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Changing depositional environments in an Upper Ordovician stratigraphic sequence, Ashlock Formation, Madison County, Kentucky

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CHANGING DEPOSITIONAL ENVIRONMENTS IN AN UPPER ORDOVICIAN STRATIGRAPHIC SEQUENCE, ASHLOCK FORMATION, MADISON COUNTY, KENTUCKY

By

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ABSTRACT

We investigate the sedimentology, stratigraphy, and depositional environments of a 7-meter, Upper Ordovician limestone sequence cropping out in Richmond, Kentucky. The stratigraphic section lies within the Ashlock Formation with good lateral exposure stretching along 200 meters of a highway roadcut. We took approximately 20 samples from the measured section, focusing on representative samples and lithologic transitions. We use standard laboratory procedures in slabbing rock samples and making thin sections.

The Ashlock Formation at this locality consists of alternating layers of limey mudstone and limestone. Megafossils - brachiopods, bryozoans, trilobites, gastropods, ostracodes, coralline algae, and bivalves - are abundant in various limestone units. The observed transitions from limestones and limy muds to lithologies with more terrigenous mud suggests any combination of: (1) migration of depositional environment with a slight increase in water depth; (2) climatic change resulting in more runoff; or (3) tectonic activity delivering more mud to the basin. These shallow water environments change to glauconitic mudstone and laminated shales, which we interpret as deeper shelf deposits. The measured section is capped by shaley limestones and mudstones that signal a return to shallow subtidal environments.

ACKNOWLEDGEMENTS

This project would not have been possible without the support of the many faculty and staff of the Department of Geography and Geology at Eastern Kentucky University. I have a deep gratitude for Dr. Walter Borowski, as he has always been by my side giving me the mentorship and motivation to continue on in this research. It was also my privilege to be under Dr. Borowski's tutorial for the past couple of years in his many outstanding courses of study. Dr. Thomas Lierman has been an invaluable resource, both in his many memorable lectures and also for his contribution of time and talent to this senior thesis. I would also like to thank all the other professors in the department of geography and geology for their influence upon me and their genuine friendship and concern for my personal well-being. I never felt that I was ever alone, as everyone enthusiastically participated in helping me receive the education that I have today. Thank-you Eastern Kentucky University for the wonderful educational experience. It will not be forgotten.

Most importantly, I thank my wife Tomoko, and my family for their loving support and sacrifice while I was consumed in my studies of the past several years. Naomi, Jaden, Julian, Kevin Jr., and Josiah have buoyed me up out of the doldrums with their simple smiles and affectionate words. I also have my parents to thank for their loving encouragement, as they have always helped me realize my true potential.

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ILLUSTRATIONS

Chapter 1 - Introduction

Overview

The main purpose of our investigation is to determine the environments of deposition of the Upper Ordovician Ashlock Formation where it crops out in Richmond Kentucky. To do this, a stratigraphic section was measured in four parts along a 200-meter roadcut off of the exit ramp, exit 87, I-75 northbound, leading onto the Richmond Bypass (Fig.1, 8, 9). The section was measured, described, photographed, and 20 rock samples were taken with a focus to sample representative rock units, as well as lithologic transitions. Features seen in the outcrop were useful in the interpretation of the environments of deposition, but most useful information comes from slabbed samples and thin sections. The study recognized several distinct depositional environments and transgressive and regressive cycles of a warm, shallow sea. This information can be tied into future studies to provide a more detailed picture of the Upper Ordovician geologic history in the vicinity of Richmond, Kentucky.

Local Stratigraphy

The study area (Fig. 1) has been mapped (Greene, 1966) as the Ashlock Formation, which consists of the Tate, Gilbert, Stingy Creek, Terrill and Reba Members over eastern Kentucky (Weir et al, 1984). The Ashlock lies above the Calloway Creek Formation and below the Bull Fork Formation and is Maysvillian (Cincinnatian) or Ashgillian in age (Fig. 2). Specifically, the study outcrop has been mapped as the lower part (Oal, Fig.1) of the Ashlock Formation by Greene (1966).

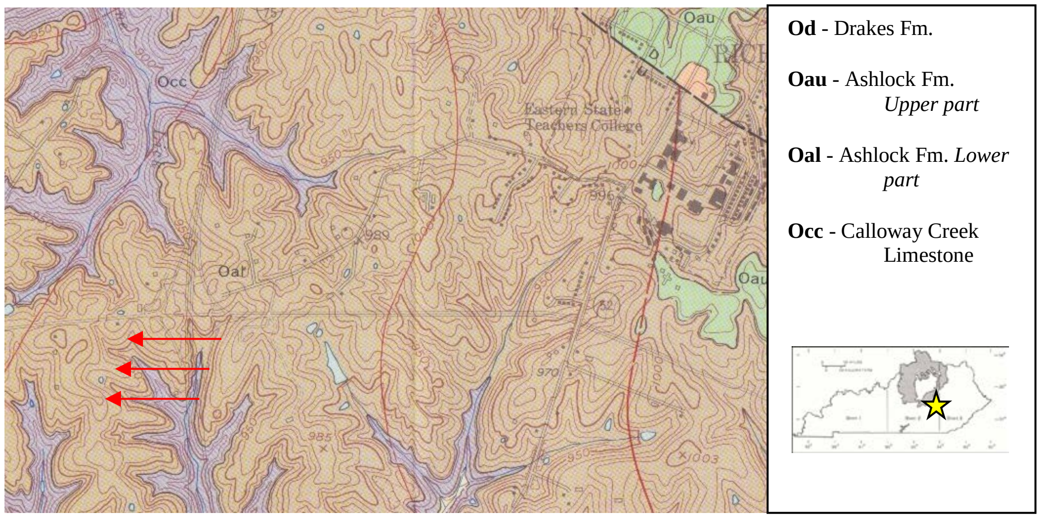


Figure 1. Left: Geologic map of the Richmond South Quadrangle, Madison County, Kentucky (Greene, 1966). Map has been cropped to highlight area of study, shown by red arrows. Right: Key to geologic map symbols with oldest rock unit at bottom; inset map shows general location of study area with a yellow star.

From this geologic mapping and description of the stratigraphic section in Weir et al (1984), we infer that study rocks are part of the Gilbert Member, but we are uncertain of this determination, so we will refer to the study unit generally as the Ashlock formation.

The Ashlock Formation at this locality consists of alternating layers of shaley limestone and limestone, the latter usually wackestone or packestone (Fig. 3). The Gilbert Member ranges in thickness from a few feet to about 20 feet as it outcrops in Richmond (G.W. Weir, 1984), and is characterized by alternating of micritic mudstone, fine-to medium-grained limestone, and calcitic silty shale. Some lithologies of the Gilbert Member are very resistant to weathering and typically form ledges of consolidated limestone. Overall, the Gilbert Member is described by Weir as" muddier and coarser grained" approaching Richmond than compared to that outcropping to the northeast.

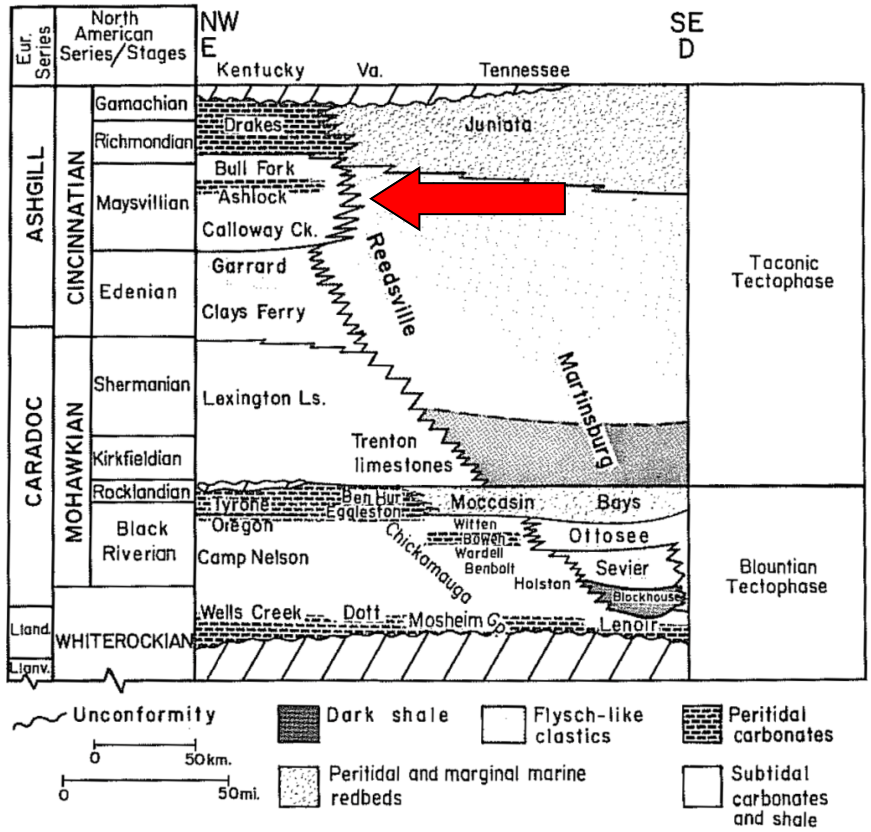


Figure 2. Stratigraphy of Upper Ordovician limestones and cross-section of the Appalachian Basin showing the cratonward migration of clastics derived from the rising Appalachian mountains during the Bloutian and Taconic tectophase (Ettensohn, 1991). The red arrow highlights the Ashlock Formation.

Paleogeographic Setting

The geologic and paleogeographic setting of Kentucky was very different during the Middle and Upper Ordovician (Fig. 4). Approximately 445 million years ago the Blue Grass region of Kentucky was positioned at about 15° south of the equator, and was covered by a shallow sea. In eastern Kentucky, the rock record shows changes in lithology produced transgressive and regressive cycles that are a consequence of: (1) plate tectonic and mountain building activity to the east; and (2) changes in eustatic sea level. Thus, it is the interplay of these two principle variables that controls the large-scale depositional patterns of the Appalachian Basin.

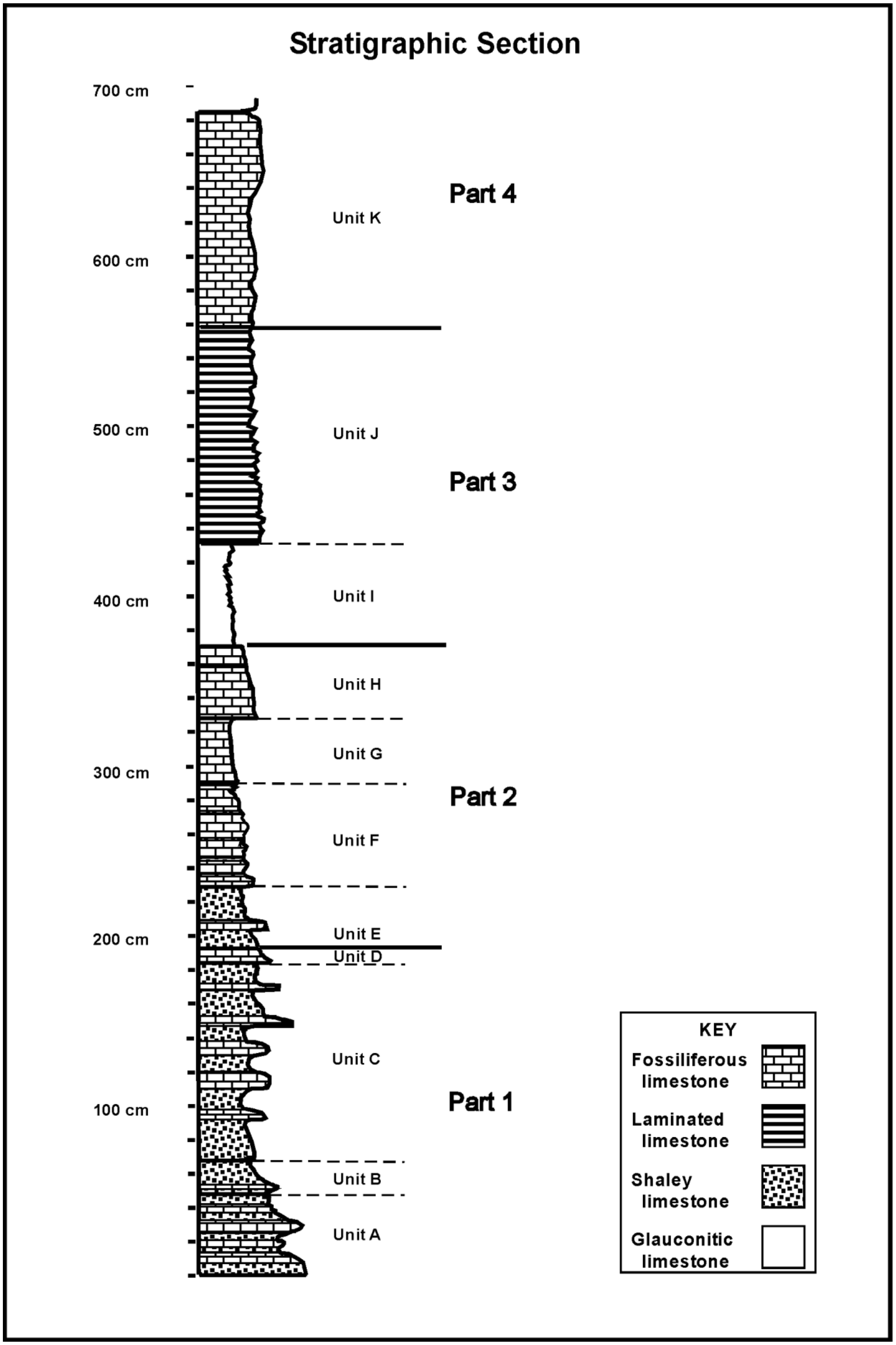


Figure 3. Schematic sketch of the measured stratigraphic section of this study.

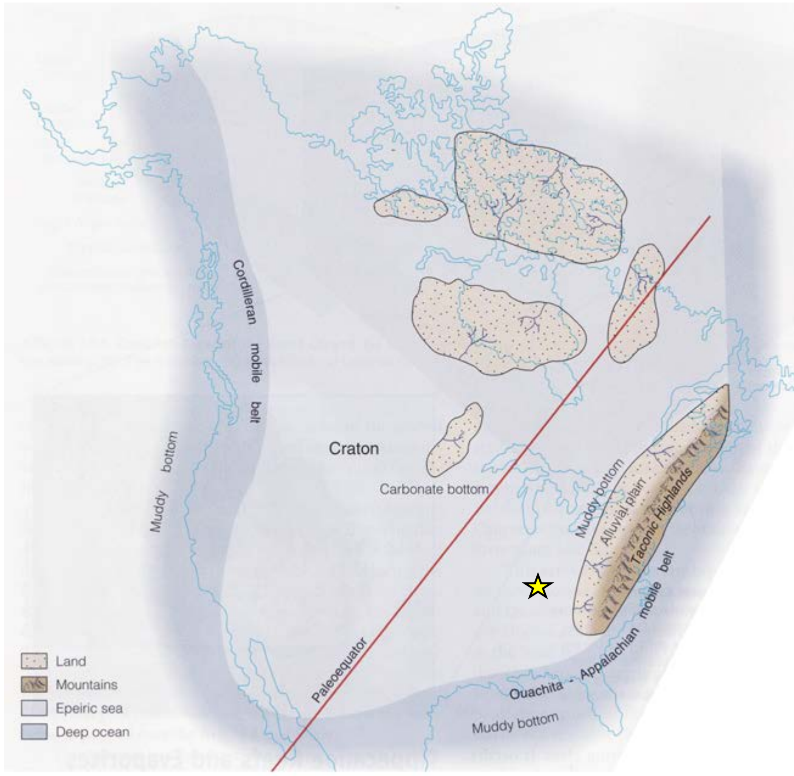


Figure 4. Paleogeographic map of the Late Ordovician Period (Wicander and Monroe, 2007). Note the position of the study area shown with a yellow star. A deep basin occurs craton-ward of the rising Appalachian mountains and shallow water depositional environments occur on the eastern margin of the craton.

The shallow seas are on the eastern margin of the craton of Laurentia, with water depth increasing toward the present-day east, into a deeper basin toward the position of the rising Appalachian Mountains (Fig. 5). The western portion of the Appalachian Basin received much less clastic sediment than did the eastern portion of the basin, which received clastic material shed by the mountains immediately to the east.

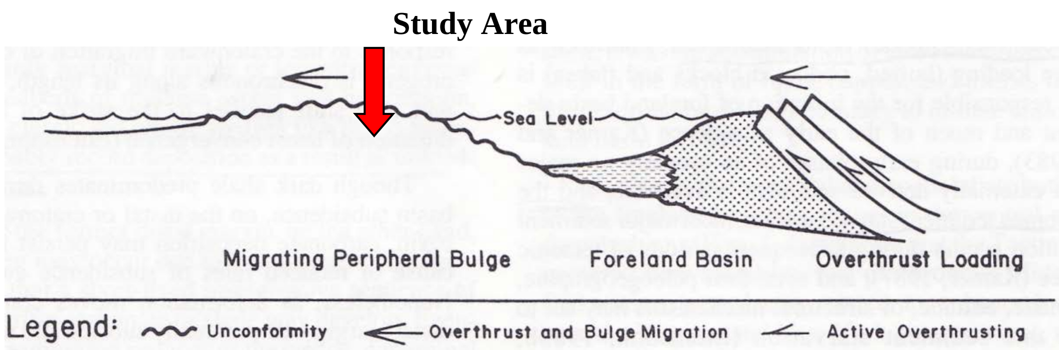


Figure 5. Deformational loading of the Appalachian orogen, leading to the development of a foreland basin and peripheral bulge (Ettensohn, 1991).

The Ordovician phase of the formation of the Appalachian Mountains occurs during the Taconic Orogeny (Ettensohn, 1991). Thrust sheets were transported westward during plate tectonic collision of Laurentian and an eastward island arc that created highlands presently east of the craton. Uplift and loading of the Earth's crust formed a foreland basin exemplified by the deeper portions of the Appalachian Basin (Ettensohn, 1991). The loading associated with the Taconic Orogeny also created a peripheral bulge craton-ward (Fig. 5) that affected deposition on the western portion of the basin where our study site is located. Ettensohn (1991) has recognized several phases of the Taconic orogeny in eastern Kentucky, namely the Bloutian tectophase and younger Taconic tectophase (Fig. 2).

Using lithospheric flexure models (Ettensohn, 1991), the foreland basin progressively migrated craton-ward over a great distance during the Ordovician, receiving the sediment eroded from the rising orogen (Fig. 5). During periods of rapid erosion and unloading, sediment filled the foreland basin as rapid subsidence occurred there. Rapid subsidence of the foreland basin is the mechanism whereby the peripheral bulge rises above sea level, and exposes carbonate sediments to weathering and /or creates conditions of non-deposition (Ettensohn, 1991). Because of the cratonward migration of the foreland basin, the peripheral bulge also migrates seaward until its former location subsides to be covered by basin waters, fostering deposition of limestone or additions of terrigenous mud as clastic sediment entered the basin. The Taconic and Bloutian tectophases are two such episodes of tectonic movement that have affected deposition around Richmond, Kentucky (Fig. 2).

Description of Study Site

The area of study is limited to the outcropping of the Ashlock Formation on the exit ramp of I-75, Exit 87 northbound, beginning < 5 m from the southernmost edge of the rock outcrop (Fig. 6). The oldest rock unit lies at the southern extremity of the outcrop and to measure the entire exposed section it was necessary to measure the section in a stair-step manner moving to the north (Fig. 7). About 7-meters of stratigraphic section were measured in 4 parts using a Jacob's staff, as laterally continuous beds were traced northward from one section part to another to tie them together and thus define a composite stratigraphic section. For example, Part 1 of the stratigraphic section was measured (Fig. 6, far right), then uppermost bed of Part 1 began the bottommost layer of Part 2 that began the Part 2 section. Each successive part of the stratigraphic section was measured in this manner, until four such parts were measured along the length of the outcrop. The four parts were described, measured, and sampled in detail.

Figure 6. Photograph of the study outcrop, looking east from off I-75 towards the outcrop.

Representative samples of unit lithologies were taken for slabbing and thin sections. Samples were coded in permanent marker with letters, numbers, and an arrow to denote upward position. For example, SS1A, was used to code Stratigraphic Section Part1, Unit A. As well, each measured part of the stratigraphic section had a letter painted on the surface of the outcrop indicative of each respective lithologic unit, beginning with Unit A through Unit K. The outcrop units are composed of intercalated shalely limestone and limestone to the south, weathering into ledges; to the north more consolidated limestone occurs and weathers with a more vertical face (Fig. 6). Each unit of the stratigraphic section is described in Chapter 2. All samples were slabbed in the lab, however not all samples were made into thin section. Only 11 of the 20 samples were made into thin section, using standard techniques. The thin sections were ground down to sufficient transparency that the light may pass through, thereby revealing the composition of the rock. These observations were then used to provide the bulk of our evidence in interpreting the environments of deposition of each successive unit. A Nikon digital camera (10 megapixel resolution) was used to take photographs of the thin sections.

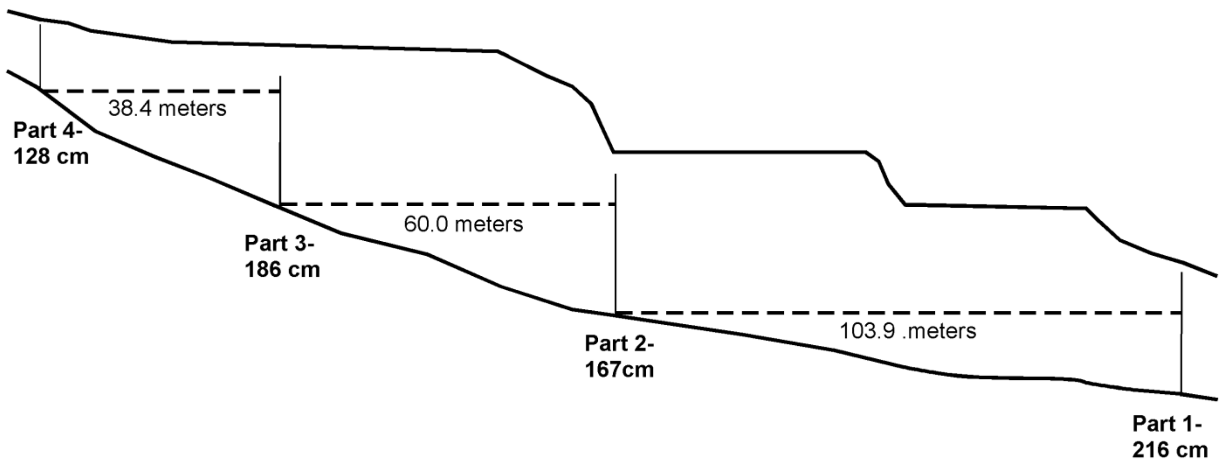


Figure 7. Schematic sketch of the study outcrop, showing how it was measured in four parts.

Chapter 2

Lithology Descriptions and Depositional Environments

Unit A

***Description*:** Unit A is represented by alternating beds (Plate 1) of wackestone and shaley limestone (Fig. 8) with sharp contacts between these lithologies. Total thickness for Unit A is 48 centimeters. Fossiliferous limestone is more resistant to weathering and forms ledges. There are a minimum of 5 to 6 ledges within Unit A, that pinch out laterally along the outcrop. The wackestone beds in A contain brachiopods, bryozoans, and crinoid columnals. There is no layering within the wackestone layers. The brachiopods are globular; articulated and disarticulated specimens can be found in abundance. The shaley limestone intervals are 5 to 10 cm in thickness, and are gray to light gray.

***Interpretation*:** Abundant and diverse fossils within the wackestone suggest deposition in a shallow marine environment, however specific water depths cannot be determined. The wackestone may represent storm deposits but as they are strongly bioturbated there is no grading, other suggestive fabrics, or silt infiltration observed (Kumar and Sanders, 1976).

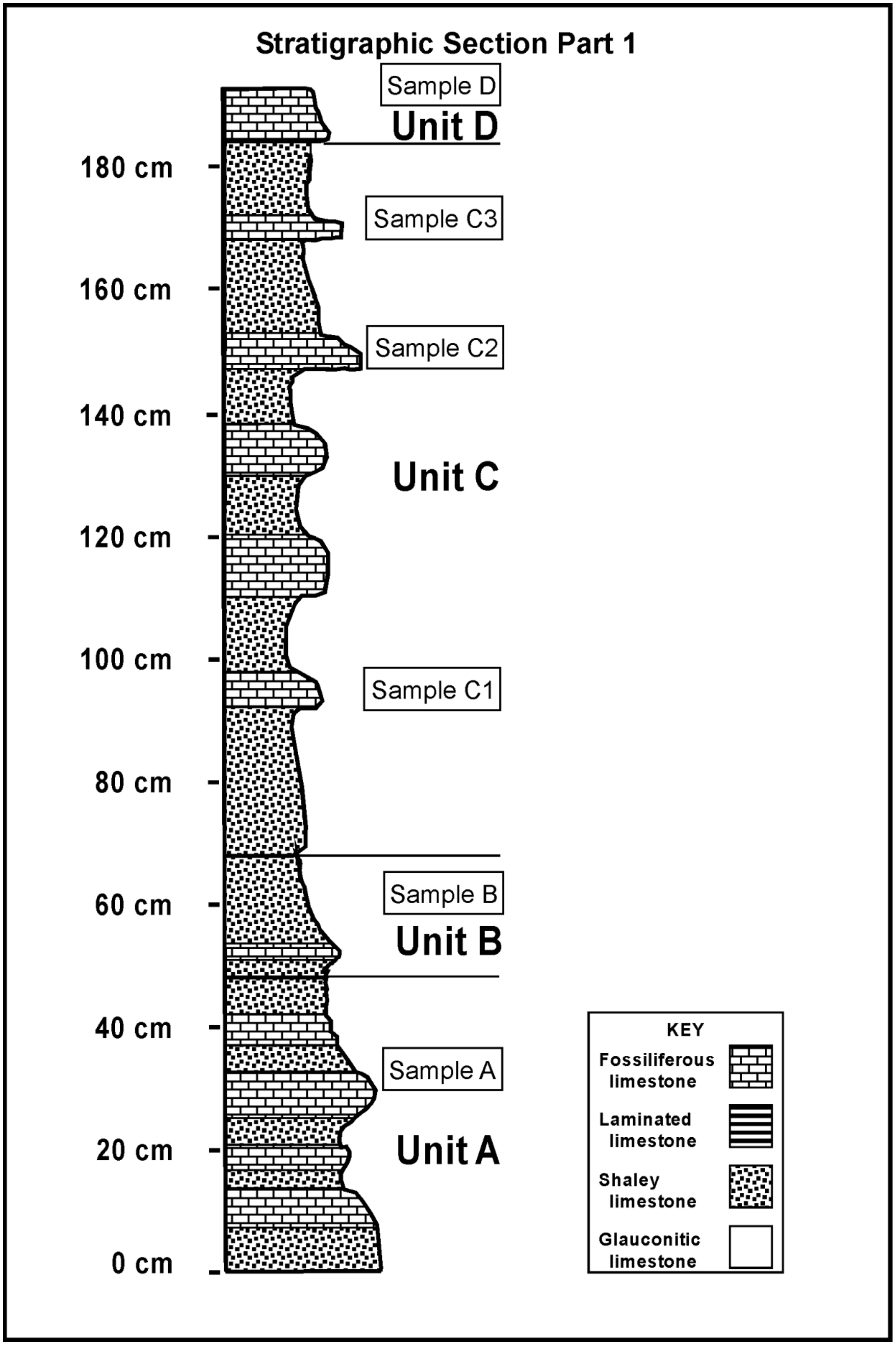


Figure 8. Stratigraphic section, Part 1.

See next page:

Plate 1A. Sharp contact between Unit A and Unit B at top of hammer handle (arrow).

Plate 1B. Shale chips from sharp contact of Unit A and B.

Plate 1C. Photomicrograph of ostracode in center of thin section. Note the thickening of valves toward one end.

Plate 1D. Cross section of a bryozoan. Chambers are fairly rounded and wall structures are thick and fibrous.

Plate 1E. Fragment of a brachiopod within wackestone.

Plate 1F. Photomicrograph of wackestone showing bryozoan, brachiopod, and ostrocode grains.

PLATE 1: Illustrations of Unit A

Unit B

Description**:** Unit B (Fig. 8) is a medium to light gray bioturbated wackestone 24 centimeters in thickness; two samples were taken from top of the unit. Unit B is characterized by the sharp shaley contact at the base with Unit A (Plate 1A) and by the abundance of articulated brachiopods at the contact that act as geopetal structures. Mud infiltrated into the brachiopod shells and eventually settled to the bottom, and sparry calcite has precipitated in the upper portion of the shell (Plate 2A). Bryozoan, brachiopod, and ostracode fragments are abundant. No internal fabric is evident within the wackestone, strongly suggestive of bioturbation.

Interpretation**:** Again, diverse and abundant fauna suggest deposition under shallow marine conditions. In Plate 2F blue-green algae is seen on the surface of the brachiopod fragment, as an example of endolithic boring. The blue-green algae suggests that the organisms lived within the photic zone prior to burial.

See next page:

Plate 2A. Photomicrograph of articulated brachiopod shell in Unit B. The shell has been replaced by sparry calcite during recrystalization. Inside the shell has been partially filled with micrite with the upper portion replaced with sparry calcite as evidence of diagenesis.

Plate 2B. Crenulations of brachiopod shell seen within micritic matrix.

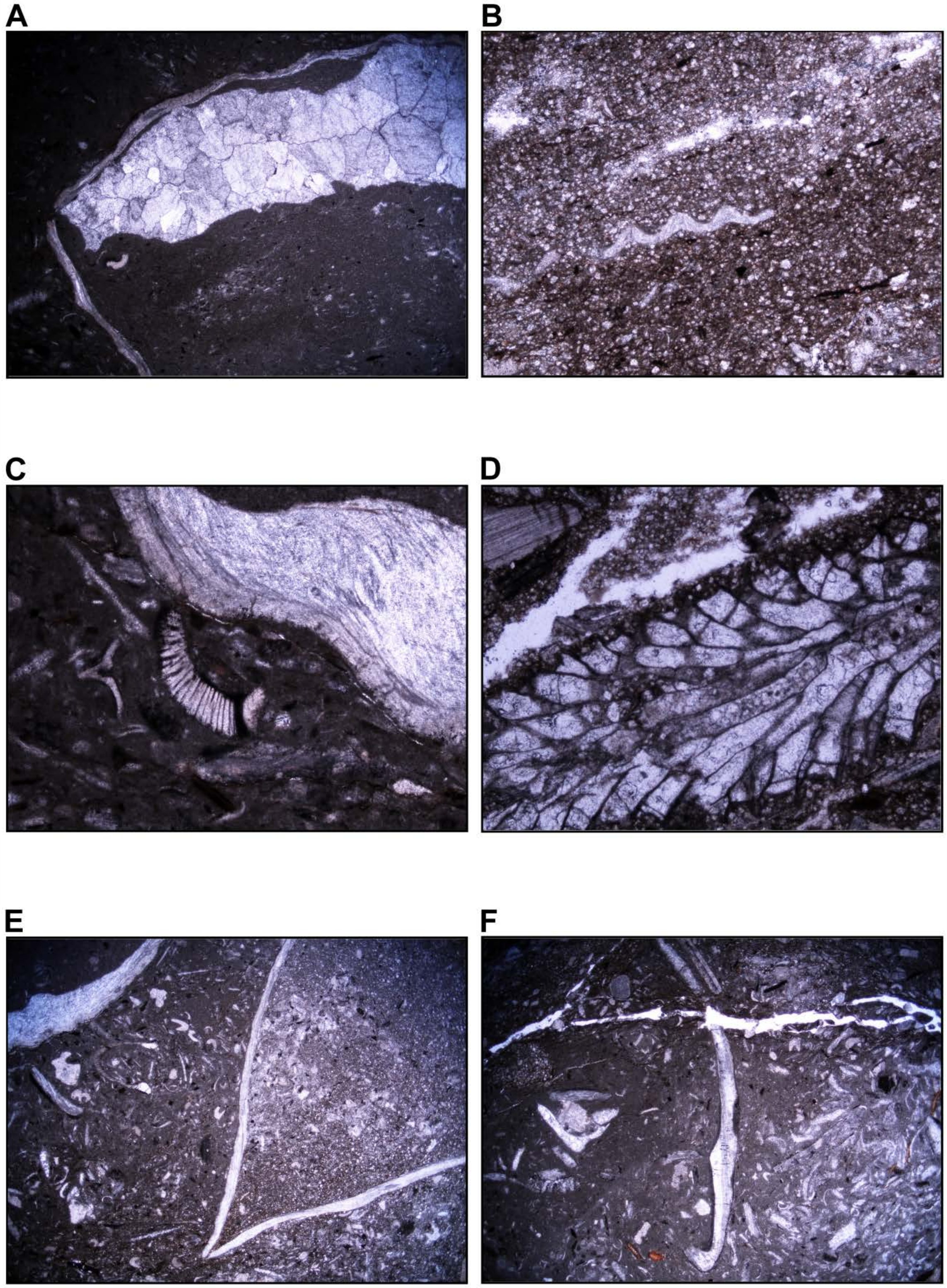
Plate 2C. Fibrous microstructure of brachiopod shell and preserved pseudopuctae, in top right corner.

Plate 2D. Longitudinal section of bryozoan colony. Zooecia curve towards outer margins showing the thickening of the structure towards the exterior.

Plate 2E. Brachiopod fragment similar to Plate 2A. Note the micritic rim.

Plate 2F. Brachiopod fragment.

PLATE 2: Illustrations of Unit B



Unit C

***Description*: ** Unit C (Fig. 8) is 112 centimeters in thickness and is characterized by alternating beds of fossiliferous packstone and shaley limestone with sharp contacts. Nests of articulated brachiopods are packed within lenses of shaley intervals. A few specimens of bryozoans occur in hand samples. Fossils become sparse nearer the top of Unit C. Three samples were taken from Unit C, but only sample 2 was slabbed and made into a thin section. Unit C contains abundant allochems. The packstone consists of bryozoans, echinoderms, brachiopods, gastropod and ostracode fragments, among others.

***Interpretation*: ** Abundant and diverse fauna again suggest deposition in shallow, marine depositional water. Less mud within suggests the packstone of a higher energy environment in contrast to Units A and B.

See next page:

Plate 3A. Position of Sample 3C before removal from outcrop.

Plate 3B. Photomicrograph of brachiopod valve fragment.

Plate 3C. Nested brachiopods in shaley interval of Unit C.

Plate 3D. Bryozoan fragments in various orientations within the packstone.

Plate 3E. Bryozoan, brachiopod and sparry calcite fragments visible at outcrop.

Plate 3F. Photomicrograph of a gastropod in Unit C, Sample 2. This is a cross section of a single whorl of a high-spired species.

PLATE 3: Illustrations of Unit C

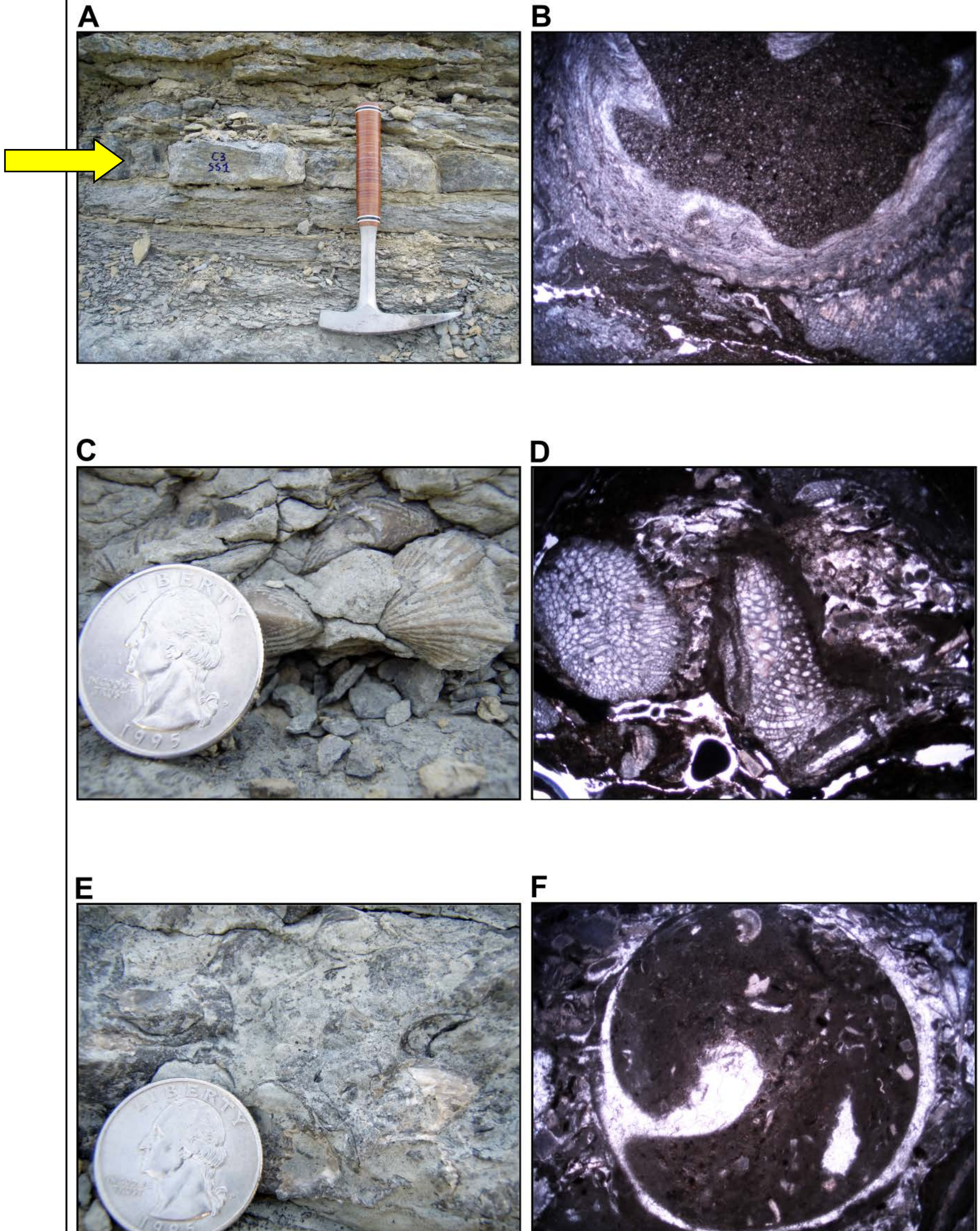


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Plate 4G. Crenulations of brachiopod fragment.

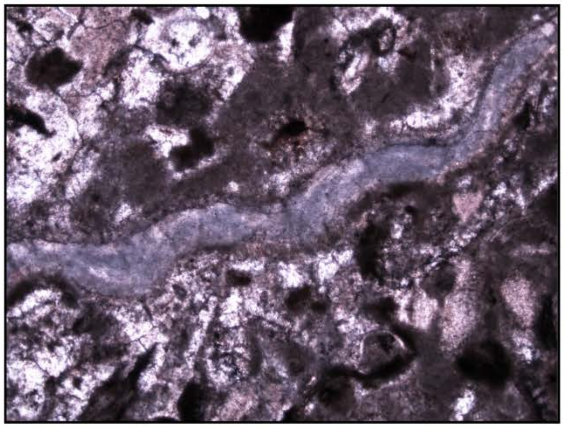
Plate 4H. Fabric of the packstone; note abundance of allochems.

Plate 4I. Unknown fossil with micritized edge.

Plate 4J. A closer look at Plate 4H. Note the cross section of the echinoderm column, possibly of a crinoid species, showing pentameral symmetry (arrow).

PLATE 4: Illustrations of Unit C Continued

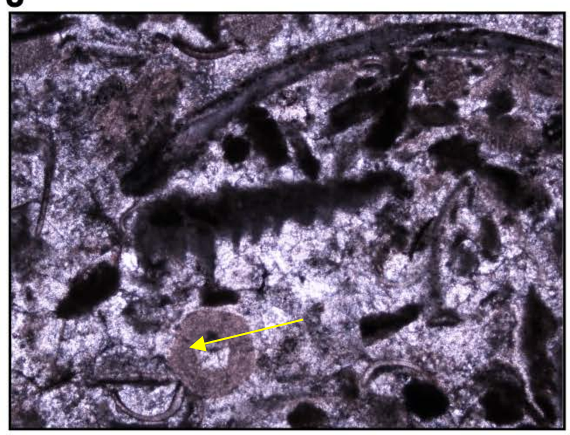
G



H

I

J



Unit D

Description**:** Unit D (Fig. 8) is the uppermost layer of stratigraphic section 1 of our study area, and characterized by a dark gray, 32-centimeter-thick ledge formed above a softer, muddy substrate. Abundant brachiopod shells are exposed. The terrigenous mud that clings to the bottom is a medium brown color.

Interpretation**:** The ledge that forms Unit D is abundant in brachiopod beds and terrigenous mud, suggesting less turbulence from a return to shallow, marine conditions.

See next page:

Plate 5A. Head of hammer is placed at transition from Unit C to Unit D.

Plate 5B to E. The bottom of Unit D forms a ledge as the soupy substrate that lies below is being slowly eroded. Articulated brachiopod shells are abundant on the bottom of the ledge.

Plate 5F. Northward view from stratigraphic section 1, showing Units A through Unit D.

PLATE 5: Illustrations of Unit D

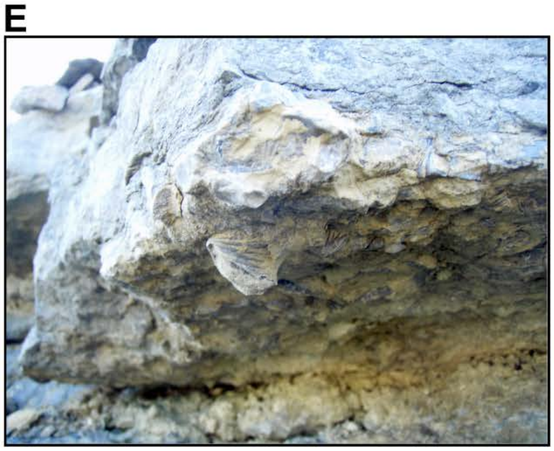
A

B

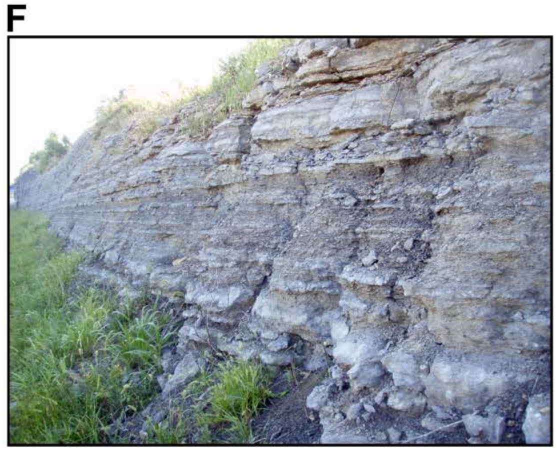
C

D

E



F



Units A-D, looking north towards exit 87

Unit E

Description**:** Unit E (Fig. 9) contains a single fossiliferous limestone bed, 37 cm in thickness, contained between two shaley beds. The shale on the bottom is dark gray, the brachiopod bed in the middle has weathered to a charcoal color, and the shaley interval on top is medium gray. The limestone bed is a consolidated packstone with a matrix dominated by mud but possessing some spar. Allochems include mostly peloids and fossils, although the clast is also supported by unarticulated pieces of brachiopods, bryozoans, ostracodes, trilobites, gastropods, and red algae. The large red algae (0.8 mm) is not fragmented suggesting that it was not transported into the area from a different locality (Plate 6C). Some of the peloids appear to be fossil fragments with micritic rind, presumably formed by the action of boring algae.

Interpretation**:** Diverse and abundant fauna suggest deposition in shallow marine conditions. The presence of red algae and micritic borings suggest that sediments were likely deposited in the photic zone.

See next page:

Plate 6A. Unit E begins at the base of staff, 37 centimeters in thickness. The shown side view was not used for measurements, but to see the single ledge that has formed by weathering of the upper and lower boundaries of Unit E.

Plate 6B. Representative sampling of the constituents of this packstone. Bryozoan, brachiopod, and ostracode fragments with interstitial spar and mud.

Plate 6C. Large red algae grain showing tubular fabric. Preservation is usually due to high Mg-calcite composition. Compare and contrast with Plate 6D, as red algae have the appearance of bryozoans but are much less abundant.

Plate 6D. Transverse cross-section of stem of bryozoan colony.

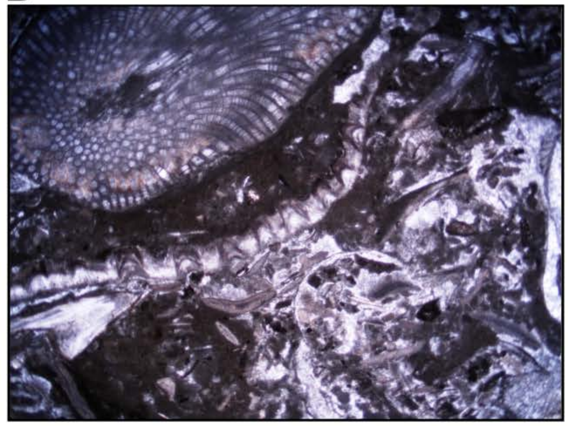
Plate 6E. Unit E is one of several bioclastic zones observed in our study area.

Plate 6F. Close-up view of Unit E, showing the bioclastic zone in detail. Note the peloids and micritized fossil fragments.

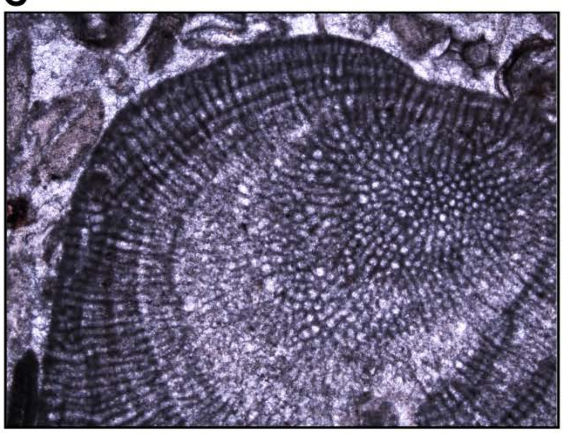
PLATE 6: Illustrations of Unit E

A

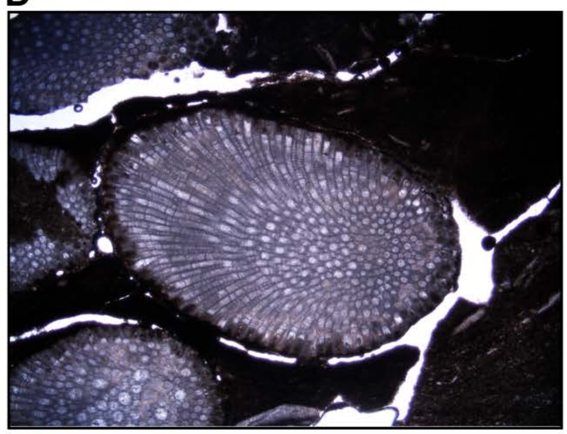
B



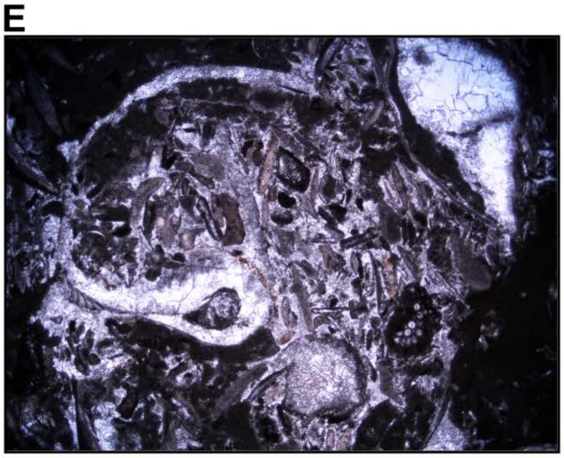
C



D



E



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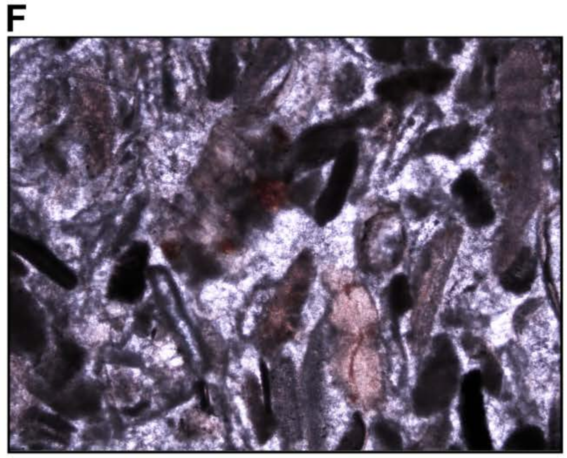


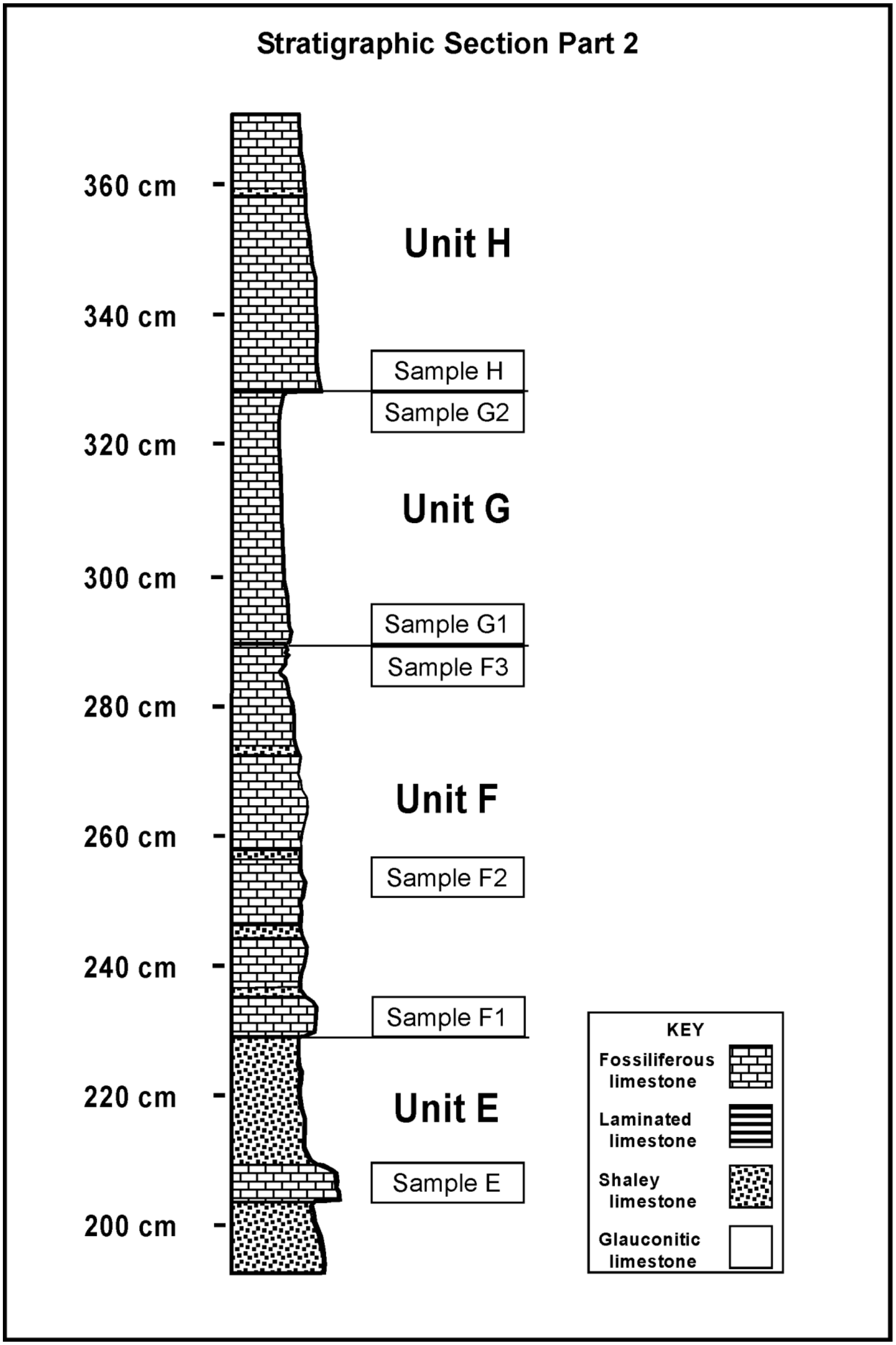


Figure 9. Stratigraphic section, Part 2.

Unit F

Description**:** Unit F (Fig. 9) is 58 cm thick, and weathers as a relatively flat vertical surface composed of limestone beds interspersed with shaley intervals. Upper boundary of the unit is reddish brown, stained from iron derived from weathering pyrite grains (Plate 7A); the reddish-brown layer does not persist more than several millimeters within the rock. All six beds weather to a dark gray. In hand sample it is very difficult to ascertain the orientation of the brachiopods because of the hardness of the rock. Three samples were taken from Unit F; the sample from the uppermost boundary of Unit F was thin-sectioned.

Interpretation**:** The paleoecology at Unit F is similar to Unit E suggesting a shallow marine environment. The algae fragment suggests formation within the photic zone. The upper boundary containing pyrite suggests a possible omission surface (or sequence boundary). The contact is sharp and can be traced along the entire outcrop. The sharp upper contact with Unit G persists through the entire outcrop. This together with the odd occurrence of pyrite suggests a possible omission surface or sequence boundary exists. This possibility can be tested with future biostratigraphic information.

See next page:

Plate 7A. Photomicrograph of upper boundary of Unit F. A reddish brown color is present due to the weathering of pryrite at this interval.

Plate 7B. Fossil grains such as peloids, micritized fossils, and red algae fragments.

Plate 7C. Single valve of ostracode shell within a matrix of mud.

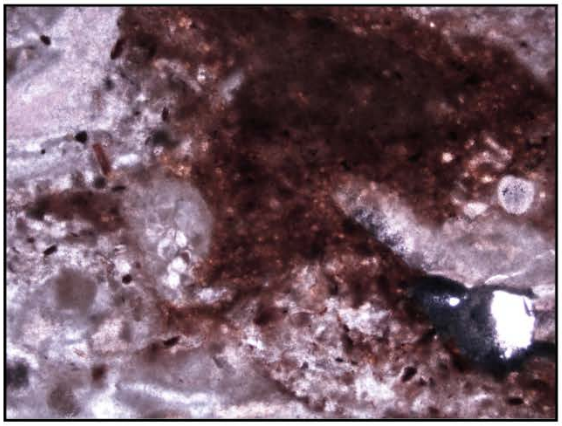
Plate 7D. Longitudinal section of high-spired gastropod. Calcite has replaced original aragonite shell.

Plate 7E. Fibrous microstructure of brachiopod shell and preserved pseudopuctae. Notice the wave-like appearance of the inner-shell.

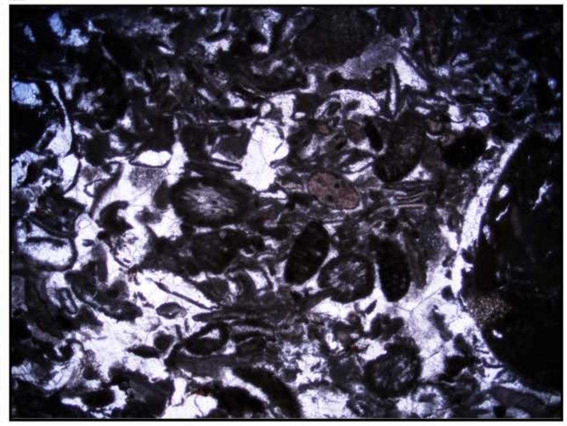
Plate 7F. Fragment of red algae.

PLATE 7: Illustrations of Unit F

A



B



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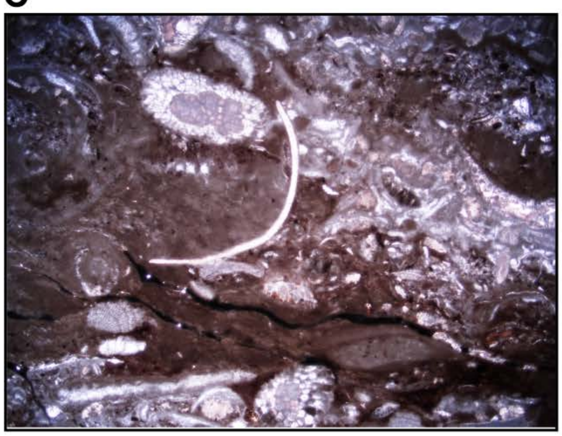

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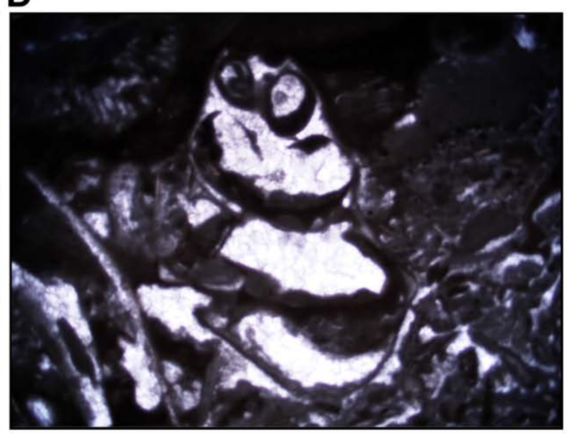
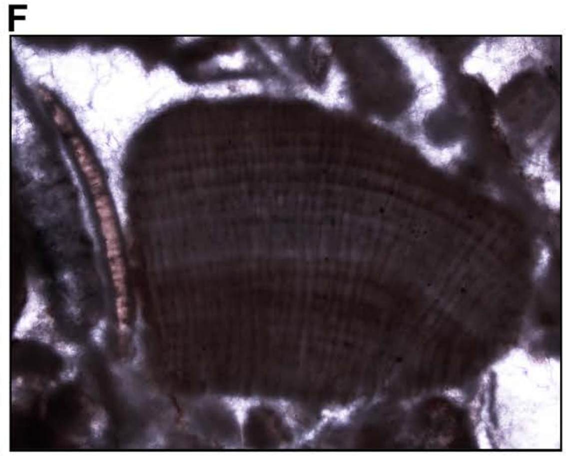


E

F



Unit G

***Description*:** Unit G (Fig. 9) is a 27-cm-thick layer of consolidated wackestone, with alternating layers of limey shale weathering from dark to light gray. The wackestone is more resistant to weathering, thereby forming ledges. Unit G has distinct upper and lower contacts (Plate 8A). The lower boundary is the reddish-brown layer of Unit F, and the upper boundary being a 1-cm ledge of limestone, dark grey in appearance and homogenous in composition. Two samples were taken from these upper and lower boundaries.

Allochems in the wackestone of Unit G are fossils and intraclasts. Fossils include bryozoans, brachiopods, algae and ostracodes (Plate 8F). Only a few intraclasts occur, and are less than ~1cm in size. The intraclasts have similar lithology as Unit G sediments with a slightly different, muddy matrix.

***Interpretation*:** The abundance and diversity of fauna in the Unit G interval suggests warm, shallow, marine conditions. The large red-algae grain in Plate 8E supports this hypothesis, however this is not certain because of the presence of intraclasts; the red-algae may have been transported from an adjacent depositional environment that is shallower. A possible single storm event is also recorded by the burial of a whole bryozoan colony, as seen in Plate 8C.

See next page:

Plate 8A. Unit G is 27 cm in thickness, beginning just above the reddish-brown boundary of Unit F.

Plate 8B. Photomicrograph of fossiliferous mudstone.

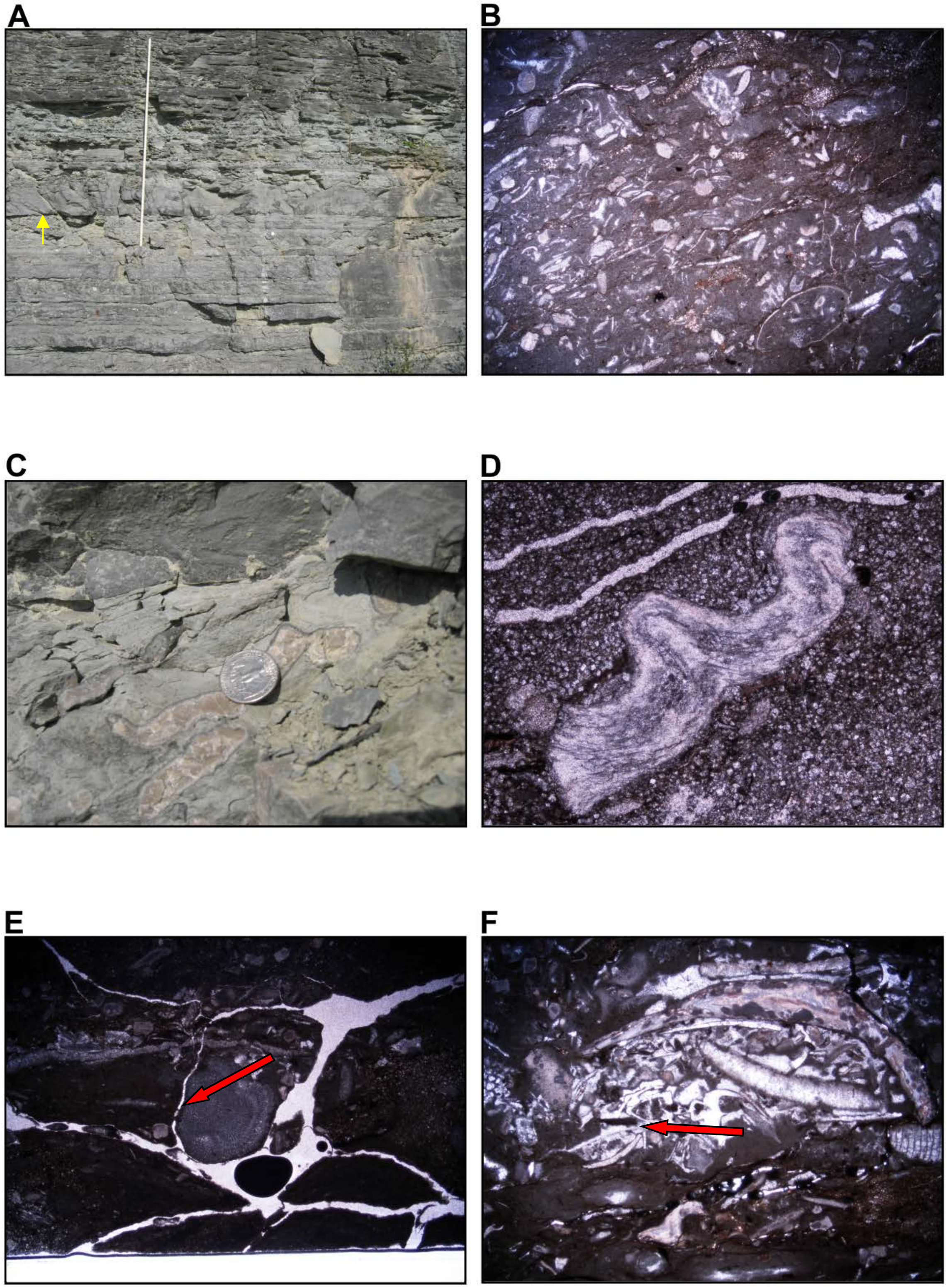
Plate 8C. Very large bryozoan colony discovered within the mostly muddy interval of Unit G.

Plate 8D. Fibrous wall of disarticulated brachiopod shell.

Plate 8E. Large red algae grain showing elongate cellular fabric around periphery of grain.

Plate 8F. Photomicrograph of fragments of bryozoa, brachiopods, and ostracode, as well as unknown fossil fragment in center (see red arrow).

PLATE 8: Illustrations of Unit G



Unit H

Description**:** Unit H (45 cm thick) consists of mostly solid wackestone with a single interval of less-consolidated limestone 5 cm thick (Fig. 9). Few fossils occur, but they, especially bryozoans, are relatively large and unbroken, suggesting non-transport (Plate 9B). Unit H is light brown but weathers to a dark charcoal color. Other than the large bryozoans, fossils are very sparse, with exception of the few fragments from the bottom of the burrow in our thin section (Plate 9C). The only discernible fossil is that of a disarticulated ostracode amongst the fragments (Plate 9D). These fossils apparently line the burrow as infill, from top to bottom. The silty micritic matrix is consistent throughout the sample.

Interpretation**:** The lack of layering within the silty micritic matrix suggests heavy bioturbation on the seafloor. The burrow (Plate 9E) offers evidence for such bioturbation. The lack of fossils suggest a different depositional environment, likely deeper waters that doesn't support more life. The large bryozoan colony was possibly infiltrated by this mud in a single storm event, as it shows the articulation of the branching colony (Plate 9B).

See next page:

Plate 9A. Unit H is 45 cm. thick; arrows denote Unit H boundaries.

Plate 9B. Articulated bryozoan colony on surface of Unit H, in an otherwise heavily bioturbated interval.

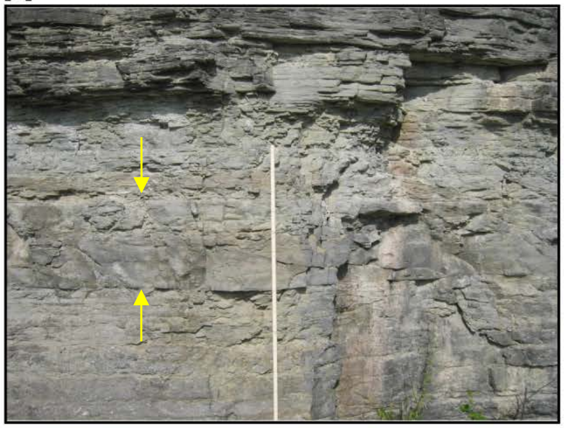
Plate 9C. Photomicrograph of vertical burrow outlined by the yellow line.

Plate 9D. The bottomward extent of the burrow reveals fossiliferous fragments within micritic mud. Only a single ostracode valve is identifiable.

Plate 9E-F. The silty micritic matrix of Unit H.

PLATE 9: Illustrations of Unit H

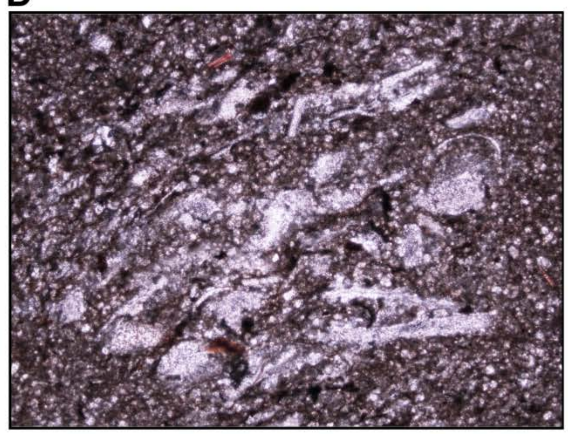
A



B

E

D



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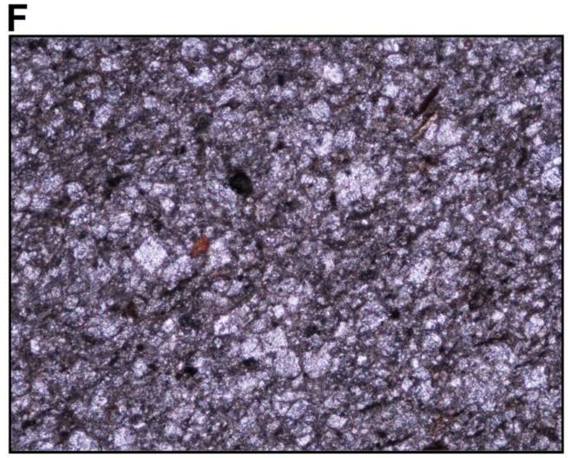
F



Unit I

***Description*:** Unit I (Fig. 10), is a green laminated, limey shale (59 cm in thickness) that is very brittle but breaks into thin, elongated pieces. The base is light brown in color and shows mottling with green laminations with bioturbation at the Unit H-I contact. The presence of glauconite gives the outcrop at Unit I a green appearance, especially visible when wet. This very different lithology was the catalyst for our investigation of this particular outcrop. The matrix also consists of small pockets of fossils, as well as glauconite within the interstices of the dolomite rhombs. The glauconite was not evenly distributed throughout the dolomitic micrite as there were varying concentrations throughout our sample (Plate 10E). The thin section revealed a cross-section of a bryozoan colony (not shown), within a dolomitic micrite matrix.

***Interpretation*:** It is uncertain whether glauconite occurs as matrix or as allochems. The glauconite does occur within the interstices of the diagenetic overprint of dolomite rhombs, however, that does not rule out the possibility that the glauconite occurs with peloids deformed and crushed to form a pseudo-matrix. It is probable that the dolomitization seen with Unit I extends laterally throughout Unit I, but it may be patchily distributed. This dolomitization of the limestone is open to interpretation as the origin of the dolomite is poorly understood, although it is certainly diagenetic (Braithwaite, 2004). Some authors suggest dolimitization occurs within the mixing zone (Braithwaite, 2004), or occurs from the dewatering of clays and/or Mg-rich fluids (Braithwaite, 2004). It would be appropriate to further investigate the origin of these dolomite rhombs that show cloudy centers.

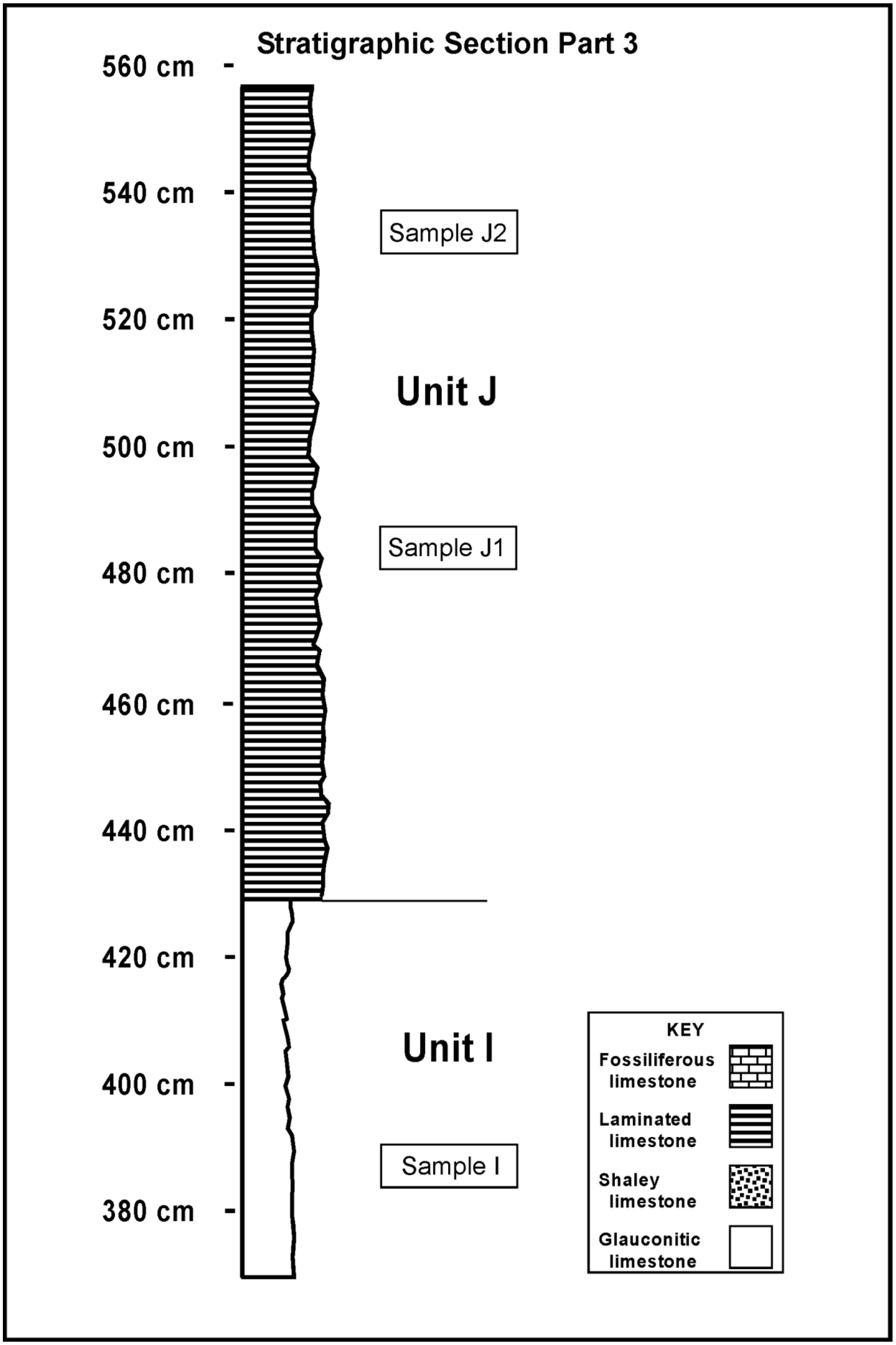


Figure 10. Stratigraphic section, part 3.

See next page:

Plate 10A. Unit I, off of Exit 87 ramp, looking south; thickness of 59 cm.

Plate 10B. Hammer lies at base of Unit I, next to sample taken from Unit I. Note the green appearance on the facies of the rock, due to the presence of glauconite.

Plate 10C. Mottling due to bioturbation at Unit H-I boundary.

Plate 10D. Fragmented fossils within the interstices of the matrix. Box outlines 10F.

Plate 10E. Photomicrograph of glauconite contained within the interstices of cloudy dolomite rhombs of Unit I.

Plate 10F. Close-up of photomicrograph 10E. Trilobite fragments and/or single valved shell fragments, perhaps ostracode in origin, replaced by calcite.

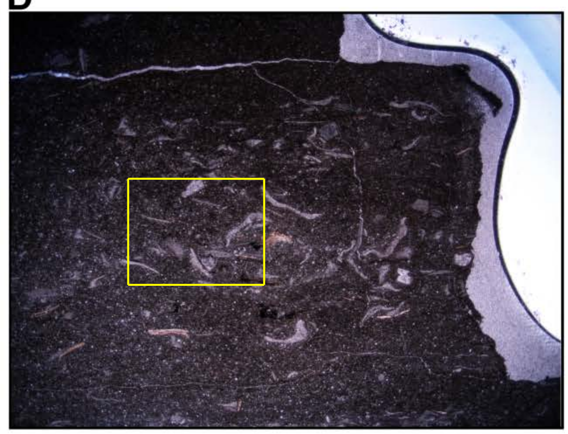
PLATE 10: Illustrations of Unit I

A

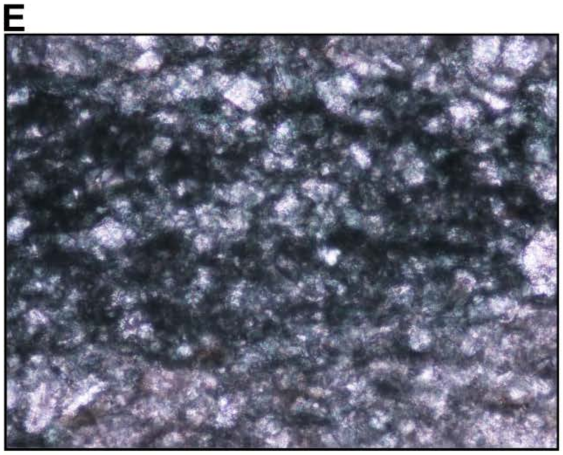
B

C

D



E



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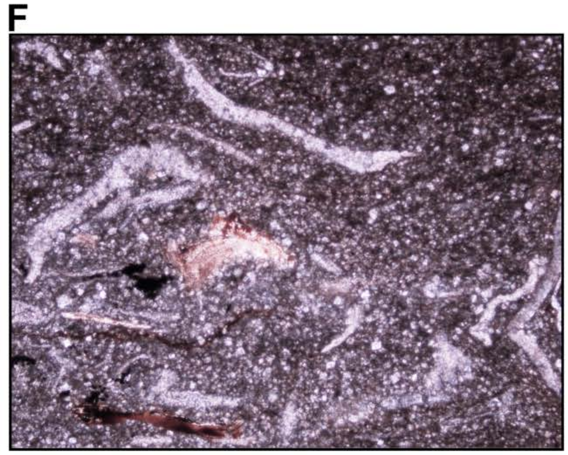


Unit J

Description**:** Unit J (Fig. 10) is a bioturbated calcareous mudstone and is very thick compared to other units, with a total thickness of 127 cm. It consists of very fine to thick laminations of shaley limestone consisting of silty micritic terrigenous mud. The outcrop of Unit J weathers to a very dark gray and as a vertical face. As it is composed of mostly laminations, the only fossil found was a single valve of an ostracode, as the only identifiable fossil.

Interpretation**:** The fine-grained nature of the rock suggests a low energy environment found in deeper marine conditions. The single valve of the ostracode is evidence of lack of turbulence, as it is unbroken. Also, the laminated terrigenous mud that is lacking in fossils is 1) typical of seafloor depths beyond the photic zone, and 2) indicative of a lack of turbulence in the water creating disoxic conditions not conducive to life. The laminations also demonstrate that bioturbation did not occur within this interval, and suggest a deposition of mud in still or slow-moving currents. The single example of ripple marks (Plate 11B), as seen on the surface of the outcrop, indicate the occurrence of shallow water, or mark the interval of a storm wave base.

See next page:

Plate 11A. Unit J, thickness 127 cm. weathers to a dark gray, giving a tar-like appearance.

Plate 11B. Unit J laminations, from thick to very thinly laminated. Ripple marks highlight the laminations in the center of photo.

Plate 11C. Side-view of thin laminations.

Plate 11D. Unit J, Sample J1, before being slabbed. The sample was about 60 cm long by 5 cm wide.

Plate 11E. Photomicrograph of thin laminations within Unit J, Sample 1. The transparent material is epoxy holding the laminations together.

Plate 11F. Single ostracode valve within micritic muddy matrix.

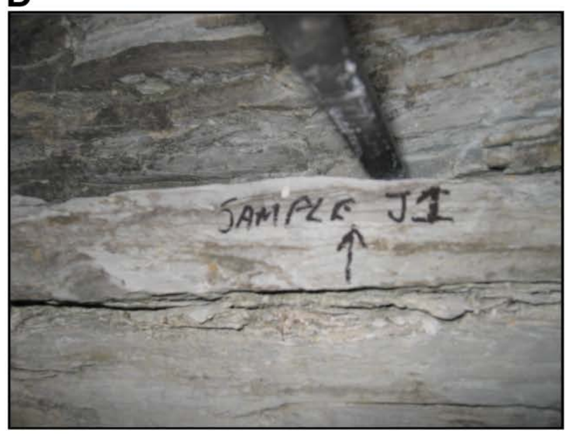
PLATE 11: Illustrations of Unit J

A

B

C

D



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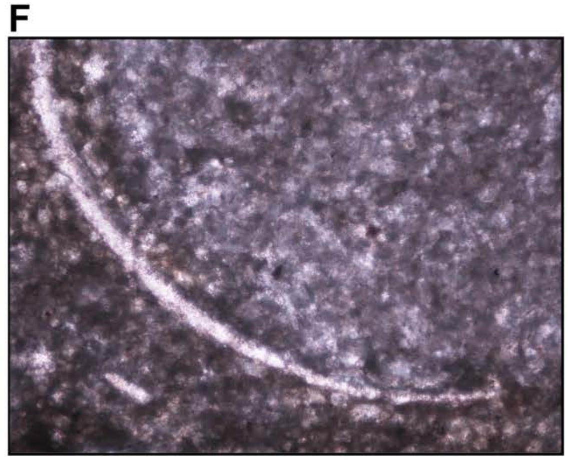


Unit K

Description**:** Unit K (Fig. 11) is a thick, fossiliferous wackestone that is consolidated and weathers uniformly. Measured section is massively bedded, 128 centimeters in thickness, and the color is light brownish-gray to medium gray. Large specimens of bryozoan colonies and brachiopods are abundant; cephalopods also occur (see Plate 12B). Other allochems are found in abundance.

Interpretation**:** Unit K confirms a return to shallow, marine conditions because of the abundant life found in sample rock. Units E and F are very similar in lithology to Unit K, however the lack of algae suggests that Unit K did not necessarily occur within the photic zone.

See next page:

Plate 12A. Unit K showing sharp shaley contact with uppermost boundary.

Plate 12B. Lithified cephalopod chamber, note the roundness and concavity of disk.

Plate 12C. Unit K, Sample 1(renamed from "Sample K Top 3"), is composed of fossiliferous wackestone.

Plate 12D. Photomicrograph of Unit K, Sample 1, showing pseudopunctate brachiopod fragment in center surrounded by several bryozoan fragments.

Plate 12E. Photomicrograph of Unit K, Sample 1, showing fabric of fossiliferous wackestone.

Plate 12F. Crenulations of brachiopod shell seen in center of photomicrograph.

PLATE 12: Illustrations of Unit K

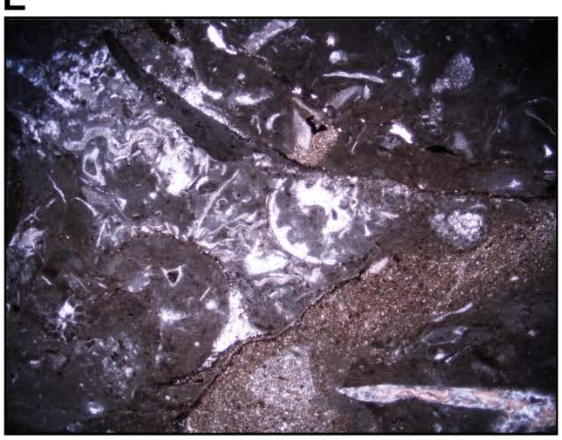
A

B

C

D

E



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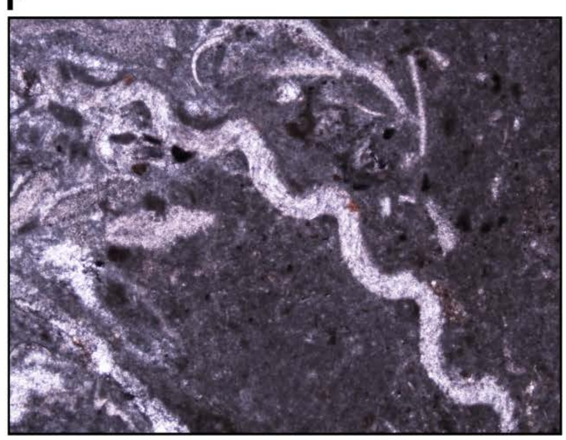

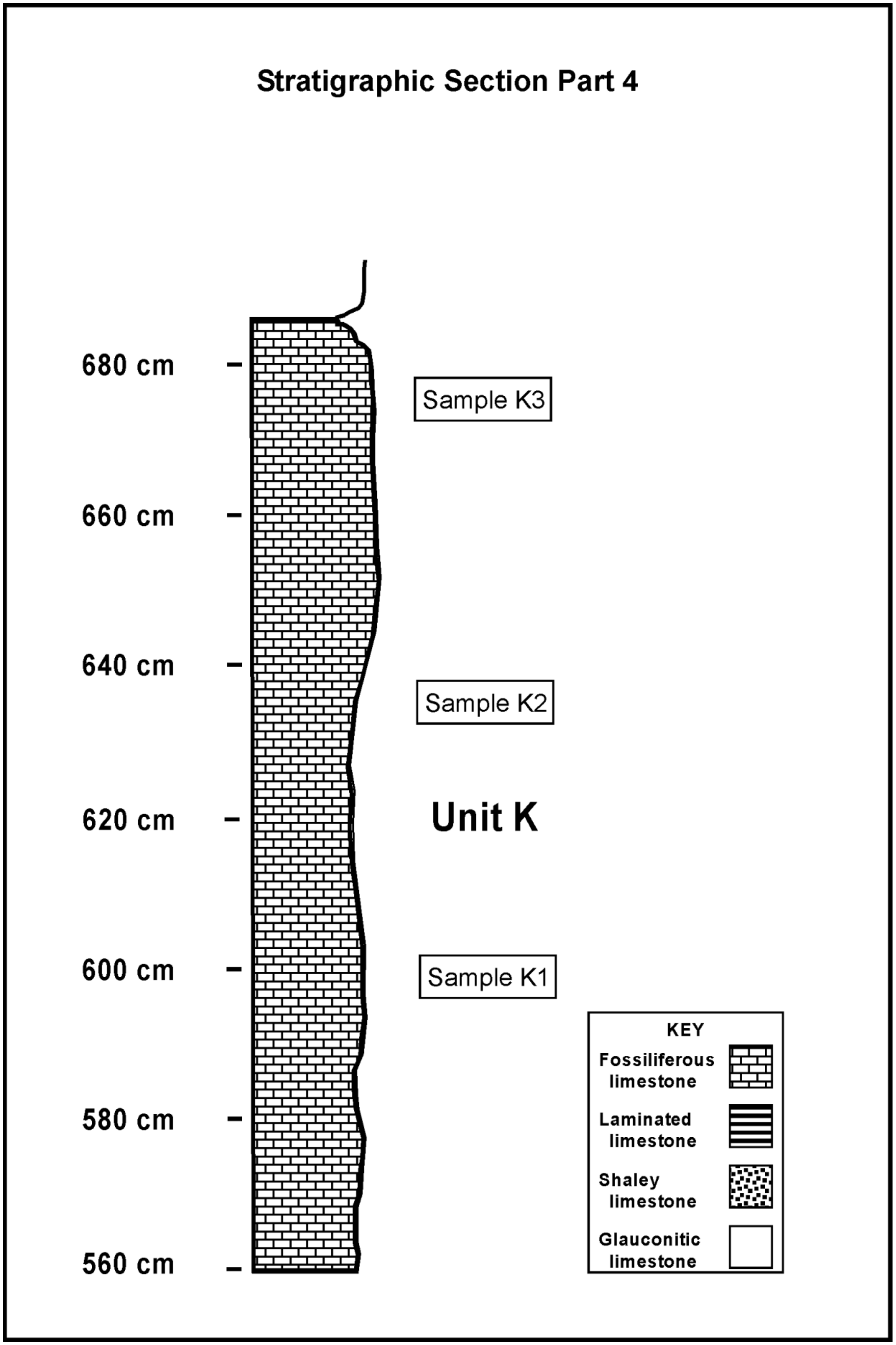

Figure 11. Stratigraphic section, part 4.

Chapter 3

Synthesis

It is problematic to determine the exact depositional environments and hence water depths responsible for the observed rock units. Analysis of the rock-unit lithologies strongly suggest that all the limestone depositional units have a subtidal origin most likely with normal salinity. Depositional and biotic features of supratidal and intertidal depositional environments are absent. Likewise any features indicative of deep-water are also absent, and would not be consistent with the well-known paleographic setting. Sedimentary structures suggestive of storm deposits are also absent either because sediments were deposited below storm wave base or because subsequent bioturbation destroyed any diagnostic sedimentary structures. We do know that sediment was deposited in the basin of a shallow sea, and that life persisted despite the influx of terrigenous mud and migrating depositional environments. The dominant fossils - brachiopods, bryozoans, trilobites, gastropods, ostracodes, and coralline algae - are common in various limestone units. The observed diversity and abundance of fossils at the study site suggests that these organisms were living within shallow waters of normal salinity. Where algae are preserved, it is likely that these sediments were deposited in sunlit, shallower waters of the photic zone. Consequently we infer that limey shales, wackestones, and packstones were deposited in shelfal depositional environments, perhaps deeper than the shallowest, subtidal depositional environments (that would possibly display higher organism diversity and less mud) but not deeper than storm wave base (that would preserve sedimentary structures generated by storms). The observed transitions from limestones to shaley and limy muds within units A through H and Unit K suggests any combination of: (1) apparent increase in water depth caused by lateral migration of depositional environments; (2) climatic change resulting in more runoff, and hence an increase in clastic input; or (3) tectonic activity delivering more terrigenous mud to the basin.

The transition from limestone lithologies (units A through H) to glauconitic (Unit I) and laminated (Unit J) clastics strongly suggests a shift to very different depositional environments. It is this transition from limestone lithologies, to glauconitic and laminated clastics within rock Units I and J, that is particularly interesting.

The formation of glauconite has occurred under varying conditions throughout geologic time. Glauconite formation has been linked to reducing, diagenetic conditions (e.g., McRae, 1972) but in modern oceans glauconite forms in water depths of mid-shelf to upper slope where slow sedimentation rates occur (Chafetz et al, 2000). Moreover, glauconite formation seems to be associated with transgressive deposits (Stonecipher, 1999), consistent with our interpretation for Unit I. Thus, we infer that the Unit I was likely formed in deeper depositional environments than that of Units A through H, and Unit K.

Unit J is a laminated mudstone that is devoid of fossils. Laminated sediments generally occur under any of the following situations that act to exclude burrowing megafauna: (1) intertidal to supratidal conditions that change rapidly with regard to temperature, salinity, and /or exposure; (2) rapid deposition and burial of sediments, generally in prodelta settings; (3) overlying water with little or no oxygen; and (4) deeper waters whose overlying, surface waters exist under oligotrophic conditions. As mentioned above, none of the rock units exhibit characteristics indicative of tidal-flat depositional environments. Climatic changes involving increases in rainfall and thus runoff could conceivably create conditions for the formation of deltas that are areally small-scale and short lived, but we have no corroborative evidence for this scenario. Likewise, we cannot address possible anoxic conditions. The latter possibility seems most plausible because of the paleogeographic setting and because the laminated unit lies between fossiliferous rock units with a demonstrable shallow subtidal origin. Under this scenario, the depositional environments must be on the shelf below storm wave base because fining-upward sequences or hummucky cross-stratification, which would suggest storm deposits, is absent.

My interpretation of water depth for the depositional environments of each rock units is summarized in Figure 12. Three relative water depths are shown on the summary figure ranging from the shallowest depth (1) to intermediate depth (2) to deepest depth (3). Rock units with fossil algae or micritic algal envelopes likely were deposited within the photic zone and thus occur in the shallowest depositional environment (1). Rock units with high fossil diversity but lacking algal fossils are interpreted to originate in slightly deeper water (2). Finally, glauconitic rocks (Unit I) and laminated rocks (Unit J) likely originated in still deeper depositional environments for reasons discussed above.

Based on this reasoning, we can recognize one transgressive-regressive cycle within this stratigraphic section. Units A through H were deposited in subtidal marine environments whose sediments either contain coralline algae (units B, E, F, and G) or do not (units A, C, H). One interpretation for these observations is that water depth oscillated from shallower to slightly deeper depositional environments in response to sea level changes; an alternate interpretation is that depositional environments conducive to

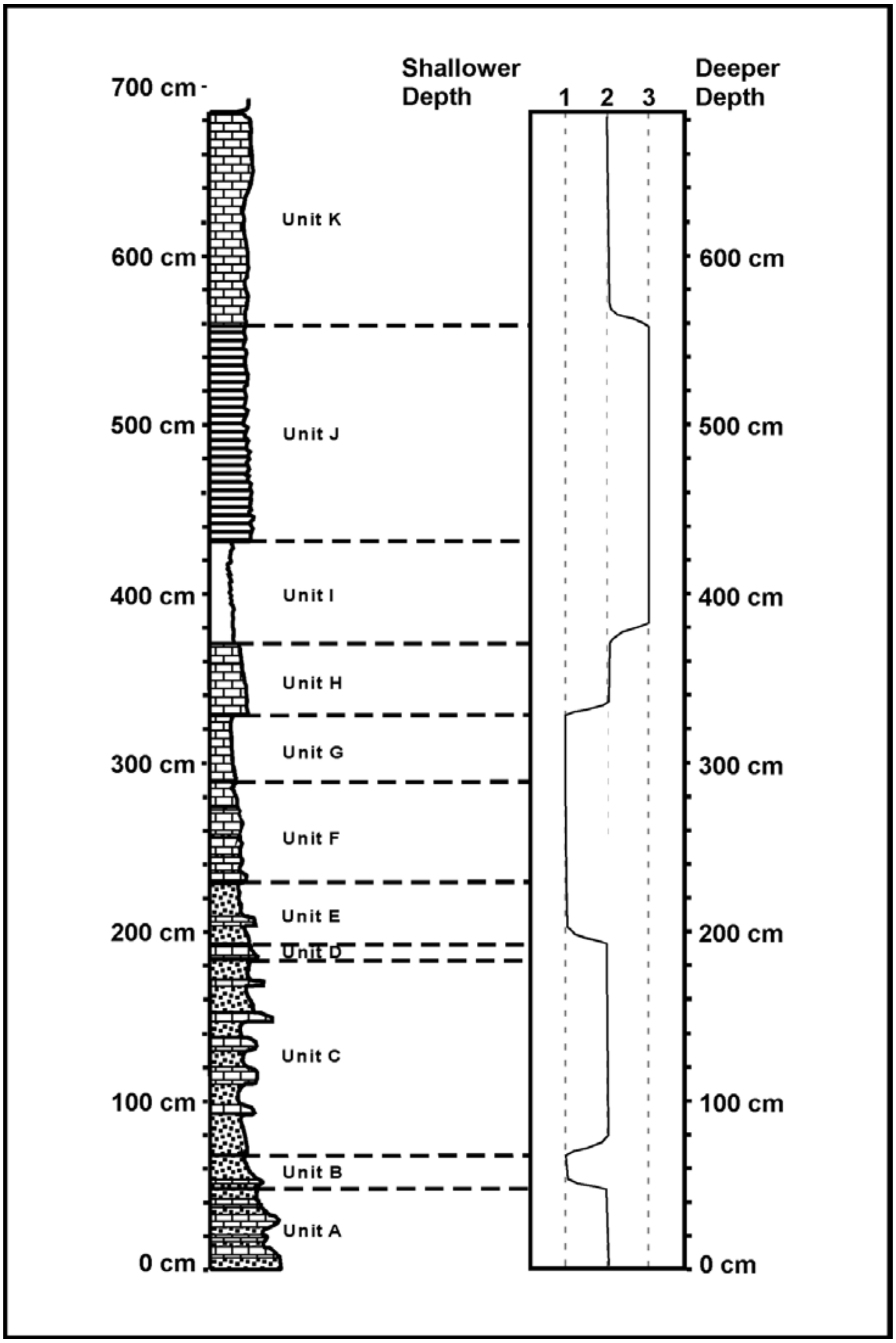

Figure 12. Schematic drawing of the study's stratigraphic section with a paleobathymetric interpretation of each unit.

algal growth and preservation migrated laterally over those environments less suitable for photosynthesizers. Thus, water depth changes may be non-existent or minimal. Beginning with Unit I and into Unit J, water depth deepens – perhaps significantly. These sediments are devoid of fossils, contain glauconite (Unit I), or are laminated (Unit J) suggesting this increase in water depth. Unit K once again contains diverse and abundant marine fauna signalling a return to shallow, subtidal conditions.

List of References

Braithwaite, Colin J. R., 2004, The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs: The Geological Society of London, p. 256.

Chafetz, H.S., and Reid, A, 2000, Syndepositional shallow-water precipitation of glauconitic minerals. *Sedimentary Geology*, Volume 136, Issues 1-2, October 2000, Pages 29-42

Ettensohn, Frank R., 2002, Evidence and Implications of Possible Far-field Responses To Taconian Orogeny: Middle –Late Ordovician Lexington Platform and Sebree Trough, East-Central United States*: Southeastern Geology*, V. 41, No. 1, March 2002, p. 1-36.

Ettensohn, Frank R., 1991, Flexural Interpretation of Relationships Between Ordovician Tectonism and Stratigraphic Sequences, Central and Southern Appalachians, U.S.A.: *Geological Survey of Canada*, *Paper 90-9*, p. 213-224, 1991.

Greene, Robert C., 1966, Geologic Map of The Richmond South Quadrangle, Madison County, Kentucky: USGS Washington D.C., Map GQ-479.

Kumar, Naresh, and Sanders, John E. 1976, Characteristics of shoreface storm deposits: modern and ancient examples, *Journal of Sedimentary Research;* March **1976**; v. 46; no. 1; p. 145-162.

Majewske, Otto P., 1969, Recognition of Invertebrate Fossil Fragments in Rocks and Thin Sections: E. J. Brill, Leiden, Netherlands, 280 photomicrographs

McRae, S.G., 1972, Glauconite, *Earth Science Reviews*, v. 8, no. 4, 397-440.

Norris, Marc Jeffrey, 1979, Depositional Environments of the Upper Ashlock Formation, Upper Ordovician of East-Central Kentucky, Eastern Kentucky University, Master's Thesis, 64 pp.

Ordovician_Fossils_WestVir_wvgs_wvnet_edu.pdf

Scholle, Peter A., 1978, A Color Illustrated Guide To Carbonate Rock Constituents, Textures, Cements, and Porosities: AAPG Memoir 27, 241 pp.

Stonecipher, Sharon A., 1999, Genetic characteristics of glauconite and siderite: Implications for the origin of ambiguous isolated marine sandbodies. In: K.M. Bergman and J.W. Snedden, Isolated Shallow Marine Sandboadies, *SEPM Special Publication 64*, pp. 191-204.

Weir, Gordon Whitney, Peterson, W.L., and Swadley, W.C., 1984, Lithostratigraphy of Upper Ordovician Strata Exposed in Kentucky, U.S.G.S. Professional Paper 1151-E, p. 41-52.

Weir, Gordon Whitney, 1965, Calloway Creek Limestone and Ashlock and Drakes Formations (Upper Ordovician) in South Central Kentucky: *Geological Survey Bulletin 1224-D*, 35 p.

Wicander, Reed, and Monroe, James S. (2007, Fifth Edition), Historical Geology: Evolution of Earth and Life Through Time, Thomson Brooks/Cole, pp 440.