic Sections

KEY TO ROCK TYPES

- ARGILLACEOUS WACKESTONE/MUDSTONE
- BIOCLASTIC WACKESTONE/PACKSTONE
- BIOCLASTIC-PELOIDAL-ONCOIDAL PACKSTONE/
- DISRUPTED LAMINATES
- PLANAR LAMINATES
- UNLAYERED MUDSTONE
- FENESTRAL LIME MUDSTONE
- CRYPTALGAL PELOIDAL MUDSTONE
- PELOID-INTRACLAST WACKESTONE/PACKSTONE

KEY TO SYMBOLS

- UNIT BOUNDARY
- BURROW MOTTLES ALONG BEDDING PLANES
- BEDDING PLANE
- PLANAR LAMINATES
- DISRUPTED LAMINATES
- CRYPTALGAL LAYERING
- SILT
- PELOIDS
- ONCOIDS
- BIOCLASTS
- DESICCATION FEATURES
- STYLOLITES
- BURROWED/BIOTURBATED

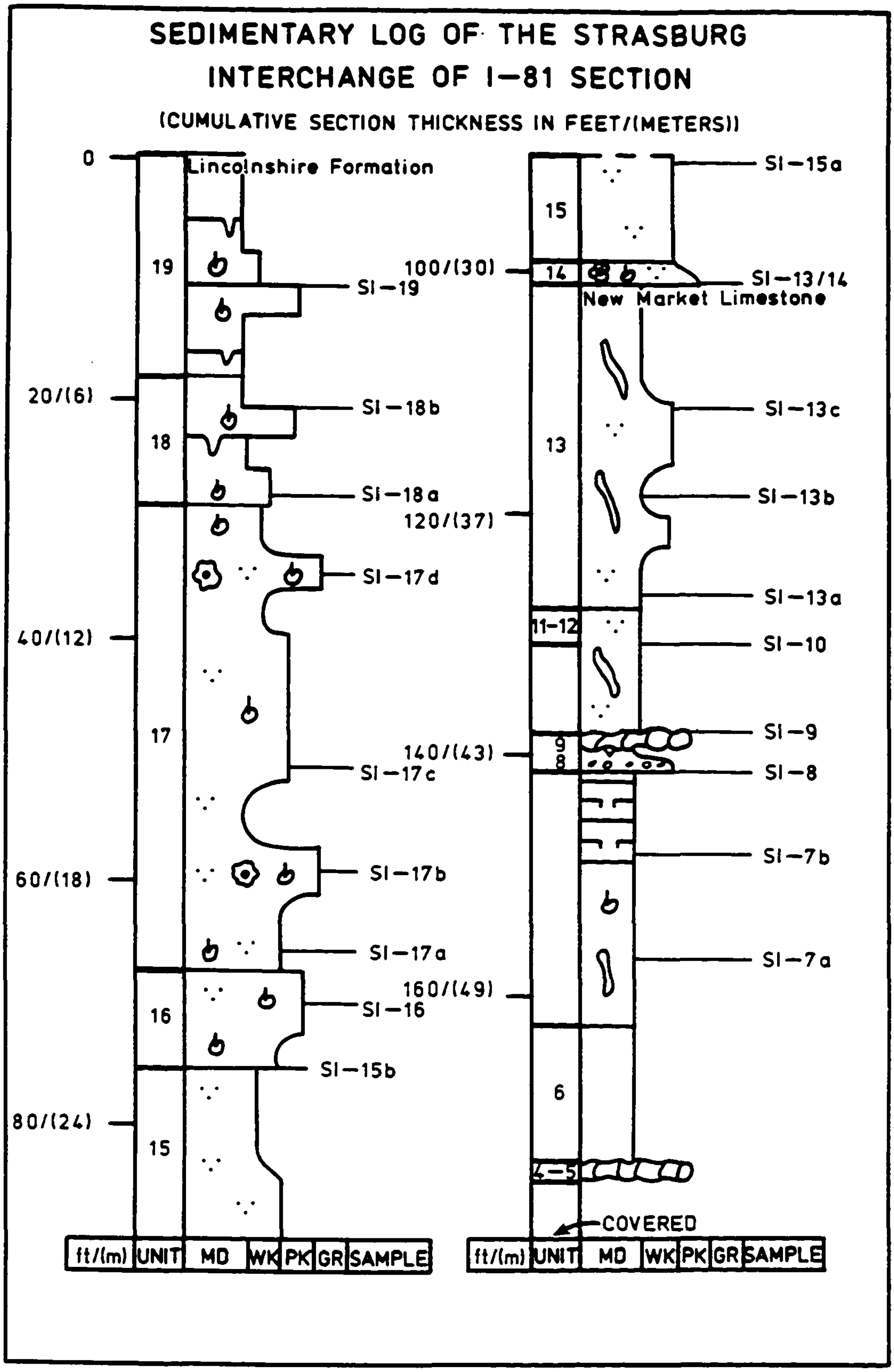
STRASBURG INTERCHANGE SECTION, INTERCHANGE NO. 75
OF INTERSTATE HIGHWAY 81, MIDDLETOWN 7.5-MINUTE QUANDRANGLE, VIRGINIA

(Section was measured along the northeast acceleration lane and the northwest deceleration lane of the junction of Interstate 81 and U.S. Highway 11. Beds strike N 71°E and dip 34°SE.)

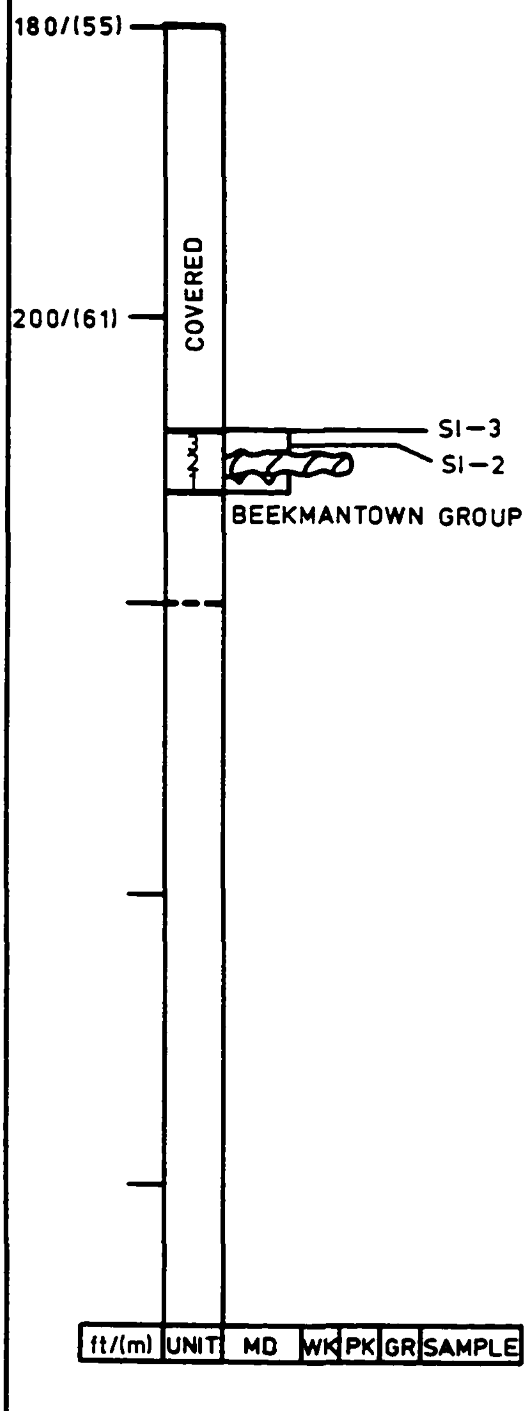
UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
19	5.5/(18.0)	Bioclastic mudstone to packstone, fine-grained; medium light gray; well bedded, 0.05 to 0.3 feet thick; shale partings, medium dark gray; fossiliferous; bedding parallel chert; tension fractures. Few interbeds of bioclastic grainstone, coarse-grained to conglomeratic; medium dark gray, with coated (black) rounded clasts, possibly oncoids.
18	3.1/(10.2)	Bioclastic mudstone with several interbeds of bioclastic grainstone, fine-grained; medium light gray; well bedded, 0.1 to 0.05 feet thick, uneven bedding plane surfaces; shale partings, medium dark gray; fossiliferous; tension fractures; no chert.
17	12.2/(39.9)	Bioclastic-Peloidal-Oncoidal mudstone to grainstone, fine-to coarse-grained; light-to medium light-gray; poorly bedded, uneven bedding plane surfaces; fossiliferous; tension fractures. Few interbeds and bottom 6 feet of unit is a coarse-grained bioclastic grainstone to conglomerate with black coated clasts up to 0.04 feet in diameter (oncoids); medium light- to dark-gray; beds of variable thickness ranging from 0.15 to 0.6 feet thick, uneven bedding surfaces; some laminated beds of fine-grained grainstone; fossiliferous, shell hash; tension fractures.
16	2.6/(8.5)	Bioclastic-Peloidal wackestone to fine-grained grainstone; medium gray; poorly to massively bedded, uneven bedding plane surfaces; fossiliferous, lenses and pods of shell hash material (medium dark gray) along bedding planes and within vertical fractures; tension fractures.

UNIT	M/(FT.)	DESCRIPTION
15	7.1/(23.3)	Peloidal mudstone/wackestone; medium-to medium light-gray; poorly bedded; homogeneous; fossiliferous; tension fractures; bedding parallel stylolites.
14	0.6/(2.1)	Bioclastic-peloidal-oncoidal wackestone to very coarse-grained grainstone; medium light-to medium dark-gray; poorly bedded; fossiliferous; black coated clasts; tension fractures.
		NEW MARKET LIMESTONE
13	8.5/(27.9)	Bioturbated lime mudstone to wackestone with peloid intraclasts; light-to medium dark-gray; poorly bedded, uneven bedding plane surfaces with or without shale partings, medium dark gray; tension fractures.
12	0.6/(2.1)	Same as unit 13.
11	0.3/(0.9)	Same as unit 13.
10	2.5/(8.1)	Same as unit 13.
9	0.3/(1.1)	Interlaminated lime mudstone and peloidal wackestone/packstone; light gray; dolomitic shale partings, very pale orange to pale yellowish brown; birdseye fabric; bedding parallel stylolites.
8	0.7/(2.3)	Lime mudstone and peloid-intraclast wackestone/packstone; light gray; bedded (0.15 feet thick average); uneven bedding plane surfaces with dolomitic shale partings, very pale orange to dark yellowish orange; birdseye fabric; bedding parallel stylolites.
7	6.6/(21.8)	Lime mudstone; light gray; poorly bedded; calcite replaced fossils; birdseye fabric; bedding parallel stylolites. Upper 7.9 feet of unit is a dolomitic mudstone, light gray to very pale orange; poorly bedded.

UNIT	M/(FT.)	DESCRIPTION
6	3.5/(11.6)	Lime mudstone; light gray; poorly bedded; calcite replaced fossils; birdseye fabric; random interbeds of interlaminated lime mudstone and peloidal wackestone/packstone, light gray to very pale orange.
4-5	0.5/(1.6)	Interbeds of lime mudstone and peloid-intraclast wackestone/packstone; light gray; bedded, 0.1 feet thick; dolomitic shale partings, light gray; birdseye fabric.
	10/(33)	Covered interval.
3	0.3/(0.9)	Lime mudstone; light gray; laminated to thinly bedded; homogeneous; fossiliferous (mainly gastropods); bedding parallel stylolites.
2	1.0/(3.2)	Lime mudstone to peloidal wackestone; light gray; poorly bedded, uneven bedding plane surfaces; dolomitic shale partings, light gray to very pale orange; fossiliferous (gastropods and ostracods; bedding parallel stylolites.
1	0.2/(0.7)	Lime mudstone; laminated (as in unit 3).


SEDIMENTARY LOG OF THE STRASBURG INTERCHANGE OF I-81 SECTION
(CUMULATIVE SECTION THICKNESS IN FEET/(METERS))
0
20/(6)
40/(12)
60/(18)
80/(24)
100/(30)
120/(37)
140/(43)
160/(49)
Lincolnshire Formation
New Market Limestone
19
18
17
16
15
14
13
11-12
9
8
6
4-5
SI-19
SI-18b
SI-18a
SI-17d
SI-17c
SI-17b
SI-17a
SI-16
SI-15b
SI-15a
SI-13/14
SI-13c
SI-13b
SI-13a
SI-10
SI-9
SI-8
SI-7b
SI-7a
COVERED
ft/(m)
UNIT
MD
WK
PK
GR
SAMPLE

STRASBURG INTERCHANGE OF I-81 SECTION CONTINUED



TUMBLING RUN SECTION, AT FISHER'S HILL,
TOMS BROOK 7.5-MINUTE QUANDRANGLE, VIRGINIA

(Measured along State Road 601, approximately 0.3 miles west of the junction of U.S. Highway 11 and State Road 601. Beds strike N 75°E and dip 34°SE.)

UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
42	0.3/(1.1)	Bioclastic packstone, medium-to coarse-grained; poorly bedded, up to 0.3 feet thick, uneven bedding plane surfaces; very fossiliferous; shale partings; bedding parallel chert; tension fractures.
41	0.3/(1.1)	Bioclastic packstone; coarse-grained; medium dark gray; bedded, up to 0.1 feet thick, uneven bedding plane surfaces; shale partings, dark gray to black; fossiliferous (shell hash); bedding parallel chert, tension fractures.
40	0.7/(2.3)	Bioclastic packstone, fine-to coarse-grained; medium light- to medium-gray; poorly bedded, up to 0.2 feet thick; shale partings, dark gray; very fossiliferous, some shell hash beds; bedding parallel and irregular nodules of chert; tension fractures.
39	14.5/(47.6)	Bioclastic mudstone to grainstone, fine- to coarse-grained; medium gray-to medium dark-gray; well bedded, 0.2 feet thick, uneven bedding plane surfaces; shale partings, dark gray; fossiliferous, few shell hash beds, 0.1 feet thick, whole fossils in mudstone; bedding parallel and irregular nodules of chert, dark gray to black, some have lighter rims, disseminated pyrite/hematite and patches of mudstone in chert; bedding parallel stylolites, some cut through chert bedds, tension fractures.

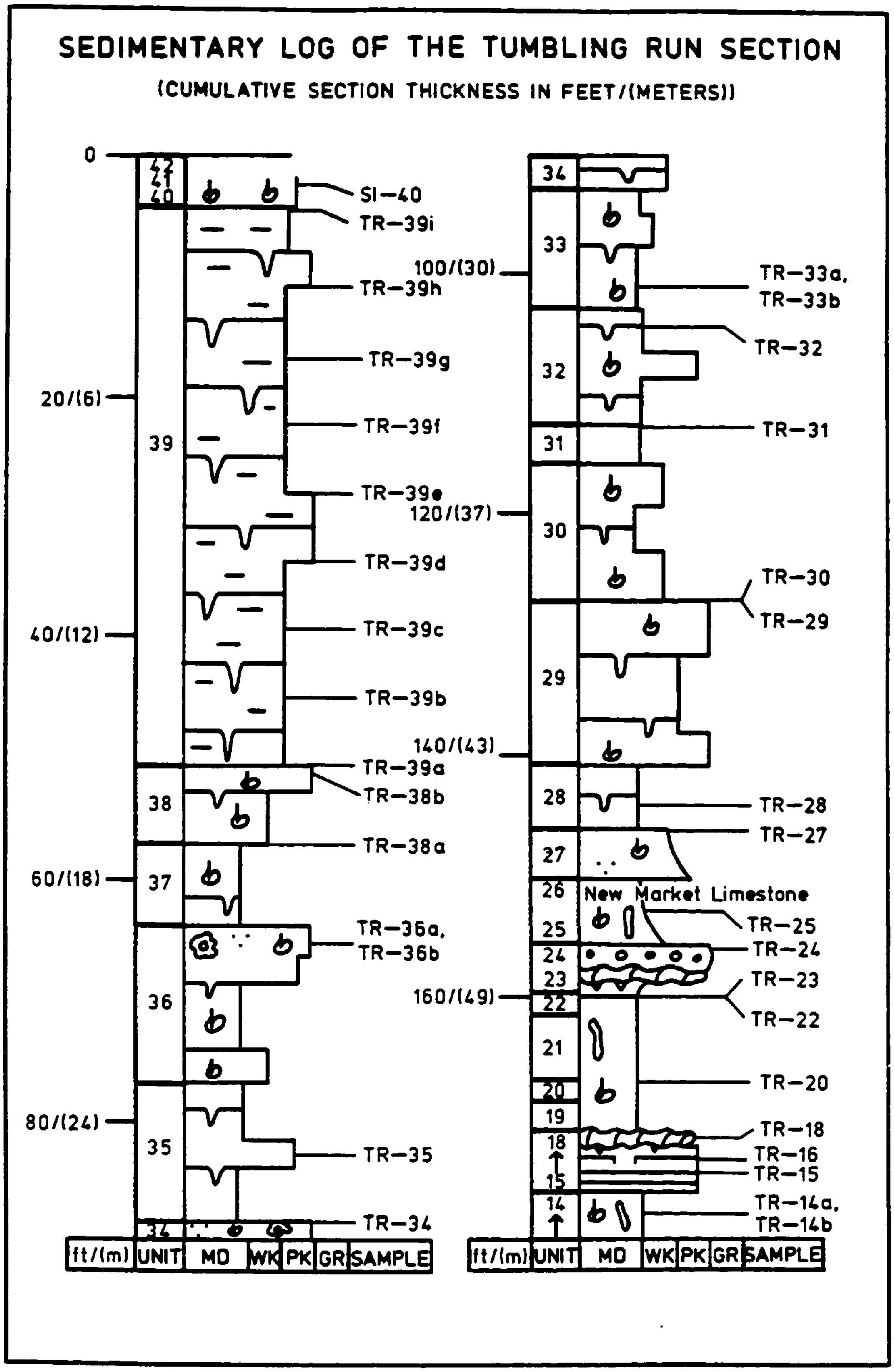
UNIT	M/(FT.)	DESCRIPTION
38	2.1/(6.8)	Bioclastic mudstone/wackestone; medium light gray; uneven bedding, up to 0.1 foot thick; fossiliferous; interbedded with bioclastic packstone, coarse-grained, medium-to medium dark-gray; bedded, up to 0.15 foot thick; packstone beds more abundant and thicker than underlying units 35,36,37.
37	2.3/(7.4)	Bioclastic mudstone, light-to medium light-gray, poorly bedded (0.1 to 0.2 foot thick), fossiliferous; with interbedded calcarenite, medium-to coarse-grained, beds up to 0.5 foot thick, abundant fossils, loading structures into underlying lutite bed, bedding parallel chert.
36	4.2/(13.7)	Bioclastic mudstone/wackestone, light olive gray to light gray, bedded (0.2 to 0.3 foot thick), fossiliferous; with interbedded calcarenite, coarse grained, bedded (0.1 foot thick) not as abundant as in unit 37, bedding parallel chert, some chert beds are continuous for the length of the outcrop (approximately 15 feet), tension fractures.
35	3.5/(11.6)	Bioclastic mudstone, medium light gray, bedded (0.2 to 1.0 foot thick), fossiliferous; few interbeds of calcarenite, medium-to-dark gray, medium-to-coarse grained, bedded (0.1 to 0.8 foot thick).
34	1.4/(4.6)	Bioclastic mudstone/wackestone, medium light-to medium gray, poorly bedded, fossiliferous, bedding parallel chert, tension fractures, some fractures cut across chert beds, bedding parallel stylolites.
33	3.0/(10)	Bioclastic mudstone/wackestone, medium light-to medium-gray; bedded (0.05 to 0.3 foot thick); shale partings, medium dark gray, patches and beds of calcisiltite to coarse-grained calcarenite (shell hash); fossiliferous; bedding parallel and nodular chert, some chert beds are continuous for length of outcrop, disseminated pyrite/ hematite and patches of mudstone in chert; tension fractures, some fractures cut across chert beds.

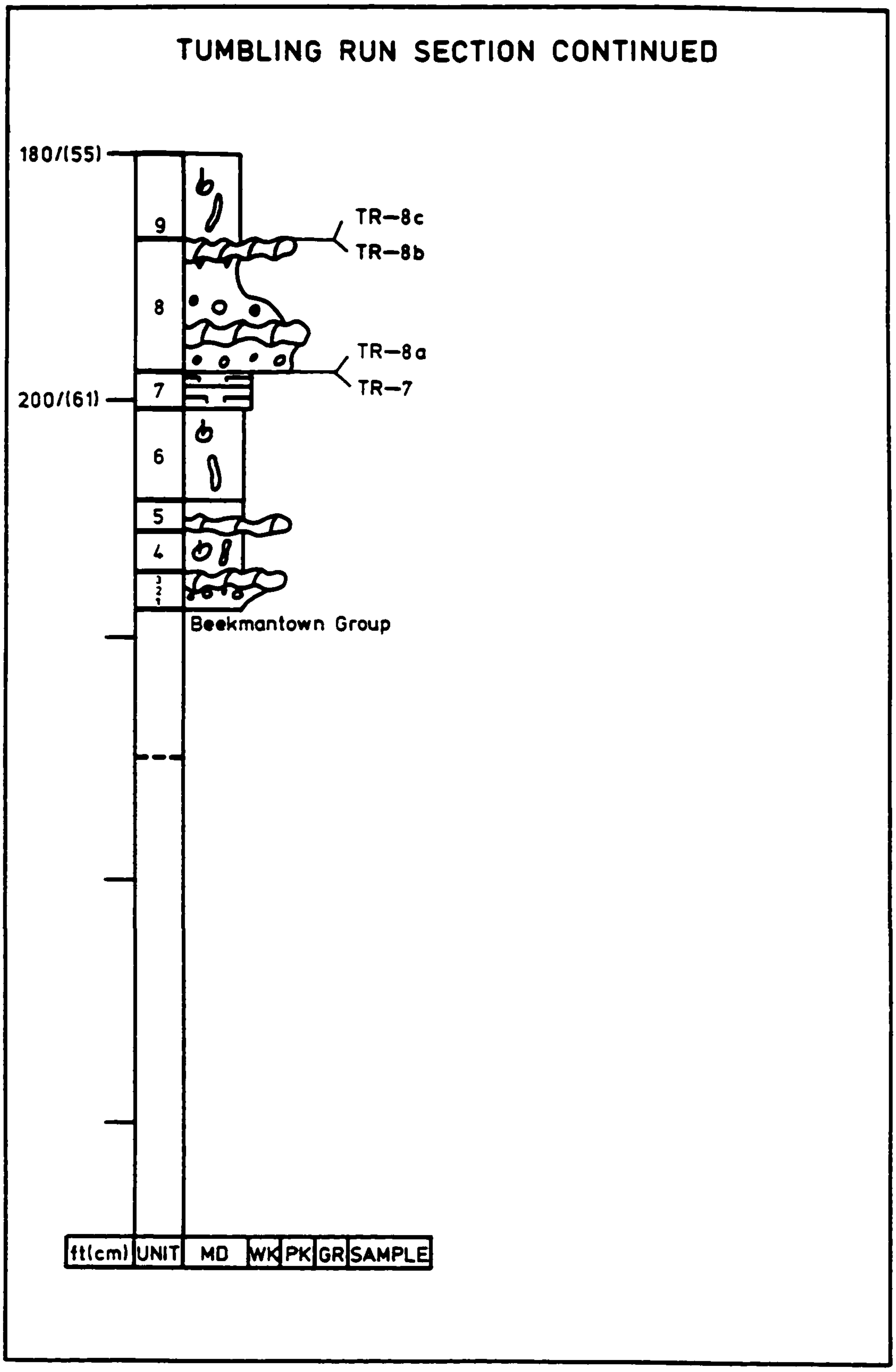
UNIT	M/(FT.)	DESCRIPTION
32	3.1/(10)	Bioclastic mudstone/wackestone; medium light-to medium-gray; in beds from 0.05 to 0.3 feet thick, uneven bedding plane surfaces; shale partings, medium dark gray; irregular patches to beds of medium-to coarse- grained bioclastic packstone (shell hash); fossiliferous; bedding parallel and irregular nodules of chert, some chert beds continuous for length of outcrop, disseminated pyrite/hematite and patches of mudstone in chert; tension fractures, some cut through chert beds.
31	1.1/(3.5)	Mudstone; medium-to medium dark-gray; well bedded, 0.05 to 0.2 feet thick, uneven bedding plane surfaces; shale partings, dark gray; bedding parallel and irregular nodules of chert; tension fractures; bedding parallel stylolites, some cut across chert nodules.
30	3.5/(11.4)	Mudstone interbedded with bioclastic wackestone to medium-grained packstone; medium-to medium dark-gray; uneven bedding, 0.1 to 0.4 feet thick; shale partings, dark gray to black; fossiliferous, silica replaced fossils stand in relief on weathered surface; bedding parallel and irregular nodules of chert with disseminated pyrite/hematite; tension fractures filled with white calcite, some cut through chert.
29	4.3/(14.1)	Bioclastic wackestone to packstone, medium-grained; medium-to medium dark-gray; bedded with shale partings,dark gray; abundant fossils; tension fractures filled with white calcite.
28	1.7/(5.6)	Mudstone; medium dark gray; uneven bedding, 0.05 to 0.15 feet thick; bedding parallel chert, dark gray to black.

UNIT	M/(FT.)	DESCRIPTION
27	1.4/(4.6)	Bioclastic wackestone to packstone, medium-grained; medium-to medium dark-gray; poorly bedded; fossiliferous; constituent particles have dark coatings; few bedding parallel stylolites; tension fractures filled with white calcite; the basal contact of unit is scourred into underlying unit by a maximum of 0.5 feet.
		NEW MARKET LIMESTONE
26	0.5/(1.5)	Lime mudstone to wackestone; light gray; poorly bedded; fossiliferous, numerous Tetradium sp. corals replaced with calcite; bedding parallel stylolites.
25	1.0/(3.3)	Same as unit 26.
24	0.1/(0.2)	Peloid-intraclast wackestone/packstones; medium light gray; thinly bedded, uneven; dolomitic shale partings, very pale orange to dark yellowish orange.
23	1.2/(3.8)	Lime mudstone to wackestone; light gray, poorly bedded, fossiliferous. With random beds of peloidal wackestone/packstone, light gray; poorly bedded; dolomitic shale partings, very pale orange.
22	0.4/(1.3)	Lime mudstone; light-to medium light-gray; thin irregular beds; dolomitic shale partings, medium gray; birdseye fabric.
21	1.7/(5.4)	Similar to unit 22.
20	0.5/(1.7)	Similar to unit 22.
19	0.8/(2.7)	Same as unit 22.
18	0.2/(0.8)	Interlaminated lime mudstone and peloidal-intraclast wackestone/packstone; light-to medium light-gray; dolomitic shale partings, very pale orange to dark yellowish orange; birdseye fabric; bedding parallel stylolites.

UNIT	M/(FT.)	DESCRIPTION
17	0.6/(2.1)	Lime mudstone; light-to medium light-gray; poorly bedded; fossiliferous, mainly ostracods and gastropods that are replaced with calcite; bedding parallel stylolites.
16	0.2/(0.5)	Interlaminated lime mudstone and peloidal wackestone/packstone; laminae are disrupted in places (as in unit 18).
15	0.5/(1.7)	Same as unit 16.
14	0.4/(1.4)	Lime mudstone; poorly bedded (as in unit 17).
13	0.4/(1.4)	Same as unit 14.
12	0.8/(2.6)	Lime mudstone and peloidal wackestone/ packstone; light gray; poorly bedded.
11	0.6/(1.8)	Lime mudstone and peloidal wackestone/ packstone; light-to medium light-gray; thin irregular beds or laminations; dolomitic shale partings, very pale orange to pale yellowish brown.
10	0.3/(0.9)	Lime mudstone; poorly bedded (as in unit 17).
9	0.8/(2.6)	Same as unit 10.
8	3.4/(11.3)	Lime mudstone; light-to medium light-gray; thinly bedded; randomly interbedded with peloidal wackestone/packstone (as in unit 24) and interlaminated lime mudstone and peloidal wackestone/packstone (as in unit 18).
7	0.8/(2.7)	Lime mudstone; light-to medium light-gray; finely laminated to very thinly bedded, bedding is disrupted by burrowing; dolomitic shale partings or laminae, very pale orange. Lime mud intraclast wackestone beds with lime intraclasts, medium-to coarse-grained with a dolomitic matrix.
6	2.4/(7.8)	Lime mudstone; poorly bedded (as in unit 17).
5	0.7/(2.4)	Interlaminated lime mudstone and peloidal wackestone/packstone; light-to medium light-gray; dolomitic shale partings, very pale orange; birdseye fabric.

UNIT	M/(FT.)	DESCRIPTION
4	1.2/(3.8)	Lime mudstone; poorly bedded (as in unit 17).
3	0.4/(1.4)	Interlaminated lime mudstone and peloidal wackestone/packstone with dolomitic shale partings (as in unit 5).
2	0.3/(0.9)	Dolomitized mudstone with lime mudstone intraclasts; medium-to coarse-grained; poorly bedded; dolomitic shale partings, very pale orange.
1	0.2/(0.6)	Similar to unit 22.


SEDIMENTARY LOG OF THE TUMBLING RUN SECTION
(CUMULATIVE SECTION THICKNESS IN FEET/(METERS))
0
20/(6)
40/(12)
60/(18)
80/(24)
100/(30)
120/(37)
140/(43)
160/(49)
SI-40
TR-39i
TR-39h
TR-39g
TR-39f
TR-39e
TR-39d
TR-39c
TR-39b
TR-39a
TR-38b
TR-38a
TR-36a,
TR-36b
TR-35
TR-34
TR-33a,
TR-33b
TR-32
TR-31
TR-30
TR-29
TR-28
TR-27
New Market Limestone
TR-25
TR-24
TR-23
TR-22
TR-20
TR-18
TR-16
TR-15
TR-14a,
TR-14b
ft/(m)
UNIT
MD
WK
PK
GR
SAMPLE


TUMBLING RUN SECTION CONTINUED
180/(55)
200/(61)
9
8
7
6
5
4
TR—8c
TR—8b
TR—8a
TR—7
Beekmantown Group
ft(cm)
UNIT
MD
WK
PK
GR
SAMPLE

TOMS BROOK QUARRY SECTION,
TOMS BROOK 7.5-MINUTE QUANDRANGLE, VIRGINIA

(The New Market Limestone was measured along the northwest wall within the flooded quarry by boat. The Lincolnshire was measured along the southeast wall of the quarry. Beds strike N 63°E and dip 29°SE.)

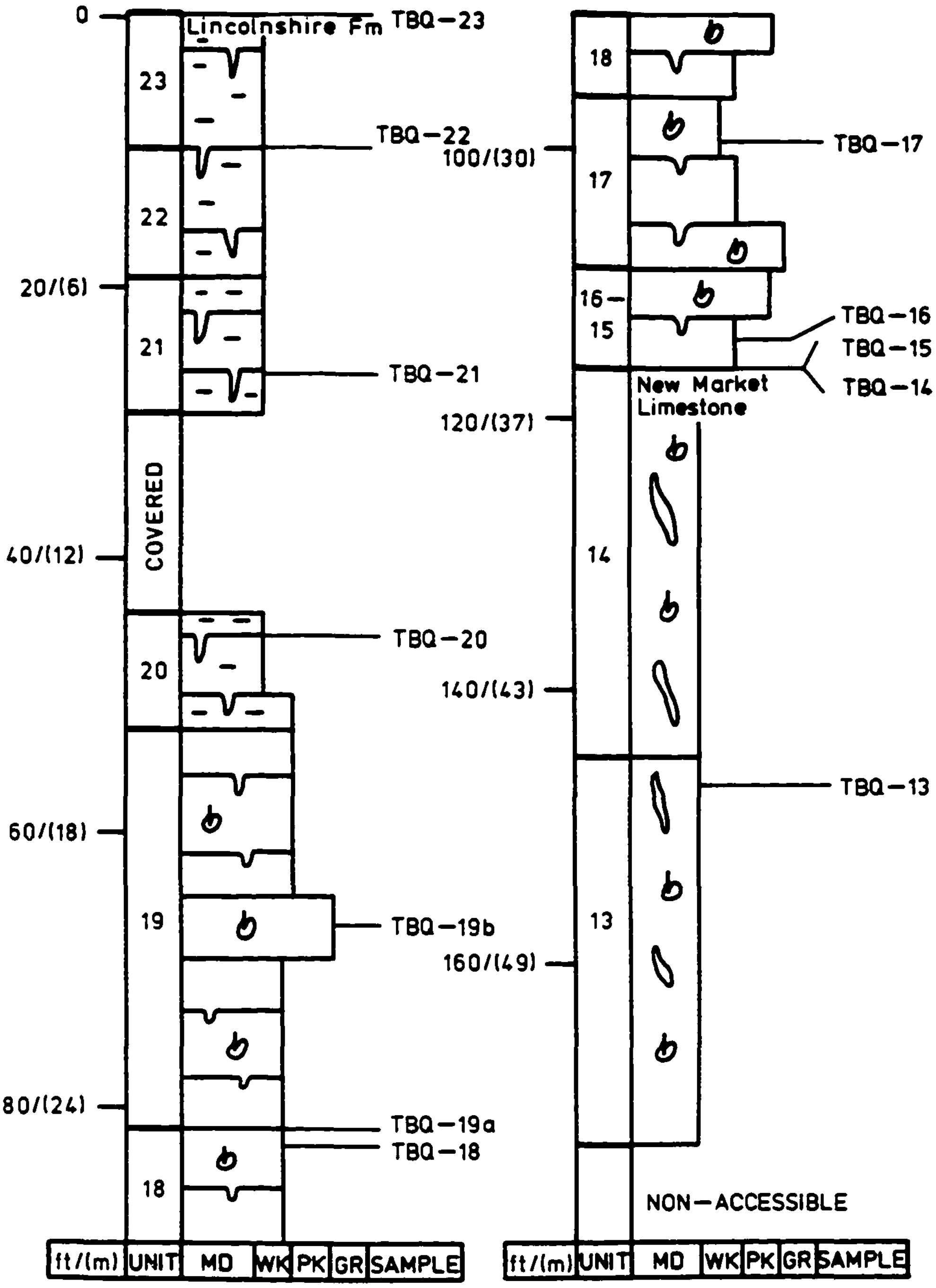
UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
23	3.0/(10.0)	Bioclastic mudstone; dark-to medium dark-gray; light red to moderate red shale partings, up to 0.05 feet thick, uneven bedding plane surfaces; minor fossils; bedding parallel chert.
22	3.0/(10.0)	Same as unit 23.
21	3.0/(10.0)	Same as unit 23.
	4.6/(15.0)	Covered interval.
20	2.7/(9.0)	Bioclastic wackestone to fine-grained packstone; medium dark gray; poorly bedded, approximately 0.2 feet thick, uneven bedding plane surfaces; few fossils; no chert.
19	9.1/(30.0)	Bioclastic wackestone to packstone/ grainstone, fine to coarse-grained; medium gray; more thickly bedded, bedding surfaces more planar; fossiliferous, shell hash; lenses to irregular nodules of chert.
18	4.6/(15.0)	Bioclastic wackestone to fine-grained grainstone; medium dark-to medium-gray; bedded, 0.1 to 0.2 feet thick; fossiliferous, few shell hash beds; lenses of chert along uneven bedding plane surfaces; tension fractures, some cut through chert nodules, chert increases upward (towards unit 19).
17	4.0/(13.0)	Bioclastic wackestone to grainstone, fine-to medium-grained; light gray to soil coated, very pale orange to dark yellowish orange and olive gray; bedded, uneven bedding plane surfaces; irregular bedding parallel chert nodules, dark gray.

UNIT	M/(FT.)	DESCRIPTION
15-16	2.3/(7.7)	Bioclastic wackestone to fine-grained packstone; medium dark gray; thinly bedded, 0.2 feet thick, uneven bedding plane surfaces; fossiliferous, some thin shell hash beds; no chert.
		NEW MARKET LIMESTONE
14	9.0/(29.4)	Lime mudstone; light gray; massively bedded; replaced fossils which stand out in relief on weathered surfaces; birdseye fabric; bedding parallel stylolites.
13	8,9/(29.1)	Same as unit 14.
	9.1/30.0)	Covered interval.
12	4.8/(15.7)	Same as unit 14.
11	1.9/(6.3)	Same as unit 14.
10	4.7/(15.3)	Randomly interbedded subfacies: 1) Lime mudstone; light gray; poorly bedded, dolomitic shale partings, very pale orange; birdseye fabric. 2) Interlaminated lime mudstone and peloidal wackestone/packstone; light gray; laminated, planar and wavy; dolomitic shale partings, dark yellowish orange to pale yellowish brown; birdseye fabric. 3) Peloid intraclast wackestone/ packstone; light gray; poorly bedded; dolomitic shale partings, very pale orange; stylolite. 4) Lime mudstone; light gray; poorly bedded, massive, calcite replaced fossils; bedding parallel stylolites.
9	0.9/(3.0)	Same as unit 10.
8	2.9/(9.6)	Same as unit 10.

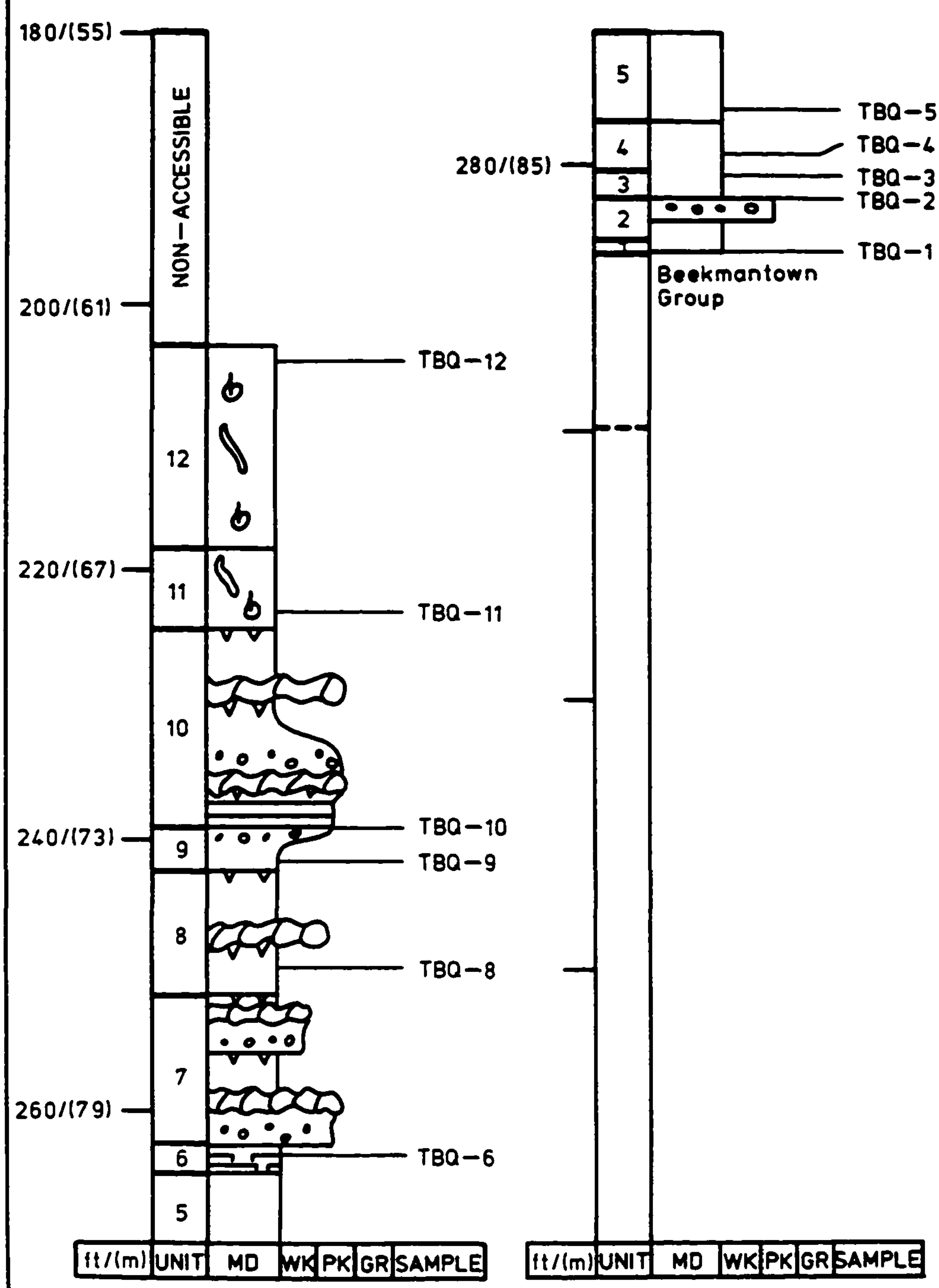
UNIT	M/(FT.)	DESCRIPTION
7	3.5/(11.5)	Same as unit 10.
6	0.2/(0.5)	Dolomitic mudstone; pale yellowish brown; poorly bedded. Few interbeds of Lime mudstone; poorly bedded with dolomitic shale partings, very pale orange (as in unit 3 and 4).
5	4.0/(13.2)	Lime mudstone; medium light gray; poorly bedded; dolomitic shale partings, pale yellowish brown to very pale orange; calcite replaced fossils; bedding parallel stylolites.
4	1.2/(3.8)	Lime mudstone; light-to medium light-gray; mottled; poorly bedded; dolomitic shale partings, very pale orange to medium gray; birdseye fabric.
3	0.6/(2.0)	Same as unit 4.
2	1.1/(3.6)	Lime mudstone with calcite replaced fossils (as in unit 5). Few interbeds of peloid-intraclast wackestone/packstone (as in unit 7).
1	0.1/(0.2)	Dolomitic mudstone (as in unit 6).

SEDIMENTARY LOG OF THE TOM'S BROOK QUARRY SECTION

(CUMULATIVE SECTION THICKNESS IN FEET (METERS))



TOM'S BROOK QUARRY SECTION CONTINUED



PUGH'S RUN SECTION, ALONG PUGH'S RUN RIVER AND STATE ROAD 663, TOMS BROOK 7.5-MINUTE QUANDRANGLE, VIRGINIA

(New Market Limestone was measured within Pugh's Run River. The Lincolnshire Formation begins at the junction of Pugh's Run River and State Road 663 and continues along State Road 663. Beds strike N 44°E and dip 39°SE.)

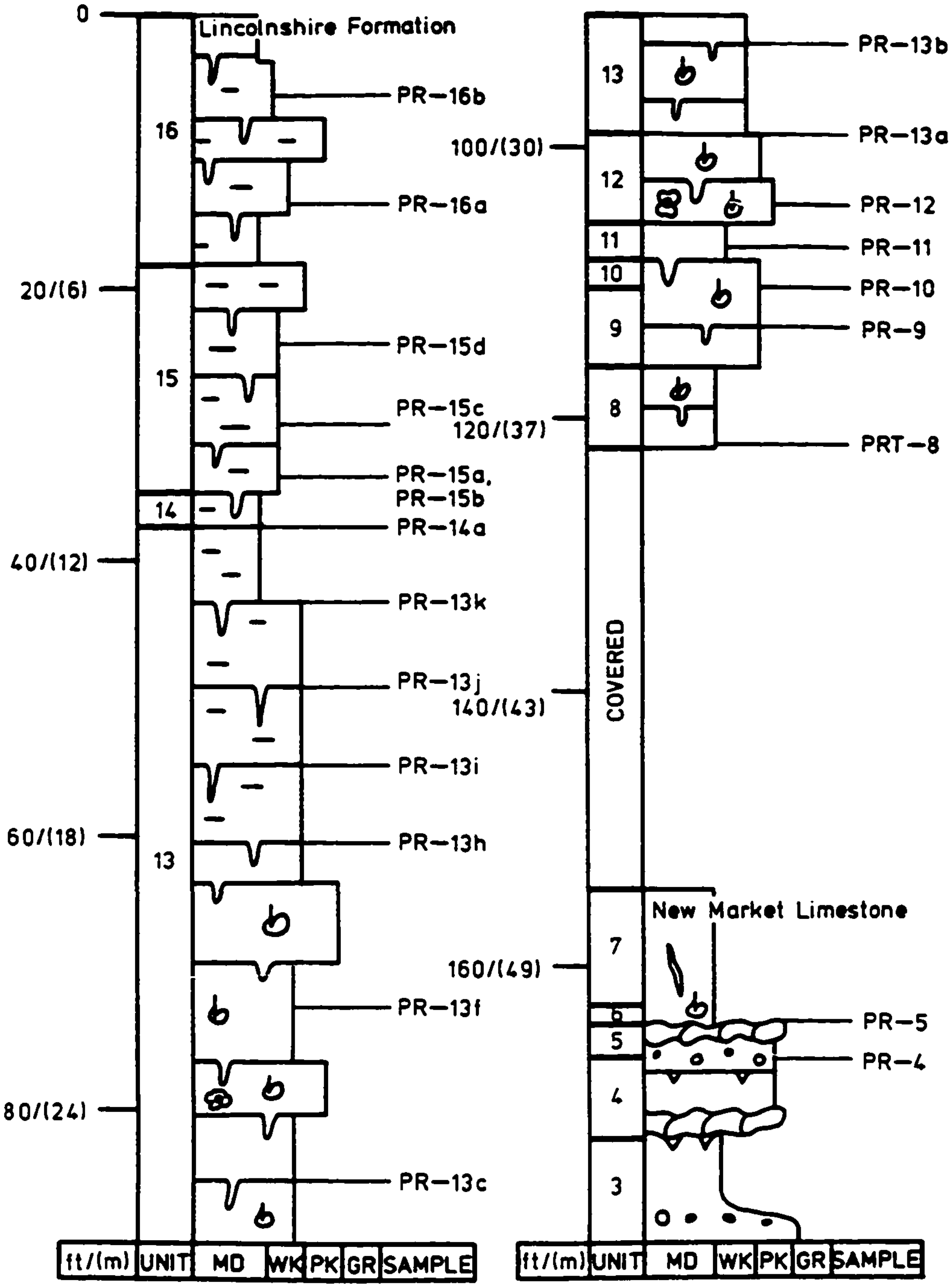
UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
16	5.7/(18.9)	Bioclastic mudstone to fine-grained packstone/grainstone; medium-to medium dark-gray; well bedded, 0.1 to 0.2 feet thick, mottled and bioturbated; fossiliferous, with lenses of pods of shell hash material, coarse-grained; bedding parallel and irregular chert nodules, more abundant chert; tension fractures, some cut through chert.
15	5.2/(17.3)	Bioclastic wackestone with interbeds of medium-grained, packstone/grainstone; medium dark-gray; bedded, 0.05 to 0.2 feet thick, uneven bedding plane surfaces; shale partings, dark reddish brown to dark gray; fossiliferous; bedding parallel chert.
14	0.8/(2.5)	Bioclastic mudstone/wackestone; medium-to medium dark-gray; thinly bedded, 0.03 to 0.06 feet thick; shale partings, dark gray; fossiliferous.
13	19.2/(63.0)	Bioclastic mudstone to grainstone, fine-to coarse-grained; medium-to medium dark-gray; well bedded, 0.05 to 0.3 feet thick, uneven bedding plane surfaces; shale partings, dark gray; fossiliferous, shell hash beds; tension fractures; no chert. Unit has more coarse-grained beds than previous units, grain size of beds alternate vertically from mudstone to grainstone.

UNIT	M/(FT.)	DESCRIPTION
12	2.1/(6.9)	Bioclastic wackestone to packstone/ grainstone; fine-to coarse-grained, shell hash; medium-to medium dark gray; bedded, 0.05 to 0.2 feet thick, uneven bedding plane surfaces; fossiliferous; bedding parallel chert.
11	0.8/(2.5)	Bioclastic mudstone/wackestone; medium- to medium dark-gray; bedded, 0.2 to 0.5 feet thick, uneven bedding plane surfaces; shale partings, dark gray to pale yellowish brown; whole fossils that are replaced with silica and stand out in relief on the surface; bedding parallel chert nodules, more abundant but not as continuous as unit 11, some fossils in chert nodules; tension fractures.
10	0.5/(1.6)	Same as unit 9 but has three continuous beds of bedding parallel chert; approximately 0.1 feet thick.
9	2.1/(6.9)	Bioclastic wackestone to packstone, fine-grained; medium dark gray; well bedded, 0.1 to 0.2 feet thick; shale partings, medium gray to pale yellowish brown; fossiliferous, some fossils that are replaced with silica stand-out in relief on weathered surfaces; bedding parallel chert, approximately 0.1 feet thick and 0.5 feet long, some chert beds are surrounded by shale which pinches out the chert and extends as shale partings along bedding planes; some chert nodules have pale yellowish brown rims. Lenses and pods of bioclastic packstone/grainstone, medium-to coarse-grained are found along bedding planes.
8	1.9/(6.3)	Bioclastic mudstone/wackestone; medium- to medium dark-gray; poorly bedded, approximately 0.1 to 0.2 feet thick; bedding parallel chert nodules, black.
	10.3/(33.7)	Covered interval.
		NEW MARKET LIMESTONE

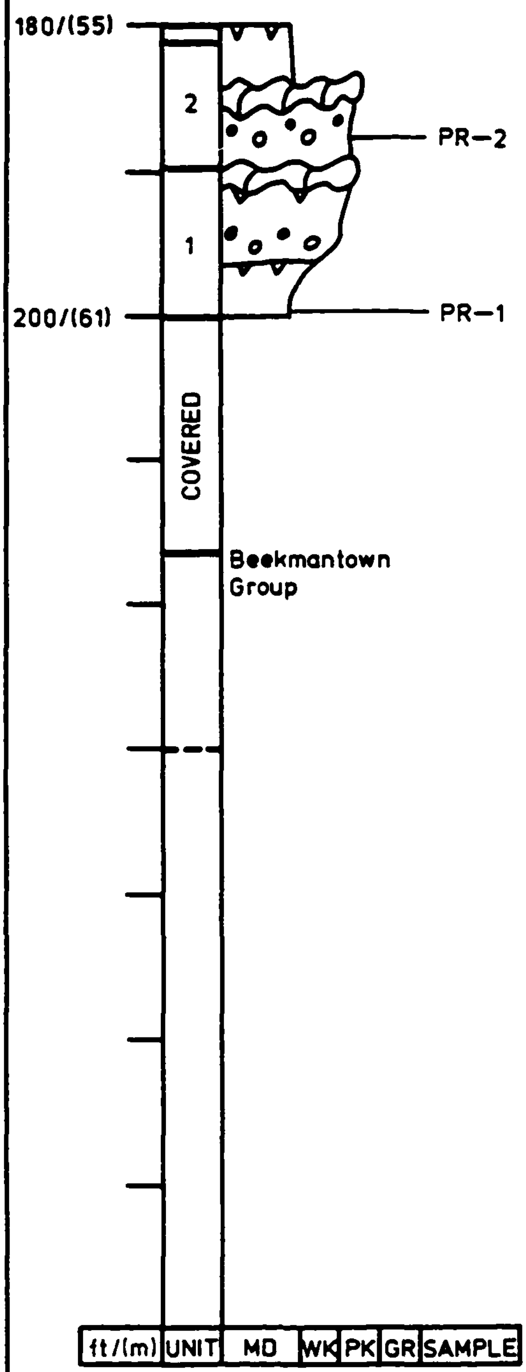
UNIT	M/(FT.)	DESCRIPTION
7	2.7/(8.8)	Lime mudstone; light gray; massively bedded; rare fossils; birdseye fabric; bedding parallel stylolites; very thin fractures filled with calcite.
6	0.37/(1.2)	Same as unit 7.
5	0.8/(2.5)	Lime mudstones to peloidal wackestones; light-to medium light-gray; bedded, 1.0 to 0.2 feet thick and laminated with stylotized, dolomitic shale partings, dark yellowish orange. The shale partings are very thin and abundant in laminated beds; rare fossils; birdseye fabric.
4	2.0/(6.4)	Same as unit 5.
3	2.3/(7.5)	Lime mudstone to wackestone; light-to-medium light-gray; bedded (0.3 to 1.5 feet thick) with very thin laminations towards the tops of beds that have stylotized dolomitic shale seams, dark yellowish orange to very pale orange; few peloid-intraclast beds, laminated to poorly bedded with stylotized dolomitic shale seams; rare fossils mainly ostracodes and gastropods; birdseye fabric.
2	2.7/(8.8)	Same as unit 3.
1	3.3/(10.7)	Same as unit 3, poorly exposed.
	5.0/(16.5)	Covered interval.

SEDIMENTARY LOG OF THE PUGH'S RUN SECTION

(CUMULATIVE SECTION THICKNESS IN FEET/(METERS))



PUGH'S RUN SECTION CONTINUED



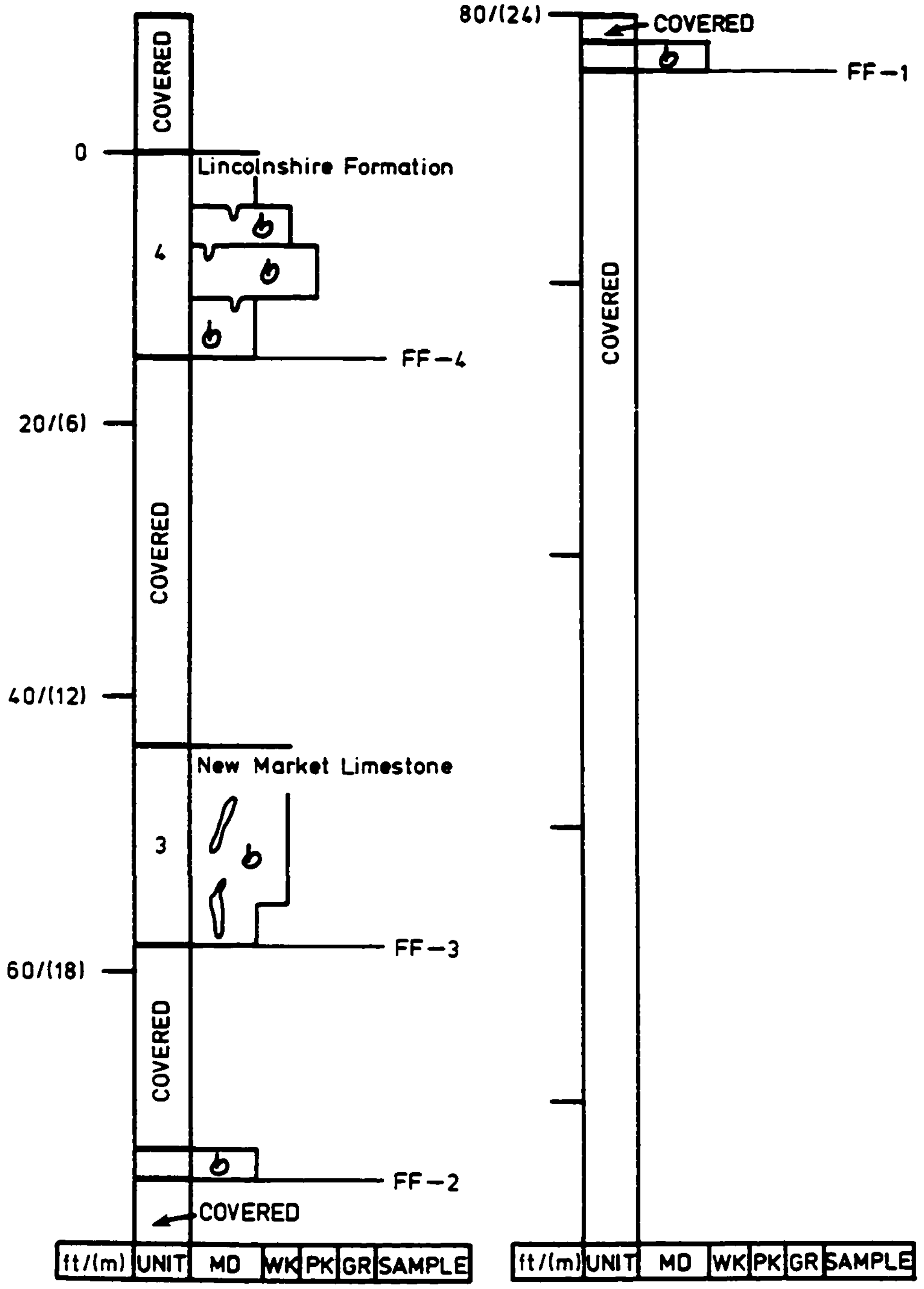
FLEMMING FARM SECTION, AT MR. AND MRS. FLEMMING'S FARM, LOCATED ALONG STATE ROAD 681 WEST NEAR ALONZAVILLE, VIRGINIA, WOODSTOCK 7.5-MINUTE QUADRANGLE, VIRGINIA-WEST VIRGINIA

(Section was measured in farm field behind chicken house. Beds strike N 63°E and dip 71°NW.)

UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
4	4.6/(15.0)	Bioclastic mudstone to packstone, fine- to medium-grained; medium light gray; bedded, 0.3 feet thick, uneven bedding plane surfaces; fossiliferous; few coarse-grained, bioclastic packstone/grainstone beds, very fossiliferous with shelter porosity, intraclasts, coated grains, and burrows.
	9.1/(30.0)	Covered interval.
		NEW MARKET LIMESTONE
3	4.9/(16.0)	Lime mudstone to bioclastic wackestone; light gray; massive; fossiliferous, fossils replaced with calcite; patches of peloidal wackestone; bedding parallel stylolites.
	4.9/(16.0)	Covered interval.
2	0.7/(2.2)	Same as unit 3.
	2.1/(6.8)	Covered interval.
1	0.7/(2.3)	Same as unit 3.
		Covered interval.

SEDIMENTARY LOG OF THE FLEMMING FARM SECTION

(CUMULATIVE SECTION THICKNESS IN FEET/M(METERS))



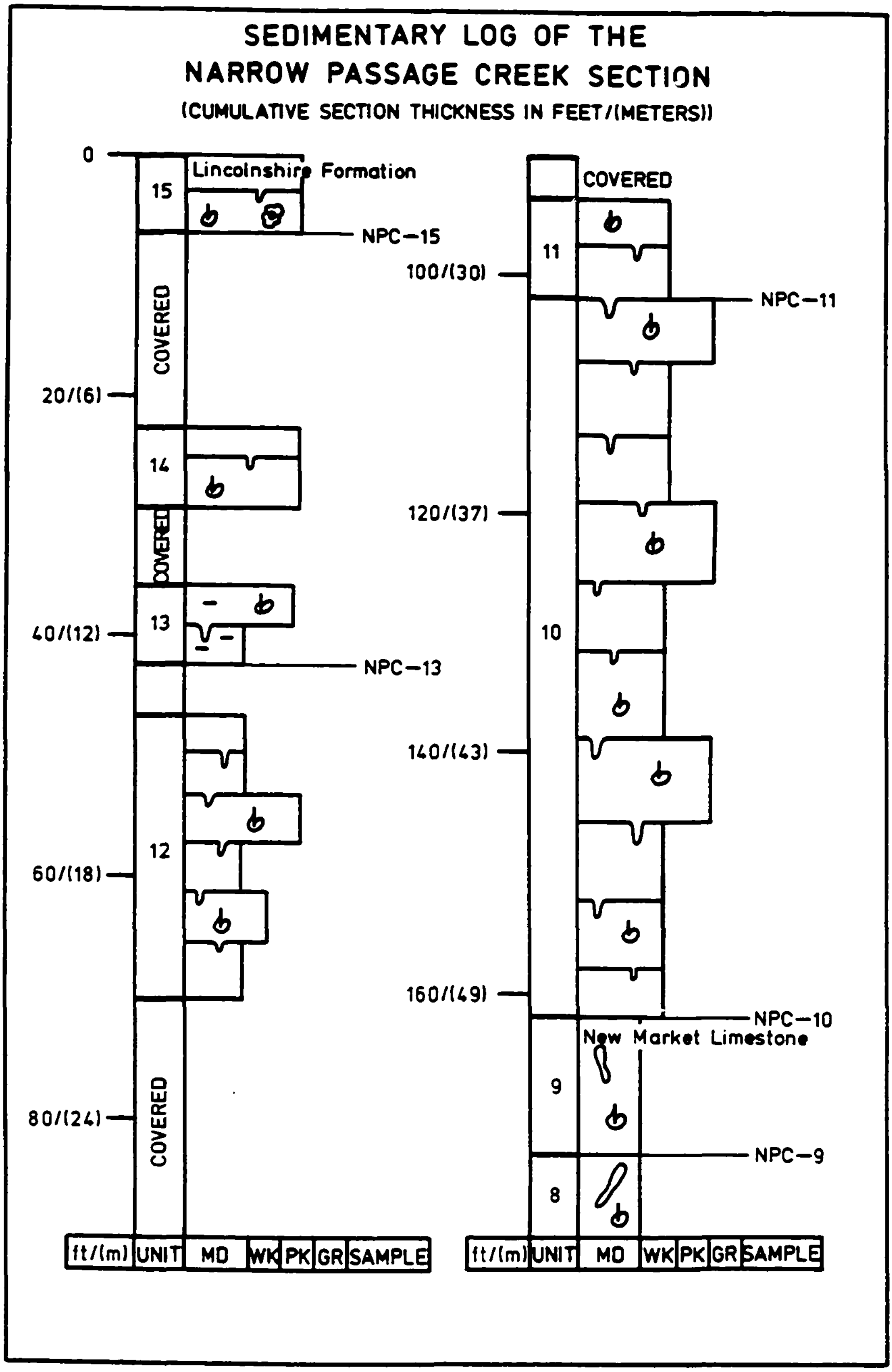
NARROW PASSAGE CREEK SECTION, HELEN WILKEN'S FARM,
ALONG STATE ROAD 605 NEAR ST. LUKE, VIRGINIA
WOODSTOCK 7.5-MINUTE QUANDRANGLE, VIRGINIA-WEST VIRGINIA

(Section measured on top of a small "ridge" in the field north of the farmhouse and Narrow Passage Creek. Beds strike N 20°E and dip 56°NW.)

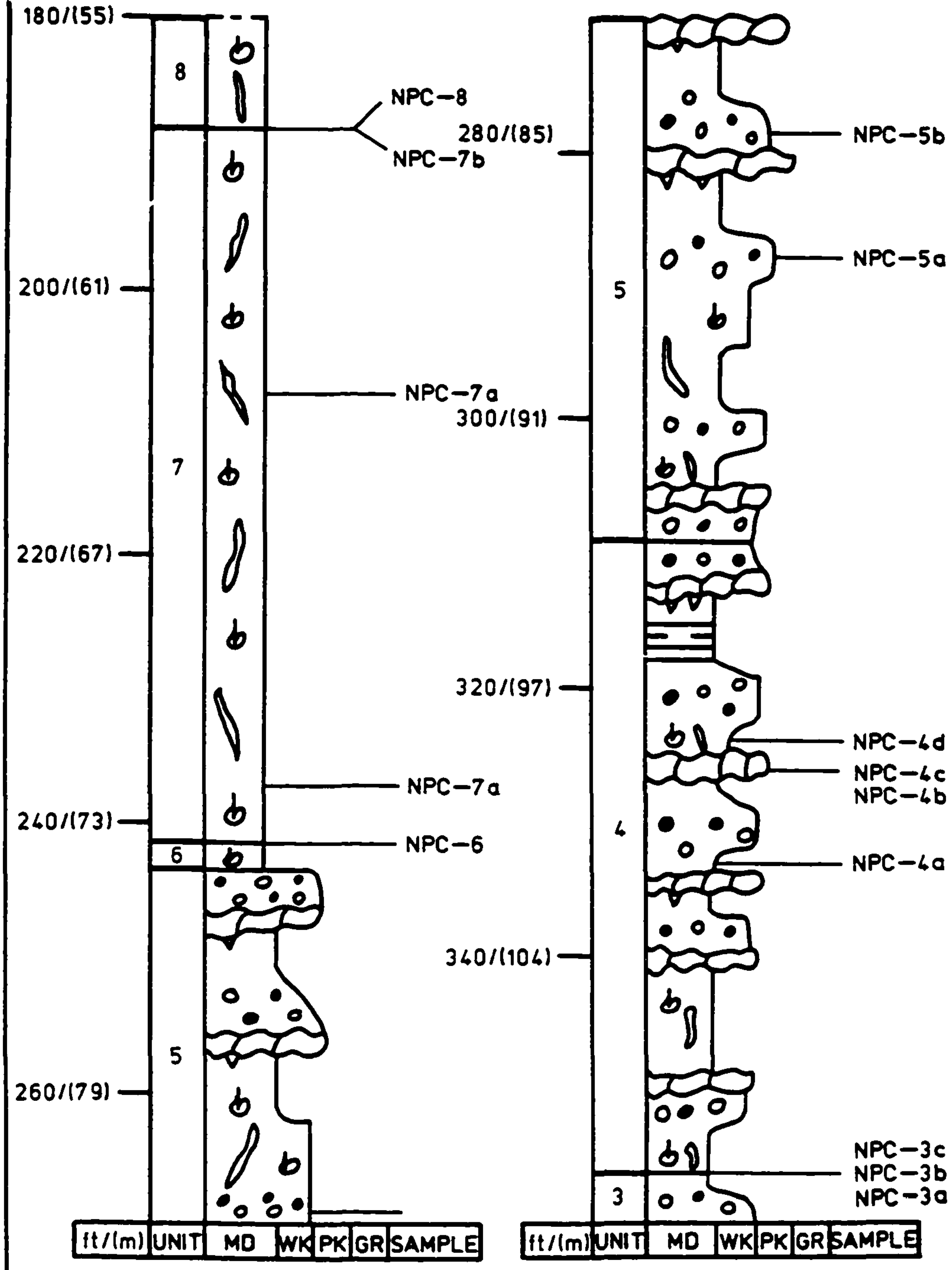
UNIT	M/(FT.)	DESCRIPTION
		LINCOLNSHIRE FORMATION
15	2.0/(6.4)	Bioclastic packstone/grainstone, fine- to medium-grained and conglomeratic; medium- to medium dark-gray; uneven bedding, 0.1 to 0.25 feet thick; fossiliferous, tension fractures; conglomerate bed at top of unit is 0.7 feet thick, very fossiliferous, with intraclasts and coated rounded grains.
	5.2/(17.0)	Covered interval.
14	2.0/(6.4)	Same as unit 15 but no conglomerate beds.
	2.0/(6.4)	Covered interval.
13	2.0/(6.4)	Bioclastic mudstone to fine-grained, grainstone; medium-to medium dark-gray; uneven bedding, 0.1 to 0.25 feet thick; fossiliferous.
	1.3/(4.4)	Covered interval.
12	7.4/(24.3)	Same as unit 13 but has bedding parallel chert beds and nodules.
	7.4/(24.3)	Covered interval.
11	2.7/(8.8)	Bioclastic wackestone to packstone/ grainstone; fine-to coarse-grained; medium light-to medium-gray; bedded, 0.25 to 0.35 feet thick; fossiliferous, some fossils replaced with silica; bedding parallel chert is more abundant.
10	18.7/(61.3)	Same as unit 11 but few conglomeratic beds discussed above, little to no chert.

UNIT	M/(FT.)	DESCRIPTION
		NEW MARKET LIMESTONE
9	3.7/(12.2)	Lime mudstone; light gray; mottled; poorly bedded; fossils replaced with calcite; bedding parallel stylolites; birdseye fabric; veins filled with white calcite.
8	4.3/(14.2)	Similar to unit 9, except larger and more abundant birdseye fabric, filled with clear calcite and often surrounded by medium dark gray rims.
7	16.7/(54.9)	Lime mudstone; light gray; bedded (0.2 to 1.5 feet thick) to poorly bedded; fossils replaced with calcite; bedding parallel stylolites.
6	0.6/(1.9)	Lime mudstone, light-to medium light-gray; mottled, bedded (0.07 to 0.2 feet thick); fossils replaced with calcite; birdseye fabric.
5	20.5/(67.2)	Lime mudstone with some peloidal wackestone/ packstone; light gray, mottled; poorly bedded (0.1 to 0.3 feet thick) and massive; stylotized; irregular dolomitic shale partings, very pale orange; fossils replaced with calcite; bedding parallel stylolites, birdseye fabric.
4	14.9/(48.8)	Lime mudstone to peloidal wackestone/ packstone. Alternating random sequence of three rock types: 1) Lime mudstone with abundant birdseye. 2) Interlaminated lime mudstone and peloidal wackestone/packstone. 3) Lime mudstone (with patches of peloidal wackestone/packstone), abundant fossils replaced with calcite; light gray; thinly bedded (0.05 to 0.2 feet thick, some as thick as 0.5 feet thick), with (stylolitized) dolomitic shale partings, very pale orange to dark yellowish orange and pale yellowish brown; fossiliferous, fossils are replaced with calcite.
3	12.4/(40.6)	Same as unit 4.
	2.5/(8.1)	Covered interval.

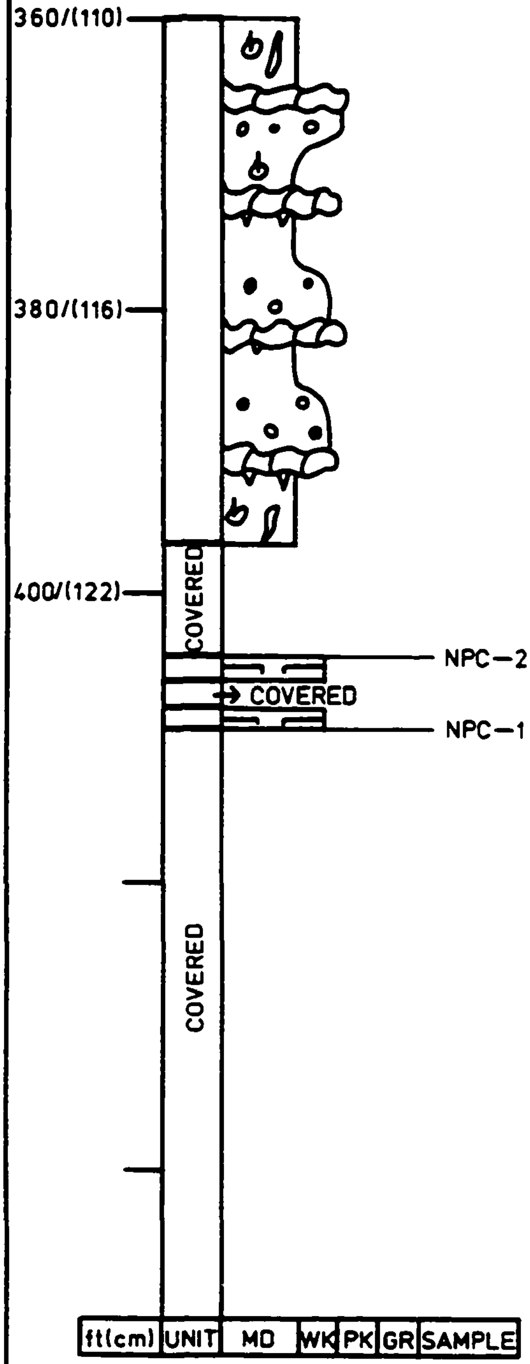
UNIT	M/(FT.)	DESCRIPTION
2	0.6/(2.1)	Random interbedded subfacies: (Some with sharp contacts) 1) Lime mudstone and peloidal wackestones; light gray; thinly bedded to laminated; dolomitic shale partings between beds, very pale orange; few fossils; birdseye fabric. 2) Dolomite; very pale orange (to tan) weathering; poorly bedded, thin units in sharp contact with lime mudstones. 3) Lime mud intraclast wackestones described in unit 1.
	0.6/(2.1)	Covered interval.
1	0.2/(0.5)	Lime mud-intraclast wackestone, composed of lime mud intraclast; light gray; sand to pebble size in coarser dolomitic silt, very pale orange weathering.
		Covered interval.


SEDIMENTARY LOG OF THE
NARROW PASSAGE CREEK SECTION
(CUMULATIVE SECTION THICKNESS IN FEET/(METERS))
0
15
Lincolnshire Formation
NPC–15
COVERED
20/(6)
14
COVERED
13
40/(12)
NPC–13
12
60/(18)
COVERED
80/(24)
ft/(m)
UNIT
MD
WK
PK
GR
SAMPLE
COVERED
11
100/(30)
NPC–11
120/(37)
10
140/(43)
160/(49)
NPC–10
New Market Limestone
9
NPC–9
8
ft/(m)
UNIT
MD
WK
PK
GR
SAMPLE

NARROW PASSAGE CREEK SECTION CONTINUED



NARROW PASSAGE CREEK SECTION CONTINUED



APPENDIX B

Acetate Peel and Staining Procedures

ACETATE PEEL AND STAINING PROCEDURES

I. Slab Preparation:

1. Saw carbonate rock specimens perpendicular to the bedding planes.

2. Grind surfaces with carborundum powder with 400 grade powder; final polish with 600 grade powder.

3. Thoroughly wash surface.

II. Etching the Slab:

1. Prepare acid solution using 8 to 10 ml HCL acid in 100 ml water (Lamar, 1950).

2. Expose polished surface to acid solution for 20 seconds to 2 minutes, depending on sample fabric and minerlolgy. Wash surface with running water to stop etching process.

3. Examine surface to make sure that relief has developed. Avoid touching the etched surface as delicate etched fabrics will be destroyed.

III. Staining the Slab:

1. Prepare stain: Alizarin red S in 30% NaOH.
   a) Use equal parts of alizarin red S and 30% NaOH solutions.
   b) Alizarin red S solution is prepared by dissolving 0.2 g of the dye in 25 ml methanol, by heating if necessary (Friedman, 1959). Replenish any methanol lost by heating.
   c) 30% NaOH solution is 30 g of NaOH dissolved in 70 ml of water.

2. Pour mixture of Alizarin red S in 30% NaOH solution into a basin and bring to a boil. Place slab specimen, so that etched side is immersed in the solution, for approximately 20 seconds or more depending on the rock fabric and dolomite content.

3. Gently rinse with water and examine the surface. The minerals which stain purple are dolomitic. X-ray diffraction of selected samples supports the results of the staining technique.

IV. Preparation of the Acetate Peels:

1. Following staining proceedures, place rock specimen, with polished surface up, on an incline into a tray, pan or dish filled with coarse sand or gravel. The latter will hold the specimen in place and absorb the spilled acetone.

2. Have ready a piece of commercial grade acetate film (0.005 inch) slightly larger than the polished rock surface.

3. Wet the entire inclined surface with acetone from a squeeze bottle so that there is an accumulation of acetone on the lower edge of the specimen.

4. Quickly place the piece of acetate film in the acetone on the lower edge of the specimen, gradually letting the film down onto the etched surface in a way that will push the acetone up the inclined surface of the specimen.

5. Leave slab with attached acetate film dry for about 20 minutes.

6. Carefully peel the acetate film from the slab.

7. The stained acetate peel is then mounted between glass plates for preservation and storage.

APPENDIX C

Lithofacies/Subfacies with Corresponding Rock Sample and Acetate Peel List

LITHOFACIES/SUBFACIES WITH CORRESPONDING
ROCK SAMPLE AND ACETATE PEEL LIST

LITHOFACIES I: LAMINATED FACIES

1) Very Thinly Bedded Subfacies A:

Peloidal mudstones-
SI-2, SI-3, SI-6.
TR-1, TR-2 (bottom).
TBQ-3, TBQ-4, TBQ-6 (bottom), TBQ-7a.
PR-1, PR-3.

Cryptalgal peloidal mudstones-

SI-9.
TR-3, TR-8b, TR-15, TR-16a, TR-16b, TR-18.
PR-5a.
NPC-3b, NPC-4b, NPC-4(c-1), NPC-4(c-2).

Peloid-intraclast wackestone/packstones-

SI-5, SI-8.
TR-8a, TR-24.
TBQ-2b, TBQ-7b.
PR-2, PR-4, PR-5.
NPC-4a, NPC-5a, NPC-5b, NPC-5c.

2) Unlayered Mudstone Subfacies B:

SI-7a.
TR-8c, TR-14a, TR-14b, TR-20, TR-22, TR-23.
TBQ-2a, TBQ-5, TBQ-8, TBQ-9.
NPC-2 (bottom), NPC-3a, NPC-3c, NPC-4d.

3) Planar Laminate Subfacies C:

TBQ-10.

4) Disrupted Flat Laminate Subfacies D:

TR-7.
NPC-1, NPC-2 (top).

5) Disrupted Dololaminate Subfacies E:

SI-7b.
TR-2.
TBQ-1, TBQ-6 (top).
NPC-2 (top).

LITHOFACIES II: UNLAYERED MUDSTONES

SI-10, SI-11, SI-13a, SI-13b, SI-13c.
TR-25.
TBQ-11, TBQ-12, TBQ-13, TBQ-14, TBQ-15.
PR-6, PR-7.
FF-1, FF-2.
NPC-6, NPC-7a, NPC-7b, NPC-8, NPC-9.

LITHOFACIES III: BIOCLASTIC-PELOIDAL-ONCOIDALPACKSTONE/GRAINSTONE

1) Bioclastic-peloidal wackestone/packstone-

SI-13/14 (bottom), SI-15a, SI-15b, SI-16, SI-17(a-1), SI-17(a-2), SI-17c, SI-17d.
TR-27.

2) Bioclastic-peloidal-oncoidal packstone/grainstone-

SI-13/14 (top), SI-17b, SI-17d (top).
TR-34a, TR-34b, TR-36a.
PR-12, PR-13e.
FF-4.
NPC-15.

LITHOFACIES IV: BIOCLASTIC WACKESTONE

1) Bioclastic wackestones-

SI-18a, SI-19 (top).
TR-28, TR-29, TR-30, TR-31, TR-32, TR-33a, TR-36b, TR-38(a-1).
TBQ-15, TBQ-16, TBQ-17, TBQ-18.
PR-8, PR-9, PR-10, PR-11, PR-13a, PR-13c, PR-13f.
NPC-10, NPC-11.

2) Bioclastic packstone-grainstones-

SI-18b, SI-19 (bottom).
TR-35, TR-38(a-2), 38b.
TBQ-19b.

LITHOFACIES V: ARGILLACEOUS WACKESTONE

1) Argillaceous wackestone-

TR-39a, TR-39b, TR-39c, TR-39f, TR-40.
TBQ-20, TBQ-21, TBQ-22, TBQ-23.
PR-13h, PR-13i, PR-13j, PR-13k, PR-14a, PR-15a, PR-15b, PR-15c, PR-15d, PR-16a, PR-16b.
NPC-13.

2) Bioclastic packstone/grainstone-

TR-39e, TR-39h.

SI = Strasburg Interchange Section
TR = Tumbling Run Section
TBQ = Tom's Brook Quarry Section
PR = Pugh's Run Section
FF = Flemming Farm Section
NPC = Narrow Passage Creek Section