To the Graduate Council:

I am submitting herewith a thesis written by James Kenneth Ashworth entitled "Depositional Environments and Paleoecology of Middle Ordovician Rocks in Union County, Tennessee." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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Vice Chancellor
Graduate Studies and Research

DEPOSITIONAL ENVIRONMENTS AND PALEOECOLOGY OF MIDDLE ORDOVICIAN ROCKS IN UNION COUNTY, TENNESSEE

A Thesis

Presented for the

Master of Science

Degree

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James Kenneth Ashworth

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ABSTRACT

Approximately 425 meters of Middle Ordovician predominantly carbonate rocks are exposed at Stanley Farm, Union County, Tennessee. The stratigraphic section begins at the Post-Knox unconformity and consists in ascending order of seven formations: Five Oaks Formation, Lincolnshire Formation (Eidson, Fleanor, and Hogskin members), Rockdell Formation, Benbolt Formation, Wardell Formation, Bowen Formation, and Witten Formation. Detailed field observations and petrographic analysis of 132 thin sections allowed inferences of the paleodepositional environment of each formation and member.

The Five Oaks Formation represents tidal flat deposition on the Knox karst surface. Lower and middle intervals of the formation represent supratidal to high intertidal deposition while upper intervals represent low intertidal to subtidal deposition. The Lincolnshire Formation (Eidson, Fleanor, and Hogskin members) represents an intertidal to subtidal-restricted carbonate shelf punctuated by episodes of terrigenous clastic sedimentation. The Eidson Member represents a stable, subtidal (restricted shelf) facies. The Fleanor Member represents very shallow (wave-active), current-influenced terrigenous clastic deposition. The Hogskin Member represents deposition in a Fleanor-like environment, however, the percentage of terrigenous clastic material gradually decreases stratigraphically upward. The Rockdell Formation represents stable, shallow subtidal deposition. The Benbolt Formation reflects water shallowing and an associated influx of terrigenous clastic material. The lower intervals of the Benbolt represent non-agitated, stable deposition, while the middle intervals

reflect shoaling carbonate and sporadic terrigenous clastic sedimentation. The upper intervals reflect deeper, non-agitated depositional regimes. The Wardell Formation represents a storm influenced, shallow (wave-active) facies. The Bowen Formation represents intertidal, terrigenous clastic-influenced deposition, indicative of an encroaching southeastern sediment source. The Witten Formation represents a return to stable, subtidal deposition in the lower intervals, while the upper intervals reflect shallow subtidal to intertidal regimes.

The members of the Lincolnshire Formation (Eidson, Fleanor, and Hogskin) were examined along strike for the purpose of resolving their stratigraphic relationships and mode of formation. The Fleanor, originally designated as a formation (Cooper and Cooper, 1946), lies between the Eidson and Hogskin Members and grades into the Hogskin at the Stanley Farm Section; consequently, all three units are considered members of the Lincolnshire Formation. The lens shaped configuration, rapid stratigraphic appearance, and lack of lateral interfingering suggest a deltaic paleoenvironmental setting for the Fleanor Member.

Ten bedding planes within the Benbolt Formation were chosen for the purpose of paleoecological analysis; point counts of 52 slab surfaces and microscopic analysis of 20 acetate peels allowed biovolume computations and environmental interpretations, respectively. Biovolume percentages exhibit a dominance (>99% total biovolume) of suspension feeding organisms. Furthermore, biotic diversity is highest in the lower third of the Formation. The co-occurrence of echinoderms and bryozoans and virtual mutual exclusion of echinoderms and brachiopods may be explained either by niche stratification (tiering) resulting from food partitioning in the water column, or by physical environmental

constraints. Low stress environments exhibit high diversity; assemblage composition was probably governed by tiering. Conversely, high stress environments exhibit low diversity; assemblage composition was most likely governed by organism adaptability to environmental constraints rather than food availability.

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CHAPTER I

INTRODUCTION

A. GENERAL BACKGROUND

Middle Ordovician rocks in East Tennessee are characterized by a complex mosaic of carbonates interfingered with terrigenous clastics. These facies are exposed in northeast to southwest trending linear strike belts which are bounded by and displaced from contiguous belts by southeast dipping thrust faults. Previous classification and correlation schemes of these rocks have been controversial as a result of complex lithofacies patterns and limited biostratigraphic studies. The latter may be attributed (McLaughlin, 1973) either to previous workers studying only a single taxonomic group or to their underestimation of the impact of environmental control on biotic distribution.

In an attempt to understand these complex stratigraphic relationships, a research program was begun in the early 1970's at The University of Tennessee, Knoxville, by K. R. Walker. A paleoenvironmental model for the Middle Ordovician of East Tennessee was proposed by Walker and Alberstadt (1973), and subsequent research by Walker and his co-workers has refined the model. The initial work was concentrated on strike belts located southeast of the Saltville Fault; however, more recent investigations have been concentrated on the northwest strike belts (Fig. 1-1). The area selected for the present study is the Stanley Farm Section, located in one of these northwestern strike belts, the Hunter Valley allochthon (St. Paul Belt of Prouty,

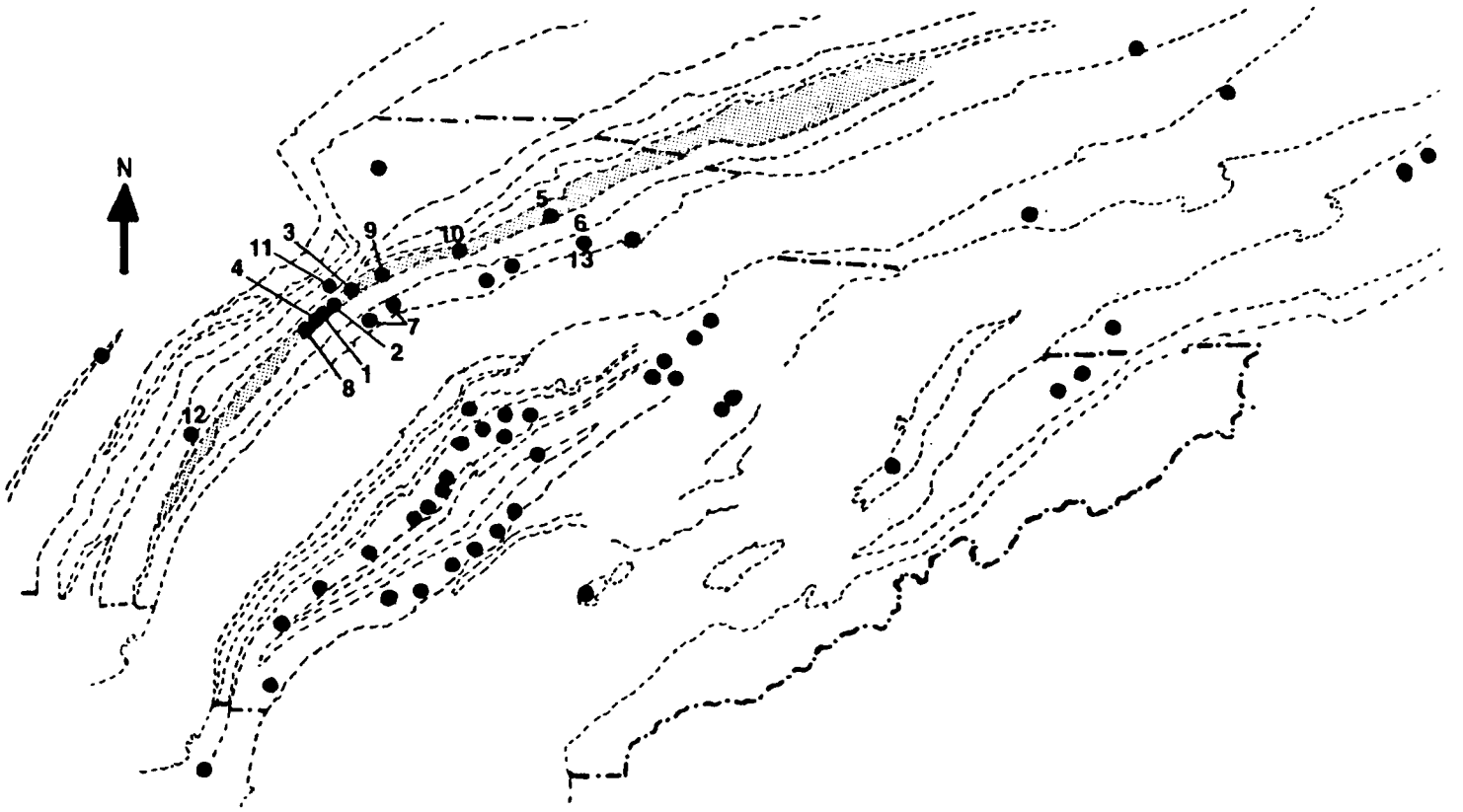


Figure 1-1. Strike belt map showing selected previous and present studies north of the Saltville Fault. Hunter Valley Allochthon stippled (after Walker et al., 1980).

(1) Harvell (1954)
(2) Causey (1956)
(3) Lomenick (1958)
(4) Belvin (1975)
(5) Sickafoose (1979)
(6) Ruppel (1979)
(7) Breland (1980)
(8) Weiss (1981)
(9) Ashworth (1982)
(10) Ewing (in prep.)
(11) Borowski (in prep.)
(12) Ghazizadeh (in prep.)

(13) Harris (in prep.)

1946). Previous and present workers in this strike belt include Harvell (1954), Causey (1956), Lomenick (1958), Fields (1960), Parker (1975), Carnes (1975), Belvin (1975), Sickafoose (1979), Weiss (1981), and Ewing (in prep).

B. STUDY AREA

The Stanley Farm Section is located near the Stanley Cemetery and in the vicinity of the intersection of Loyston and Raccoon Valley Road (Figs. 1-2, 1-3), in Union County, Tennessee (east central portion of the Big Ridge Park Quadrangle, 146-NW). The study area is located in the Hunter Valley Allochthon, bounded on the northwest by the Hunter Valley Fault and on the southeast by the Copper Creek Fault.

The lowermost 61 meters of the section are exposed in a roadcut along Loyston Road, north of the intersection of Loyston and Raccoon Valley Road. Approximately 174 meters are exposed in field outcrops on the Stanley Farm and along both sides of Raccoon Valley Road northeast of the intersection. The remaining 190 meters are exposed on the northwest flank of Bullrun Ridge (Fig. 1-3).

C. PURPOSE AND NATURE OF STUDY

The major objectives of the study are twofold. First, the lithologic units were described both macroscopically and petrographically for the purpose of paleodepositional interpretation. Second, 10 bedding planes from the Benbolt Formation were sampled for the purpose of paleoecologic analysis. The Benbolt Formation was chosen for fossil assemblage analysis primarily because (1) bedding

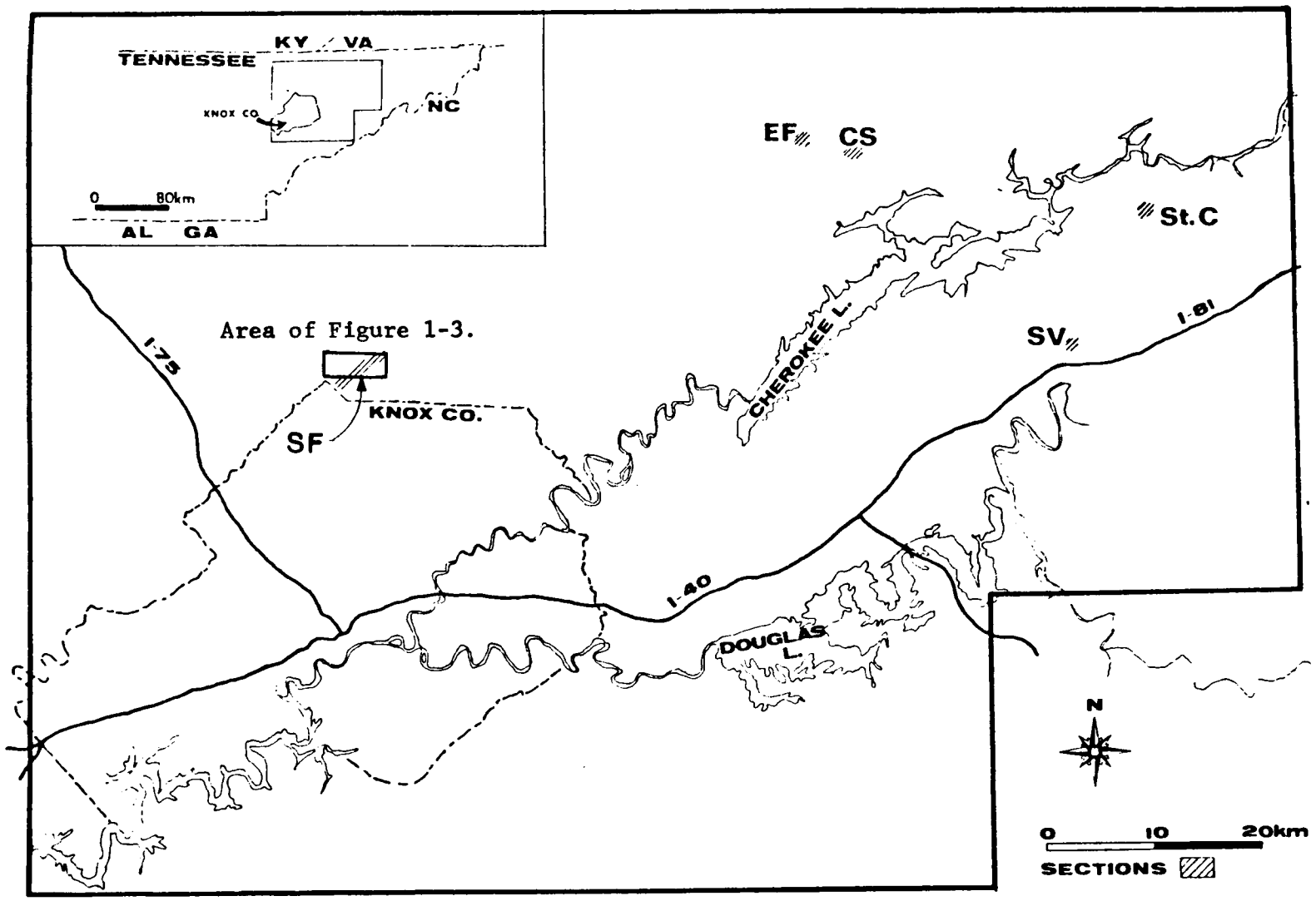


Figure 1-2. Location of the study area at the Stanley Farm Section. Other section locations also indicated by the cross-hatch pattern (modified from Maitland, 1979).

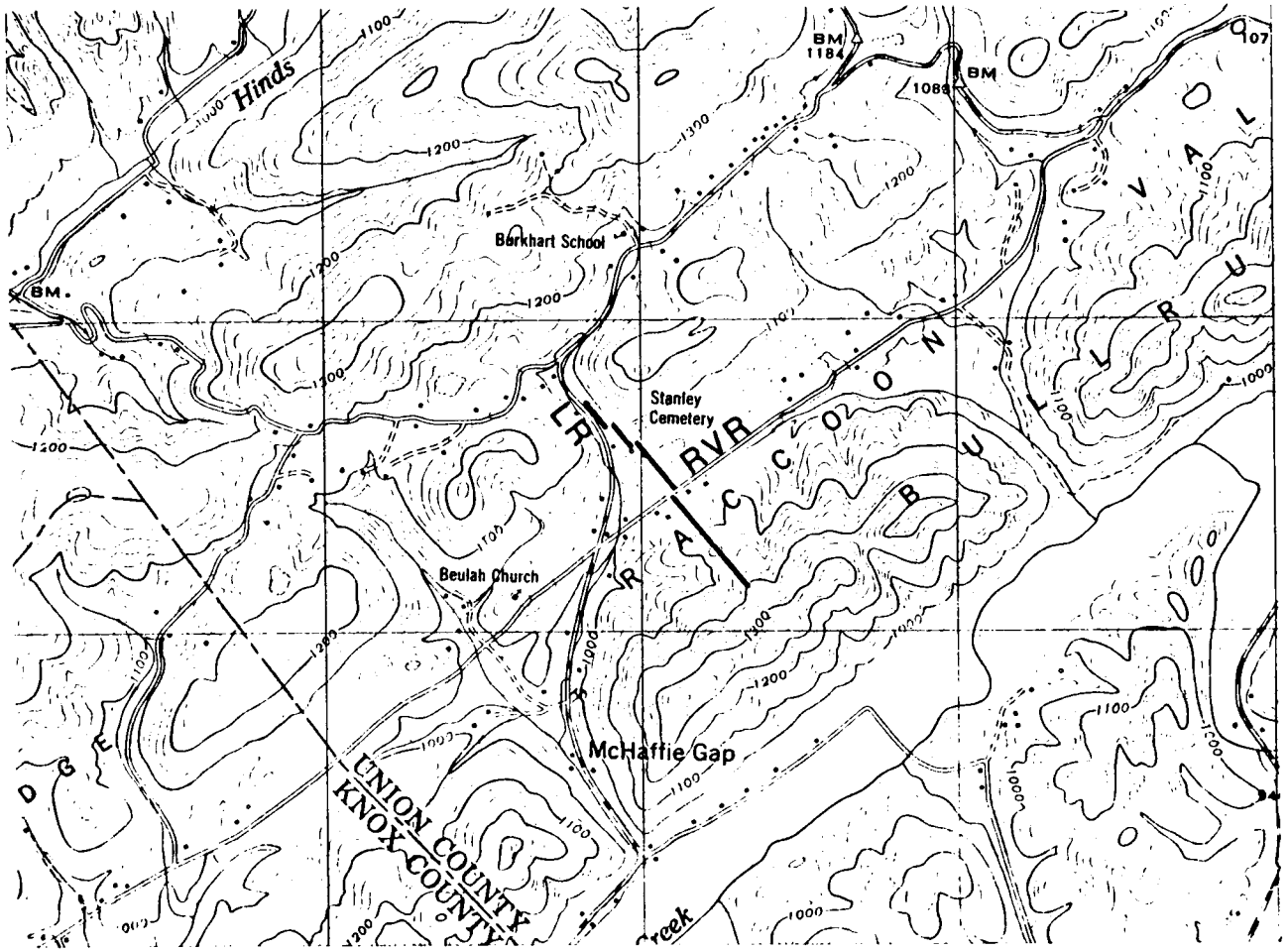


Figure 1-3. Topographic map of study area. Black lines represent measured section. LR = Loyston Road, RVR = Raccoon Valley Road. (Big Ridge Park, 7.5 Minute Quadrangle, 146-NW, 1952).

plane exposures are extremely fossiliferous, and (2) weathering of the (1-2 cm) shale beds around the thicker biomicrite and biosparite beds facilitates bedding plane sampling. Because bedding planes can be easily traced, it is possible to sample rocks representing very precise time intervals. Consequently, the various assemblages may be examined to determine environmentally related changes during Benbolt deposition.

D. PREVIOUS AND CONTINUING INVESTIGATIONS

In 1891, Hayes described rocks in Hamilton County, Tennessee, and Catoosa and Walker Counties, Georgia, under the term Chickamauga to include all of the Middle Ordovician and part of the Upper Ordovician. However, the rocks in East Tennessee are different from the Chickamauga lithologies originally described by Hayes.

Major revision of the Middle Ordovician sequence in Tazewell County, southwestern Virginia, was initiated by B. N. Cooper and C. E. Prouty (1943). Later, Prouty (1946) traced similar lithologies into northeast Tennessee (Fig. 1-4). These lithologic units include: the Five Oaks Formation (including the Blackford Member), Lincolnshire Formation, Thompson Valley Formation, Benbolt Formation, Wardell Formation, Bowen Formation, Witten Formation, and Moccasin Formation.

Rodgers (1953) regrouped the Chickamauga units, bounded by the Saltville Fault and the Hunter Valley Fault, into a more general classification scheme in order to alleviate the confusion caused by the overabundance of stratigraphic names. His grouping included 3 units: Chickamauga Limestone unit 1, Chickamauga Limestone unit 2, and the

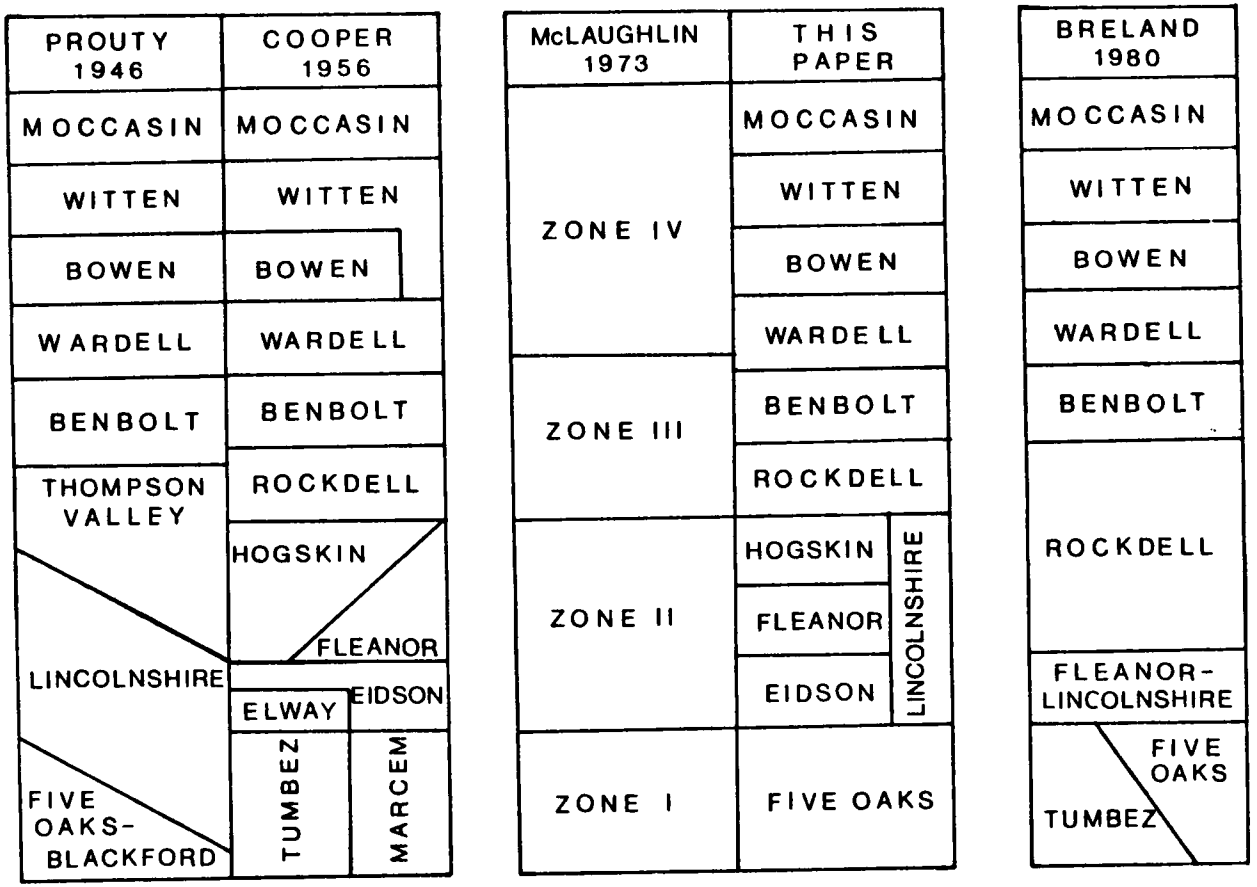


Figure 1-4. Stratigraphic classification chart for Middle Ordovician rocks in East Tennessee. Adjoining charts indicate similar lithotypes, and not chronostratigraphic correlation (modified from Carnes, 1975, and Breland, 1980).

Moccasin Formation. In contrast, most subsequent stratigraphic studies were conducted in such detail that more precise terminologies were justified, thus eliminating Rodgers' classification.

Harvell (1954) and Causey (1956) studied Middle Ordovician rocks in Anderson and western Knox counties, respectively. They recognized 6 units based on lithologic characteristics: (1) a relatively pure, gray limestone interbedded with chert and shale, (2) buff to maroon shale, (3) massively bedded gray limestone, (4) highly argillaceous, nodular weathering, gray limestone ("Lenoir" type lithology), (5) light gray, thin to massively bedded limestone, and (6) alternating gray limestones and buff to maroon shales. Formal names were not given to the 6 units. Lomenick (1958) mapped and described Middle Ordovician rocks in Raccoon Valley, Knox County, and also recognized the 6 lithologic units previously described by Harvell (1954) and Causey (1956).

In 1956, G. A. Cooper biostratigraphically reclassified the Chickamauga group using brachiopods. For purposes of widespread correlation, certain lithologic names were arbitrarily dismissed while others were retained (Fig. 1-4). The major changes in terminology (affecting the lithologies of the Hunter Valley Allochthon) were the division of the Lincolnshire Formation into the Eidson and Hogskin Members and the adoption of the Rockdell Formation instead of the Thompson Valley Formation. The Fleanor Member was considered to be correlative to the Hogskin Member by Cooper (1956); however, at the Stanley Farm Section, the Fleanor occurs between the Eidson and Hogskin Members and is regarded in the present study as a separate member of the Lincolnshire Formation.

Later studies of the Chickamauga Group include detailed geologic mapping by Harris and Mixon (1970), and detailed petrologic and ecostratigraphic studies, largely north of the Saltville Fault (e.g. Fields, 1960; Parker, 1975; Walker and Alberstadt, 1975; Belvin, 1975; Walker and Parker, 1976; Ruppel, 1979; Sickafoose, 1979; Breland, 1980; Weiss, 1981 and others, Fig. 1-1, p. 2). Fields (1960) and Parker (1975) examined brachiopod assemblages in the St. Paul Strike Belt. Belvin (1975) interpreted the sedimentary environments of the basal Chickamauga Group in Raccoon Valley, equivalent to unit 1 of Harvell (1954), Causey (1956) and Lomenick (1958). He recognized 6 units and 9 subfacies which represented a supratidal to high subtidal environmental sequence. Ruppel (1979), Sickafoose (1979), Breland (1980), and Weiss (1981), described the Middle Ordovician sequence from Cedar Springs, Evans Ferry, Beaver Valley, and Solway Bridge, respectively. For the most part, these workers used the stratigraphic classification proposed by Cooper (1956), although they carefully redefined his terms on strictly lithologic grounds.

Many workers have emphasized the biostratigraphy of the Middle Ordovician. McLaughlin (1973) developed a zonation of the Chickamauga Group based on recurrent lithofacies cycles and distinctive faunal assemblages (Fig. 1-4). He suggested that many faunal groups, particularly brachiopods, are environmentally controlled in Chickamauga rocks; consequently, much of the biostratigraphic data derived from the study of a single taxon (i.e. Cooper's, 1956, study of brachiopods) may be in serious error and may require further revision. McLaughlin's work is especially relevant to the present study because the location

for his faunal assemblage analysis is in Raccoon Valley, 15 km southwest along strike from the present study.

Brower and Veinus (1974) described crinoids from the Benbolt Formation, Carnes (1975) studied Middle Ordovician conodonts, Moore (1978) examined the distribution of benthic algal assemblages, Maitland (1979) interpreted paleobathymetry based on trilobite assemblages, Broadhead (1980) described the earliest Middle Ordovician blastoid from the Benbolt Formation, and Breland (1980) studied the stratigraphic occurrence and distribution of echinoderms in Middle Ordovician inner shelf to shelf-edge environments. Present work includes studies on the paleogeographic distribution of Middle Ordovician conodonts north and south of the Saltville Fault by Harris (in prep) and Asreen (in prep), respectively.

As a result of these previous and present studies, a depositional model has been constructed for the Middle Ordovician sequence (Walker and Alberstadt, 1973, modified and refined by Walker, 1977, and Walker et al. 1980). Primarily, the model exhibits 4 paleoenvironmental subdivisions which consist of: (1) a northwestern semi-restricted carbonate shelf lagoon, (2) a set of shelf margin facies, (3) a deep water basin composed of shales, and (4) a southeastern terrigenous clastic and carbonate shelf (Fig. 1-5). The present study examines the lithologies of a portion of the northwestern semi-restricted shelf lagoonal facies (1).

The lithologies located in the present study resemble those of Cooper (1956), with the exception of two lower units; the lowermost unit resembles the Five Oaks Formation of Prouty (1946) rather than the

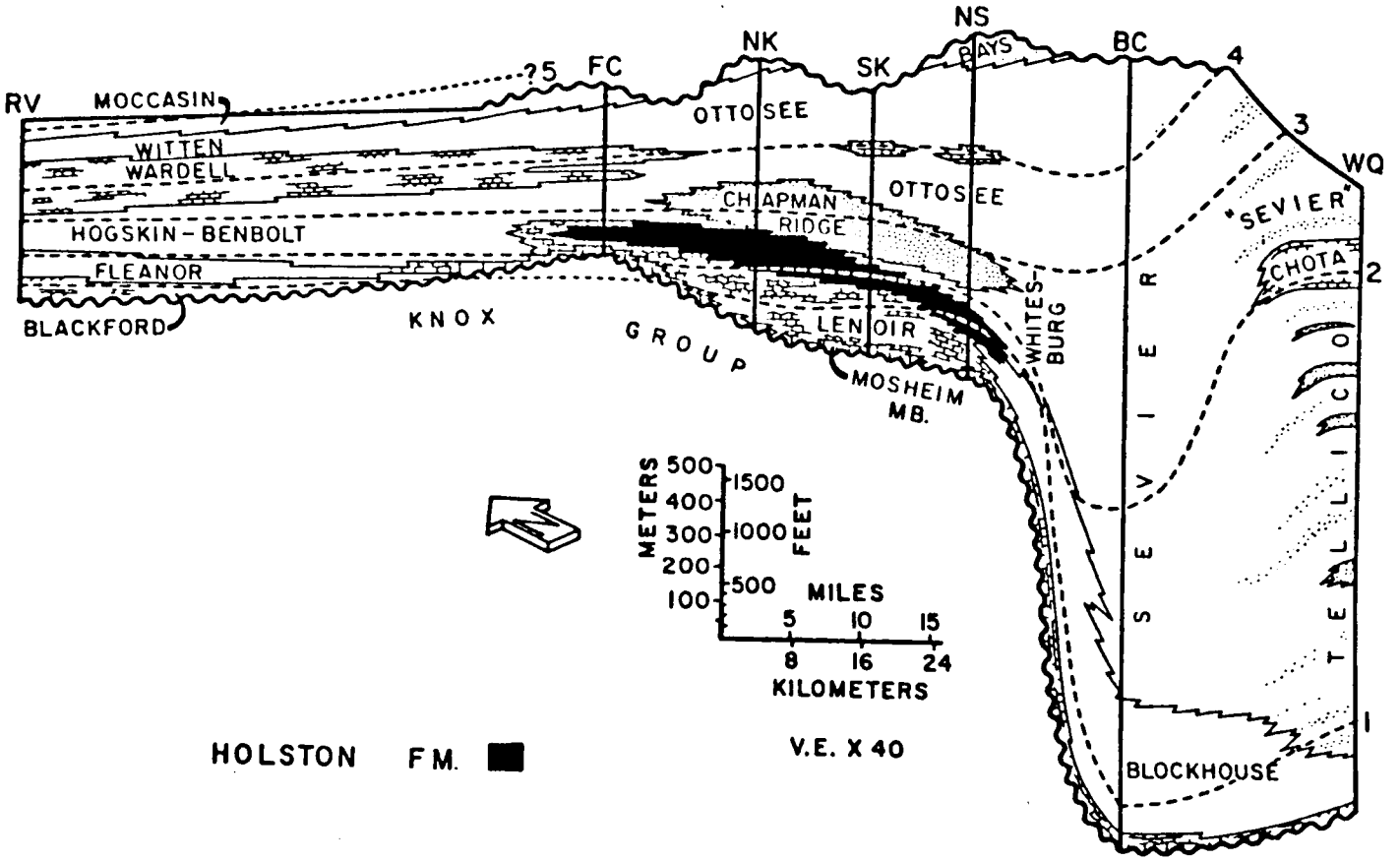


Figure 1-5. Stratigraphic cross-section of the Ordovician of East Tennessee. Northwest is to the left; southeast is to the right. Palinspastically restored (after Ruppel and Walker, 1977). Stanley Farm Section is located 15 km northeast from RV in Hunter Valley Allochthon.

Tumbez Formation of Cooper (1956). In addition, the Fleanor Member of the Lincolnshire Formation occurs between the Eidson and Hogskin Members, and not as a coeval formation as originally suggested by Cooper (1956). The Fleanor Member is especially relevant to the present study because of accessible exposures at Stanley Farm, poor exposures in previously studied areas (e.g. Breland, 1980, Fig. 1-4, p. 7), and the subsequent destruction of the type section by highway construction.

E. METHODS

Field work consisted of measuring and describing in detail the continuous 424.9 meter section bounded by the Knox/Chickamauga contact to the northwest and by the Moccasin Formation (partially faulted by the Copper Creek Fault) to the southeast. The section was then divided, based on field observations, into 31 lithic units which were grouped into 7 formations (Fig. 1-6, Appendix A). These formations stratigraphically consist of: Five Oaks Formation, Lincolnshire Formation (Eidson, Fleanor, and Hogskin members), Rockdell Formation, Benbolt Formation, Wardell Formation, Bowen Formation, and Witten Formation (terms after Prouty, 1946, and Cooper, 1956). Approximately 150 samples were collected from these units for laboratory examination. Stratigraphic separation between successive samples ranged from 0.2 meters to 15.7 meters, except for covered intervals. One hundred thirty-two 5 x 8 cm thin sections were prepared from the samples, and petrographic analysis of the thin sections combined with the study of sawn slabs and field exposures, provided the basis for paleoenvironmental interpretations. Constituent particle composition

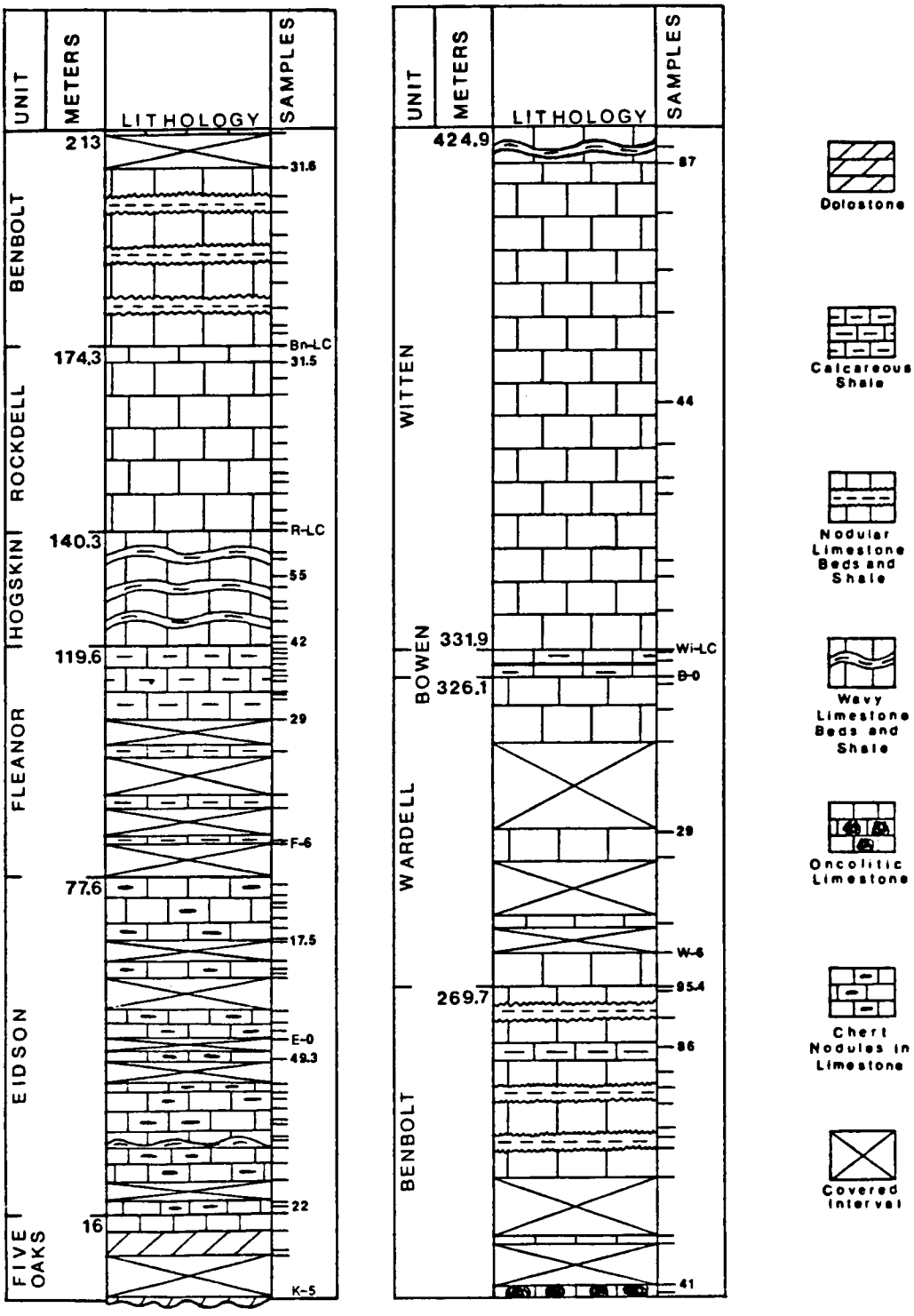


Figure 1-6. Stratigraphic section at Stanley Farm. Lines to the right of the column represent petrologic samples; numbers to the left indicate meters above the Knox unconformity.

was determined by point counting 32 selected slides (300-350 points/ slide); these data are presented in Appendix B.

In a second phase of the investigation, thin fossiliferous beds and individual fossil specimens were collected from 10 horizons in the Benbolt Formation. From these collections polished slabs and acetate peels were prepared and slab surfaces were point counted with an acetate grid (1 cm grid spacing) for the purpose of determining biovolume (Walker, 1972; Ausich, 1981). Information obtained in this phase was combined with that derived from the previously made thin sections to form the basis for paleoecological interpretations.

All materials are cataloged and stored in the collections of the Department of Geological Sciences at The University of Tennessee, Knoxville.

CHAPTER II

STRATIGRAPHY, PETROLOGY, AND PALEOENVIRONMENTAL ANALYSIS OF THE MIDDLE ORDOVICIAN AT STANLEY FARM, TENNESSEE

I. INTRODUCTION

The Stanley Farm Section was divided into 31 units and further grouped into seven formations based on lithologic characteristics. Rarely, the first occurrence of a particular fauna, or collection of diverse fauna, was used to define unit, but not formational boundaries. Based on lithology, the formations in the Stanley Farm Section were named following the terminology of Prouty (1946) and Cooper (1956), modified by the present author. The section includes, in ascending stratigraphic order: the Five Oaks Formation, Lincolnshire Formation (Eidson, Fleanor, and Hogskin Members), Rockdell Formation, Benbolt Formation, Wardell Formation, Bowen Formation, and Witten Formation. The Moccasin Formation, which comprises the uppermost unit of the Middle Ordovician at Stanley Farm, was not studied.

The following descriptions are based on (1) macroscopic field observations and (2) thin section analysis. Culminating the description of each formation (or member) is a discussion of the implied paleoenvironment.

II. POST-KNOX UNCONFORMITY

The post-Knox unconformity is fairly well exposed in the Stanley Farm Section. The actual contact is exposed in the middle of Flint

Ridge along Loyston Road (Fig. 1-3, p. 5). This resistant ridge is held up by fine to medium grained, pinkish to reddish gray Knox dolostones. (Fig. 2-1A), which contain euhedral dolomite rhombs. Rocks directly overlying the contact consist of light gray, medium grained, very poorly sorted (terminology from Folk, 1962, used henceforth), dolomitic mudstones. The basal portion of these dolomitic mudstones contains a thin (0.4 m) horizon of coarse grained, very poorly to moderately sorted, subrounded (terminology from Powers, 1953, used hereafter), cherty dolostone. The abundant (1.4 mm to 9.2 mm) chert clasts (Fig. 2-1B), derived from the underlying Knox group, are similar to those described by Belvin (1975); consequently, the first appearance of this cherty horizon is interpreted as succeeding the Knox unconformity and is used to define the base of the Stanley Farm Section.

III. FIVE OAKS FORMATION

The Five Oaks Formation is poorly exposed at the foot of Flint Ridge along Loyston Road. The Five Oaks is approximately 16 meters thick and can be divided into 4 distinct units (1-4). Covered intervals are common in outcrops of this formation.

UNIT 1. Unit 1 consists of 0.4 meters of light to medium gray, medium to coarse grained, cherty dolostone (Fig. 2-1C). Red (jasperoid) and black angular chert clasts (0.5 mm to 5 mm thick), generally restricted to a thin (approximately 10 cm) band, are prominent on outcrop. In thin section these angular to subrounded, lenticular to equant (maximum length - 9.2 mm), clasts constitute approximately 15% of rock volume. Many clasts exhibit remnant fabrics of euhedral

Figure 2-1. Photomicrographs, thin section photographs, and field photographs of the Knox Group and Five Oaks Formation.

A. Knox dolostone located at the foot of Flint Ridge along Loyston road. Pen is 13.5 cm long.

B. Thin section showing Knox derived chert clasts in the Five Oaks Formation, at the Knox-Five Oaks contact (K-5). Crossed nichols.

C. Cherty dolostone of unit 1 in the Five Oaks Formation. Key is 4.5 cm long.

D. Photomicrograph of the Five Oaks Formation showing chert clast containing remnant peloids (K-5). Crossed nichols. 10X.

E. Photomicrograph of chert clast containing euhedral dolomite rhombs in the Five Oaks Formation (K-5). 20X.

F. Photomicrograph of a zoned euhedral dolomite rhomb in the Five Oaks Formation (K-5). Crossed nichols. 60X.

G. Medium bedded packstone (biopelsparite) of unit 4 in the Five Oaks Formation.

H. Photomicrograph of biopelsparite of unit 4 in the Five Oaks Formation. Large dark objects are micrite intraclasts (K-21). 10X.

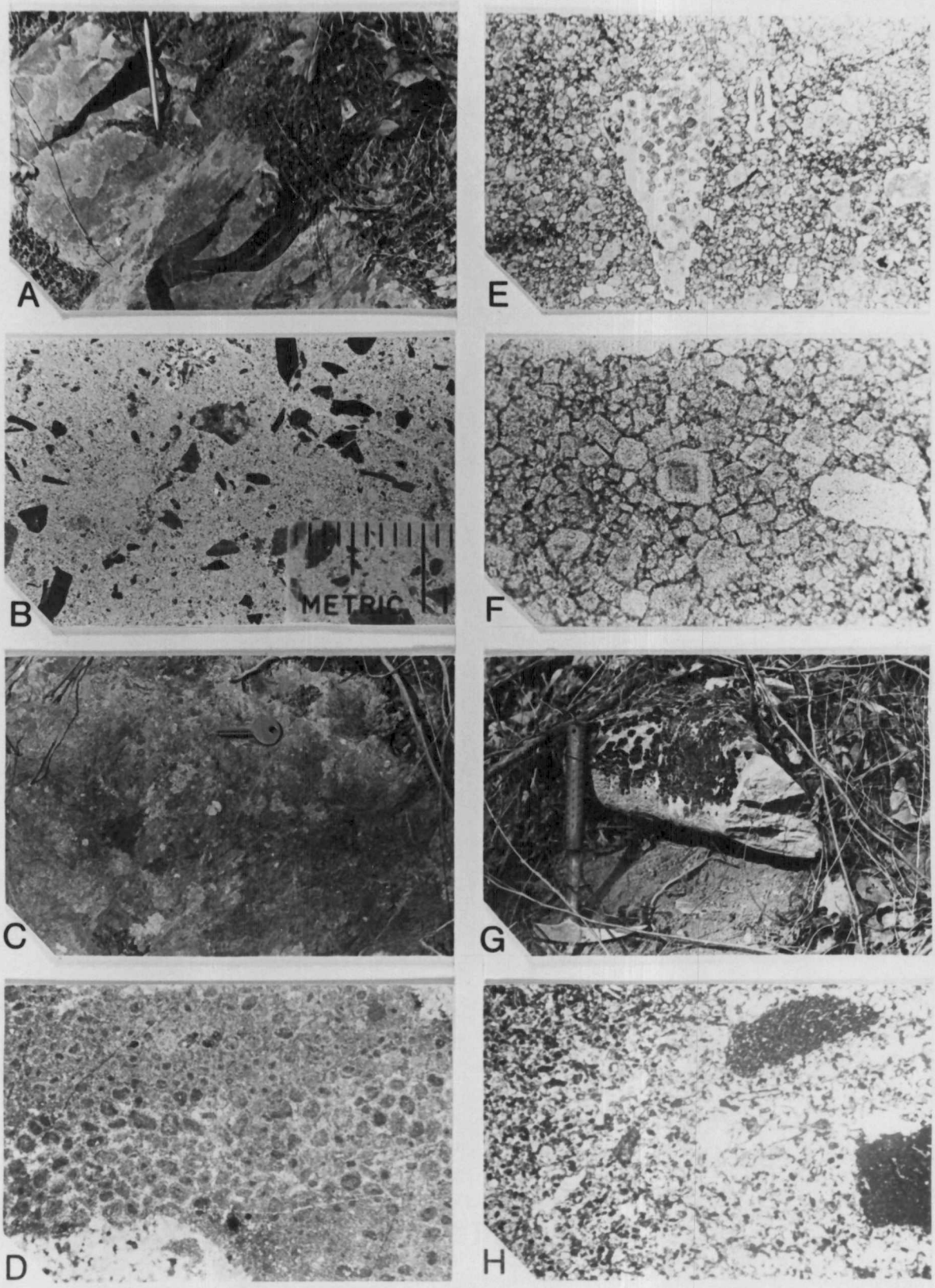


Figure 2-1.

dolomite rhombs, peloids (Fig. 2-1D), and bedding. These clasts commonly exhibit dolomitic rinds and isolated rhombs in clast interiors (Fig. 2-1E). Boundaries between angular clasts and the dolomite matrix are characterized by sharp contacts. In addition, the euhedral and unabraded nature of dolomite rhombs in both chert clasts and matrix suggests that dolomitization occurred by replacement and was subsequent to deposition of angular (Knox derived) chert clasts. This replacement fabric was previously noted by Sickafoose (1979, p. 18) in similar lithologies of the equivalent Tumbez Formation. Other clasts are composed of chalcedony and polycrystalline quartz. Because many clasts show fractures filled with dolomite, the chalcedony fracture-fill process preceded fracturing. Dolostone lithoclasts (up to 4.6 mm) are present. Unit 1 is devoid of fossil allochems. Matrix consists of unabraded, euhedral, commonly zoned dolomite rhombs (0.05 mm - 0.2 mm, Fig. 2-1F).

UNIT 2. Unit 2 consists of 8.4 meters of light to medium pinkish gray, thickly bedded (0.5 m - 1 m), fine to medium grained, nonlaminated dolomitic mudstone. Angular chert clasts and tabular dolomite intraclasts are commonly observed in outcrop. In thin section, the unit is characterized by poorly sorted, euhedral dolomite rhombs (largest $\sim$0.2 mm). Major allochems include chert clasts, peloids, and dolostone lithoclasts. Chert clasts are subangular to subrounded (average - 4.9 mm) and are commonly oriented parallel to bedding. Peloids (0.04 mm) are generally well sorted, lack internal structures, and are concentrated in thin (1.4 mm - 2.2 mm) spar cemented bands. Lenticular and equant, fine grained, dolostone lithoclasts (up to 4.6 mm),

are prominent in unit 2. Stylolites (maximum amplitude = 0.2 mm), oriented parallel to bedding, are common and are similar to the fitted fabric, poorly cemented, solution seam features discussed by Buxton and Sibley (1981) in the Devonian Alpena Limestone. Interstitial cement consists primarily of a mixture of calcite and dolomite, with calcite steadily increasing upward in the unit from approximately 10% at the base of the unit to 60% near the top.

UNIT 3. Unit 3 consists of 3.9 meters of light to medium gray, very fine to medium grained carbonate mudstone. It is less massive than unit 2, and bedding thickness varies from thinly bedded (1-10 cm) in the lower and upper portion of the unit to medium bedded (up to 0.3 m) in the middle. Angular dolostone lithoclasts are present, and fossils identified in outcrop include phosphatic inarticulate brachiopods, trilobite fragments, and ostracodes. In thin section, unit 3 consists of well sorted pelmicrite (wackestone and packstone) (classifications of Folk, 1962, and Dunham, 1962 respectively, used hereafter). Peloids ($\sim$0.05 mm) are the major allochem and although present throughout the unit, tend to be concentrated in thin (0.2 mm - 0.4 mm) spar cemented bands. Many peloids within these bands are crushed, yielding a faintly grumeleuse fabric. The majority of the remaining allochems present consist of broken and abraded fossil fragments, dominantly trilobites and (?) ostracodes. Abrasion and fragmentation are pervasive and articulation is extremely low. Micrite is present ($\sim$ 5 - 10%), although most mud-appearing material consists of crushed peloids.

UNIT 4. Unit 4 overlies unit 3 and represents the uppermost unit of the Five Oaks Formation. It consists of 3.3 meters of light to medium gray, medium to coarse grained, medium bedded ($\sim$ 0.3 m thick) biopelsparite (packstone) (Fig. 2-1G). Red and black angular chert clasts (up to 2 mm), micritic intraclasts (1 - 3 mm), and birds-eye void filling are prevalent in outcrop.

Unit 4 contains the first appearance of algae and other diverse megafossils (Figs. 2-2, 2-3; refer to for each unit hereafter) in the Stanley Farm Section (Fig. 2-1H). The allochems are poorly sorted but rounded and consist (in decreasing abundance) of peloids (27%), unidentifiable fossil material (8.2%), echinoderm debris (1.4%), ostracodes (1%), and $<$ 1% each of trilobites, inarticulate brachiopods, Hedstroemia, sponge spicules, and intraclasts. Peloids appear either as small (0.05 mm) spherical grains or as lensoid (0.1 mm x 0.05 mm) grains. Much of the interstitial material consists of crushed peloids; as a result, the distinction between this "pseudomatrix" and presumed syndepositional micrite matrix (which constitutes 21% volume) is difficult to make. Ostracodes tend to be present as randomly oriented valves; approximately 30% are articulated. In addition, many allochems exhibit extensive micritization (Bathurst, 1975); micrite rinds on ostracodes and trilobites, as well as coated grains, are prevalent. Micritic intraclasts contain skeletal fragments of ostracodes, trilobites, and other unidentifiable fossil material. Both monaxial (longest - 0.4 mm) and triaxial (class Calcarea) sponge spicules are present. Spar and microspar constitute 29% and 8.2% of thin section counts. Incipient "hummocky" stylocumulates are composed

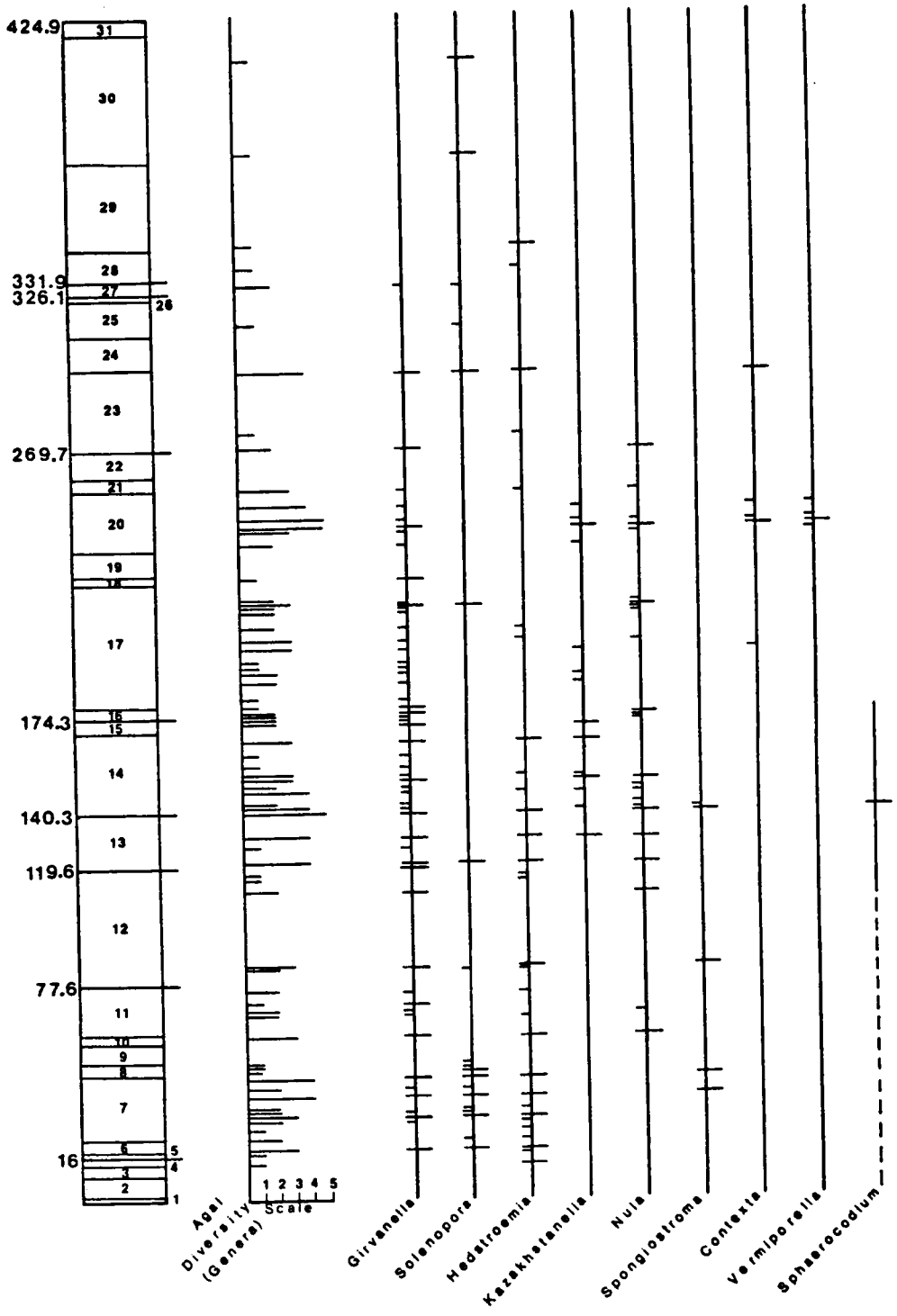


Figure 2-2. Stratigraphic distribution of algae in thin sections. Small lines to the left of each algal axis indicates algal presence in all thin sections. Small lines to the right indicate algal presence in slides point counted.

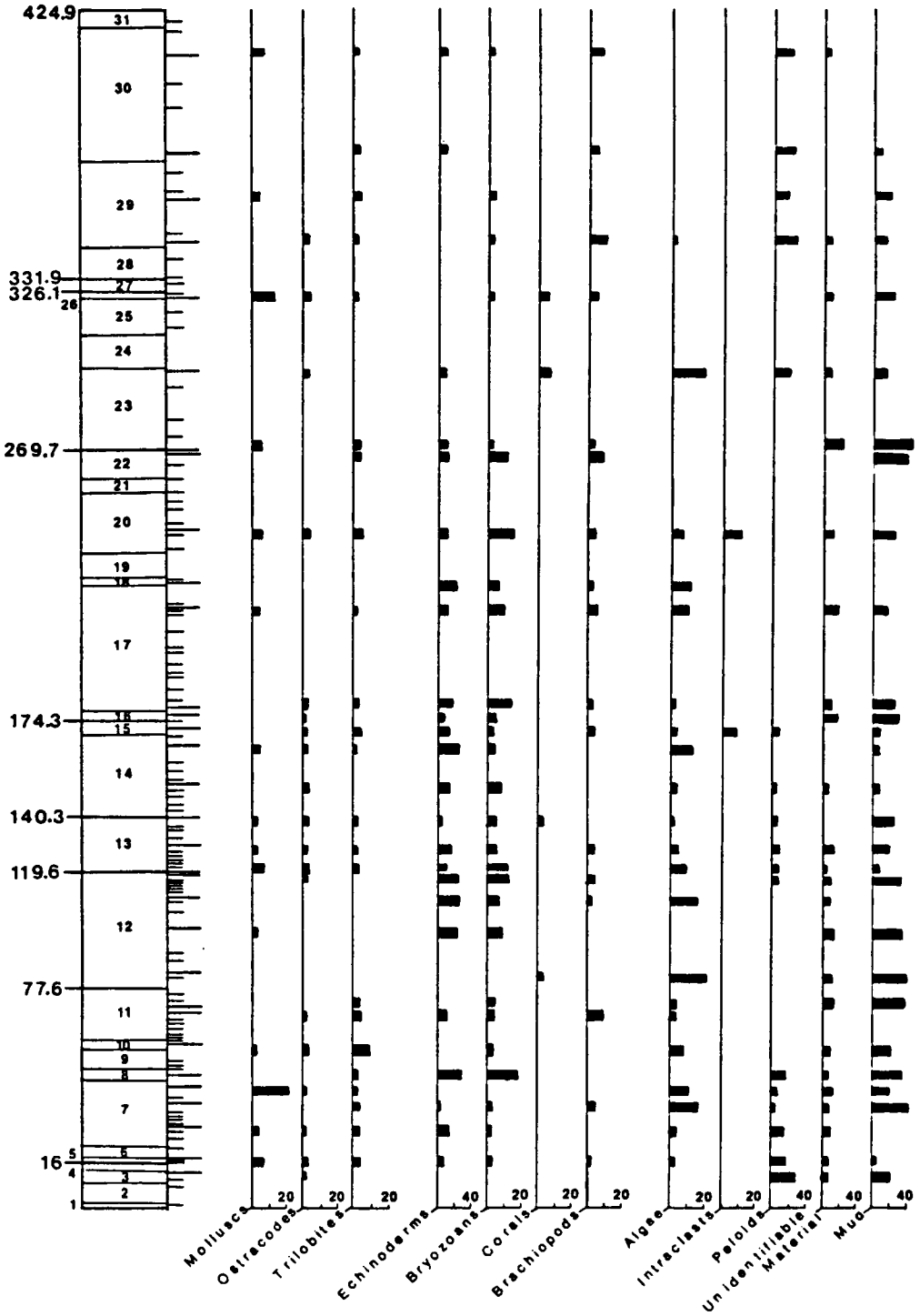


Figure 2-3. Stratigraphic distribution of allochems and matrix. Short lines to the right of the measured section represent stratigraphic position of all thin sections; long lines represent slides point counted.

of thick layers of iron coated terrigenous clay laminae and crushed inarticulate brachiopods.

PALEOENVIRONMENTAL INTERPRETATION OF THE FIVE OAKS FORMATION

The Five Oaks Formation represents deposition in a tidal flat regime. The lower units exhibit a re-activation of sedimentation on the eroded Knox supratidal surface, while the higher units reflect a gradual water deepening to subtidal conditions.

The presence of Knox-derived angular chert clasts, finer grained dolomite intraclasts, and the abundance of dolomite matrix in units 1 and 2 suggest shallow water, wave-active conditions, indicative of tidal flat regimes. Illing et al. (1965), Shinn et al. (1965), Harris (1973), Deffeyes et al. (1965), and Murray (1969), documented that dolomitization is a penecontemporaneous replacement of calcium carbonate which occurs via brine reflux through permeability conduits in supratidal to very high intertidal environments. Furthermore, Shinn et al. (1969) stated that dolomite formation is restricted to three supratidal subenvironments: beach ridges, levees, and marsh. Unit 3 reflects a slight deepening of water to intertidal - very shallow subtidal conditions. Dolomite, although not abundant (approximately 15%), may reflect periodic subaerial exposure. Fossils of eurytopic groups of organisms are highly abraded and fragmented indicating transportation, probably through tidal current activity in tidal channels or by storm waves. Laporte (1967, 1971) reported that pelletal carbonate mudstones are a common feature of tidal flat facies,

and Shinn et al. (1969) observed pelleted silt and mud in marsh zones on Andros Island; sparry peloidal bands common in unit 3 may represent deposition in energy fluctuating regimes such as intertidal areas.

Unit 4 exhibits shallow subtidal conditions as indicated by the presence of the alga Hedstroemia, which is absent from Ordovician tidal flats (Moore, 1978). Swinchatt (1969) stated that micrite rinds indicate shallow water (usually $<$ 60 feet) algal conducive environments, however, Friedman et al. (1971) reported that fungi, bacteria, and heterotropic algae are also capable of producing rinds in both shallow and deeper water environments. Nevertheless, these micritized rinds co-occurring with poorly sorted but rounded allochems, probably indicate shallow oscillating water. Furthermore, the availability of sponge spicules is governed by the limit of high tide level, if not transported. Limited subaerial exposure is suggested by fenestral structures common in outcrop, and by the presence of birdseye void fills in thin sections; however, these birdseyes probably reflect only infrequent periodic desiccation within subtidal conditions.

IV. LINCOLNSHIRE FORMATION

The Lincolnshire Formation crops out along Loyston Road and continues up section in field exposures near the Stanley Cemetry (Fig. 1-3, p. 5). This formation was originally divided into the Eidson and Hogskin Members (Cooper, 1956). The Eidson is well exposed in the roadcut along Loyston Road. The Fleanor Member, an interbedded sequence of yellow and red shales, thin shaly limestones, and siltstones,

is present between the Eidson and Hogskin Members at this section. The Hogskin and Fleanor exhibit a certain degree of lithologic similarity, which is discussed under the sections on units 12 and 13. Both units are exposed just below the Stanley Cemetery.

Based on field observations and thin section analysis, the Lincolnshire Formation was divided into 9 units with a combined thickness of 124.3 meters; units 5 through 11 (61.6 meters) characterize the Eidson Member, unit 12 (42 meters) characterizes the Fleanor Member, and unit 13 (20.7 meters) characterizes the Hogskin Member.

A. EIDSON MEMBER

The Eidson Member overlies the Five Oaks Formation and has been divided into 7 units. Because the contact between the Five Oaks Formation and Eidson Member is gradational, the boundary was chosen at the first appearance of red and black chert nodules which characterize the Eidson.

UNIT 5. Unit 5 consists of 1.2 meters of white to light gray, fine grained, cherty biomicrite (mudstone). The cobbly nature (beds 1-5 cm) is attributed to thin ($\sim$1 mm) shale laminae between limestones. Red and black chert, red in the basal portion and darker in the upper part of the unit, is present as both nodules and lenses (average = 1-3 cm thick; 5-15 cm wide). Abrasion and fragmentation are common for all allochems and articulation is rare. Allochems occur as skeletal grains except for those preserved within the chert pods. Constituents include trilobites, echinoderms, ostracodes, phosphatic inarticulate brachiopods fragments (average = 0.3 mm), and sponge spicules. Chert

fill, chalcedony rims, and grains of polycrystalline quartz are common. Small (~0.08 mm) euhedral dolomite rhombs (< 5%) are present.

UNIT 6. Unit 6 consists of 5.2 meters of light gray, coarse grained, poorly sorted, biopelsparite (packstone and grainstone) (Fig. 2-4A). Unit 6 is thicker bedded than Unit 5 (5-10 cm) and is interbedded with thin (1-6 mm) clay-rich biosparites. Constituents of the unit (1 thin section counted) include peloids (17.1%), unidentifiable fossil material (9.8%), echinoderms (8.5%), molluscs (6%), trilobites (4.4%), trepostome bryozoans (2.8%), Girvanella (1.6%), ostracodes (1.3%), Solenopora (type R) and intraclasts (1%) each, and (< 1%) each of Hedstroemia and inarticulate brachiopods. Spar cement, microspar, and micrite account for 29.5%, 9.1% and 6.5% volume, respectively. Abrasion and fragmentation are low (i.e. all allochems exhibit minimal degrees of abrasion and fragmentation, terminology used hereafter). Articulation is high for all allochems. Solenopora first appears in this unit and is present as uneroded grains (maximum size - 1.3 mm), multiple grain clumps, and slightly eroded fragments. Hedstroemia is present both as small clasts and as encrustations on abraded fossil material. Girvanella forms small (0.5-2 mm) oncolites. Micritization is pervasive; rinds are extensive on practically all fossils, especially trilobites and ostracodes. In addition, coated grains (~2.6 mm) are prominent. Many peloids, both lensoidal (0.24 mm x 0.1 mm) and equant (p.15 mm) exhibit internal filamentous structures which indicate an algal origin. Spar cement exhibits well developed triple junctions (Bathurst, 1975).

Figure 2-4. Photomicrographs, thin section photographs, and field photographs of the Lincolnshire Formation: Eidson and Fleanor Members.

A. Photomicrograph of a grainstone of unit 6. Large allochems pictured are a trilobite fragment and the red alga Solenopora (type R of Moore, 1978) (K-23). 10X.

B. Thin section showing a packstone/grainstone of unit 7. Large round allochems are the red alga Solenopora (type P of Moore, 1978); tabular allochems are micrite intraclasts (K-43).

C. Thin section of Spongiostroma-Girvanella-Hedstroemia microboundstone in unit 7 (Eidson Member) (K-49.3).

D. Typical Eidson exposure of wackestone and packstone interbedded with pods and lenses of black chert. Located along Loyston road.

E. Thin section of algal-bryozoan boundstone in the Eidson Member (E-28).

F. Outcrop of Fleanor Member: interbedded quartz siltstones, shales, and packstones.

G. Thin section showing storm produced disrupted shale laminae of the Fleanor Member (F-32.5B).

H. Thin section showing tabular shaped micrite intraclasts located in grainstone of unit 12 in the Fleanor Member (F-37).

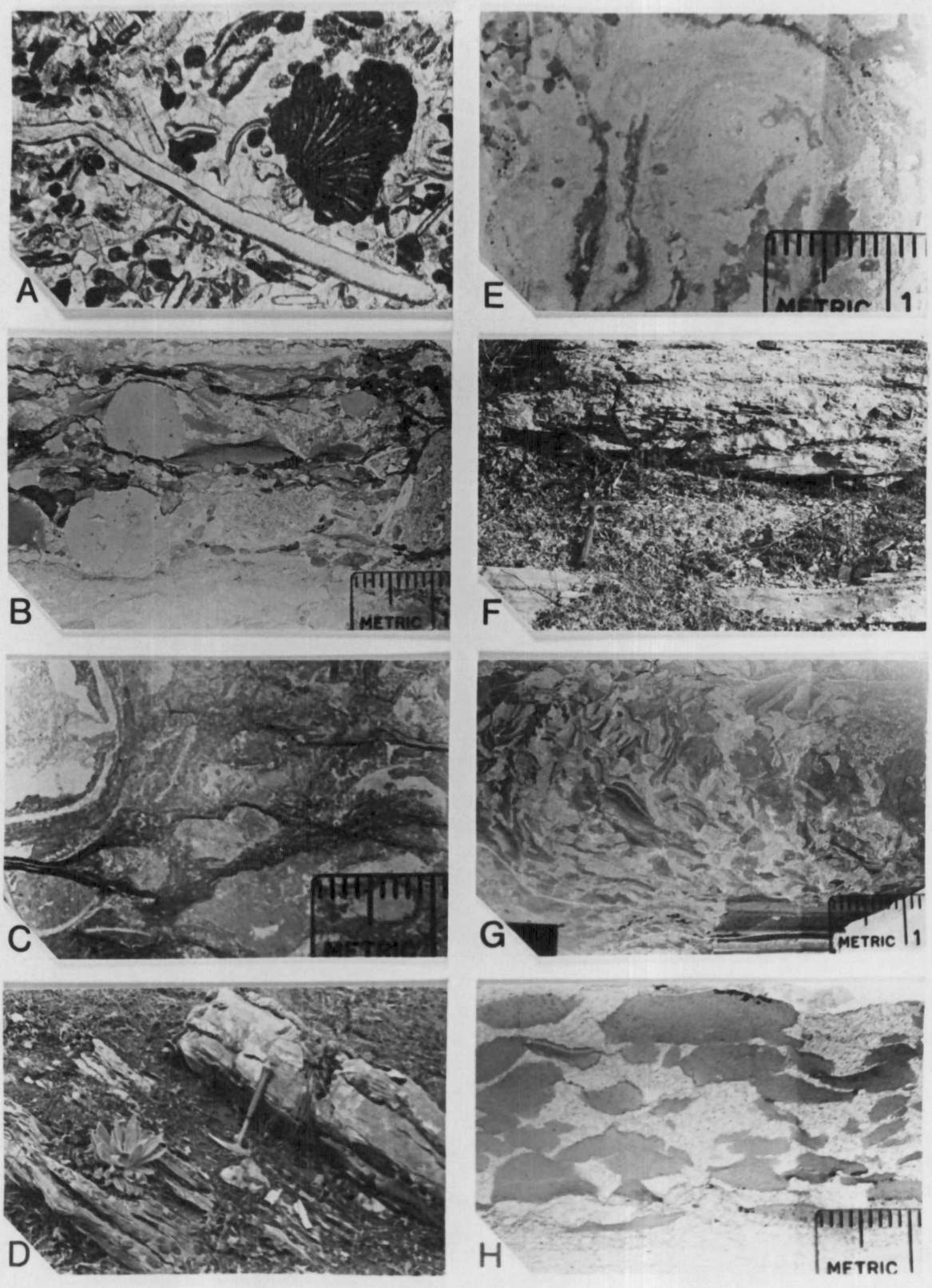


Figure 2-4.

UNIT 7. Unit 7 contains 25.8 meters of interbedded gray shale, biomicrite (packstone), and pelbiosparite (packstone and grainstone), which overall become more terrigenous rich toward the upper portion of the unit. Because the lithologies are highly variable, 3 intervals (the lower 4.3 meters, the middle 8.5 meters, the upper 12 meters) within the unit were described and a slide from each point counted.

The lower 4.3 meters consist of fine to medium grained, thinly bedded (3-10 cm), pinkish gray to pinkish blue biosparite (grainstone), interbedded with light maroon to blue, fine grained, thin to thick bedded (3 cm - 1 m) shale and siltstone. The bluish color of the shales appears to be a result of weathering. Lenses of red chert (up to 8 cm long) are occasionally interbedded with the shale and carbonate. The middle 8.5 meters likewise display the interbedded sequence of light gray packstone and grainstone, and lenses of red chert; however, shale only occurs sporadically throughout the interval. The upper 12 meters of the unit consist of medium gray, medium to coarse grained, biosparite. Micritic intraclasts (1-5 mm) are common on outcrop, as are fragments of brachiopods, trilobites, ostracodes, bryozoans, and gastropods.

Constituents of the unit include Spongiostroma (24.7% - Upper interval), Hedstroemia (4% - U), Girvanella (2.2% - Lower interval), gastropods (20.9% - U), peloids (12.7% - L, 4.4% - M, 3.8% - U), Solenopora (type P) (< 1% - L, 16% - M, < 1% - U), echinoderms (11.5% - L to 1.2% - U), unidentifiable fossil material (~ 8% - L, M, U), trilobites (~ 3% - L, M, U), ostracodes (~ 1.2% - L, M, U), and intraclasts (~ 1.5% - L, M). An indeterminable fossil (? tintinnid,

calcisphere, ostracode) constitutes 11 volume % in the lower interval. Interstitial components include micrite (~1% - L, 40.6% - M, 17.3% - U), spar (37.4% - L, 16.2% - M, 9.6% - U), and microspar (1.5% - L to 3.6% - U).

Hedstroemia occurs as small (0.3 mm) abraded grains and as encrustations, while Girvanella is present as small clasts (0.8 mm), as isolated tubules in micrite matrix, and as encrustations. Solenopora (type P) occurs as small (0.4 mm) abraded grains in the lower part of the unit; in contrast, middle to upper intervals contain large (11.3 mm), unabraded, extremely well preserved hemispheric Solenopora biscuits (Fig. 2-4B, Plate E-6). Spongiostroma is virtually absent in the lower interval, however, the upper interval, especially the upper 5.7 meters, consists of microboundstone (microbiolithite) formed as a direct result of sediment trapping and binding by the green algae Spongiostroma, Girvanella and Hedstroemia (Fig. 2-4C). In addition to sediment trapping, Spongiostroma exhibits a very high affinity for encrustation of gastropod shells. Micrite peloids, both equant (0.05 mm) and lenticular (0.2 mm x 0.05 mm) are often crushed yielding a "pseudomatrix" fabric. Micritization is extensive and increases in severity toward the top of the unit. Allochems especially susceptible to borings include trilobites, ostracodes, and molluscs. Micritization is so extensive in the upper 5.7 meters of the unit that many of the peloids are completely micritized fossil fragments. Additional allochems include trilobite fragments exhibiting geopetal fabrics in spines, ramose bryozoans (most in life position), and ostracodes. Articulation of ostracodes increases from approximately

25% near the base of the unit to approximately 83% near the top. Some articulated ostracodes contain drusy mosaic spar filling although the majority (65-75%) contain mud fillings. Disarticulated valves tend to be randomly oriented, but those which are concave up contain either mud fill or algal encrustation. Fragmentation and abrasion gradually decrease in intensity from medium to low (i.e. all allochems exhibit moderate to minimal degrees of abrasion and fragmentation, terminology used hereafter) in the lower part of the unit, to very low (i.e. abrasion and fragmentation effects are minimal to non-existent for all allochems) upper intervals.

The lowermost intervals contain vertical burrows, while upper intervals exhibit segregated spar cemented bands ($\sim$12.2 mm thick) containing allochems and micrite-rich intraclasts; the layering possibly reflects bioturbation. Laminae in the lower intervals are slightly iron stained, and syntaxial overgrowths are common on abraded echinoderm fragments. Throughout the unit, chert tends to replace echinoderms and in microboundstones chert, where present, replaces virtually everything. Many areas surrounding chertified allochems often contain chalcedony.

UNIT 8. Unit 8 consists of 4.5 meters of light to medium gray, coarse grained, thin to medium bedded (3 - 30 cm), very poorly sorted biosparite (grainstone) and silty biosparite (silty packstone) interbedded with lenticular (2 - 5 cm) dark gray to black chert. These biosparites contain up to $\sim$ 44% quartz silt. They generally are much more massive than previous units and exhibit a sugary texture upon weathering. Furthermore, megascopic, thin, fining upward sequences

are evident in some horizons. Constituents (recalculated without quartz) include echinoderms (28%), peloids (12.6%), trepostome bryozoans (10.2%), unidentifiable fossil material (7.7%), cryptostome bryozoans (5.5%), and (< 1%) each of trilobites, ostracodes, brachiopods, and Solenopora (type P). Interstitial spar constitutes 33.2% of the total volume. Solenopora is present as large (up to 11.2 mm) biscuits and Nuia (?) occurs as very small (~ 0.1 mm) grains. The majority of peloids present appear to be derived from fragmented and rounded Solenopora grains. Quartz silt is concentrated in thin layers (0.2 - 3.9 mm); the grains are often draped with terrigenous clay. Hematite completely replaces euhedral dolomite rhombs in rare instances.

UNIT 9. Unit 9 consists of 6.5 meters of tan to light medium gray, very fine to fine grained, very thin bedded (1-2 cm), silty dismicrite (shaly mudstone). Only 0.4 meters of outcrop are well exposed; the remaining 6.1 meters are characterized by a shaly, light yellowish brown weathered residuum. Horizontal burrows are prominent in thin section; burrow infills consist of coarser grained mud, very fine grained quartz and peloids (< 0.01 mm).

UNIT 10. Unit 10 consists of 1.6 meters of stylolitic, light gray, medium to coarse grained, poorly to moderately sorted biomicrite (wackestone). This unit is distinctive from underlying and overlying beds because of its resistivity to weathering and its thick bedding (0.5 - 1 meter). Fossils, extremely well preserved on outcrops, include ramose bryozoans, gastropods, echinoderms, algae, sponges, ostracodes, and trilobites. Constituents in thin section include

sponge spicules (28%), unidentifiable fossil material (8%), Girvanella tubules (5%), Nuia (2%), ostracodes (2%), trilobites and gastropods (1.8%) each, and bryozoans (< 1%). Interstitial micrite accounts for 50% total volume. Girvanella, in addition to small clumps and isolated tubules, occurs as encrustations on trepostomes and trilobites. Encrustation may be partial to complete, as in the oncolites. Nuia is present as unabraded grains with single and multiple growth rings. Most ostracodes tend to be articulated (up to 85%) and either spar filled or chert replaced. Two or three different gastropod taxa are present; shapes vary from planispiral to slightly helical. Many gastropods contain drusy mosaic fabrics which indicate an infilling sequence of 1) calcite rim, 2) secondary replacement of the calcite by chert, and 3) quartz center. Cryptostome bryozoans (up to 14.4 mm) are well preserved. Fragmentation and abrasion intensities are low.

UNIT 11. Unit 11 consists of 16.8 meters of light to medium gray, fine to coarse grained, poorly to well sorted, thin to medium bedded (2-20 cm), biomicrite (wackestone), cherty biopelsparite (packstone) and bryozoan biolithite (boundstone). Interbedded with these carbonates are nodular pods and lenses of thin (2-5 cm) black chert characteristic of the Eidson Member (Fig. 2-4D, p. 28). Shale laminae are irregularily spaced within the unit such that upon weathering, a cobbly, or hummocky appearance is produced.

Silicified fossils weather out in relief on outcrop and include abundant brachiopods (e.g. Dinorthis holdeni (Willard)), ramose and encrusting bryozoans, gastropods, echinoderms (e.g. Carabocrinus), sponges, trilobite fragments, algae and algal oncolites, ostracodes,

and orthoconic cephalopods. The uppermost 4.4 meters of the unit consist entirely of algal-bryozoan boundstone (biolithite). Unit 11 represents the uppermost interval of the Eidson Member and the contact between this interval and the succeeding Hogskin Member was chosen at the non-resistant shale unit directly overlying the chert-algal-bryozoan rich boundstone unit.

In thin section (2 slides point counted), constituents include sponge spicules (5-31%, all ranges are from bottom to top of the lower 12.4 m of the unit), echinoderm debris (38-10.4%), unidentifiable fossil material (5-1.4%), brachiopods (5.7-0.7%), detrital quartz grains (5%, Upper interval only), trilobites (4.4-2%), dolomite rhombs (4.4%, Lower interval only), Girvanella tubules (1.1-3%), bryozoans (0.2-4%), ostracodes (2.2-0.4%), and peloids (2.2%, Lower interval only). Micrite ranges from 36% to 58.9%, while microspar and spar accounts for approximately 4% and 1% volume, respectively. Girvanella is the most common alga in unit 11 and occurs as small eroded clumps ($\sim$ 0.2 mm), oncolites, as encrustations, and as isolated tubules in the micrite matrix. Hedstroemia occurs in clumps, some encrusted by Girvanella. Girvanella ranges in size from clumps to peloids (2.3-0.07 mm). Fragmentation and abrasion are low and articulation is high (85% for ostracodes). Disarticulated ostracodes and bivalves exhibit concave up orientations (up to 70%). Neomorphism is common in unit 11; microspar is abundant both inside of articulated ostracodes and in the matrix.

The upper 4.4 meters of the unit consist of algal-bryozoan boundstones (Fig. 2-4E, p. 28). Trepostome bryozoans and minor Girvanella

are the major binding agents in these rocks. Sponge spicules (0.4 mm x 0.017 mm) are well preserved and constitute the major allochem within stylocumulates.

PALEOENVIRONMENTAL INTERPRETATION OF THE EIDSON MEMBER

The Eidson Member reflects deposition in a subtidal lagoonal-restricted shelf environment; small individual facies are recognizable within the formation. The lower intervals represent deposition in subtidal, agitated water, as evidenced by complete and eroded algal grains and oncolites. Algae proliferate in the photic zone limited only by high tide level; Ginsburg (1960) reported that modern oncolites form in water depths of 0-6 meters. Extensive micritization also indicates shallow water conditions. Swinchatt (1969) limited micritization to depths of 60 feet, however, Mørk and Worsley (1980) stated that micritization is most common above wave base.

The Eidson has a diverse algal assemblage (Fig. 2-2, p. 22) with Girvanella and Solenopora constituting the major algae. Girvanella tubules dominate the lower intervals (units 5-6) while Solenopora (type P) dominates the middle (unit 7). These large Solenopora biscuits are characteristic of areas of increased current activity (Moore, 1978). Furthermore, the segregated bands of spar containing allochems and micrite-rich intraclasts suggest alternations of current-active and quiescent periods. These conditions are commonly found in tidal channels or lagoonal (restricted shelf) shoaling areas. The upper intervals of unit 7 exhibit trapping and binding of loose allochems and mud by Spongiostroma and Hestroemia.

Neumann et al. (1970) discussed the trapping action of green and red algae and the binding action of blue-green algae. They stated that this binding action can occur under various energy conditions. Harland (1981) noted that Spongiostroma, Hedstroemia, and minor amounts of Solenopora and Girvanella perform a major binding and trapping function in small patch reefs in the Middle Ordovician Steinvika Limestone. As a result, the combination of microboundstone-forming algae, Solenopora (type P), Girvanella isolated tubules, and intense micritization suggests deposition in restricted shelf mudbanks (Moore, 1978) which were heavily influenced by tidal channels or shoaling waters. Units 8 and 9 reflect similar environmental conditions but with an introduction of terrigenous silt. Either migrating channels or storm generated waves could be responsible for the terrigenous influx; however, most allochems are not abraded or fragmented and the quartz tends to be concentrated into bands which exhibit small scale fining-upward sequences. Therefore, storm waves rather than channel migration were more likely responsible for the terrigenous input.

The upper intervals of the unit represent deposition in subtidal, quiet to slightly agitated waters. Oncolites are common, however, current activity was not intense as articulation is high and disarticulated shells are in hydrodynamically unstable orientations (concave up). Fragmentation and abrasion are very low; nonresistant fossil allochems (e.g. cryptostome bryozoans, see Chave, 1964) exhibit little abrasion. Well preserved sponge spicules and isolated Girvanella tubules, a prominent matrix component of mud flat

environments (Moore, 1978), suggest quiet, restricted water sedimentation.

The uppermost intervals of unit 11 represent subtidal, low to moderate current-active environments. This is evidenced by well preserved sponge spicules and the abundance of algal-bryozoan boundstone. These organic carbonate buildups may have formed as mounds, domes, or heads; these boundstones were smothered by influx of terrigenous clastic material which marked the beginning of Fleanor deposition.

B. FLEANOR MEMBER

The Fleanor Member of the Lincolnshire Formation overlies the Eidson Member and, based upon field observations and thin section analysis, represents one unit (12) with a total thickness of 42 meters. The contact between the two members is characterized by the termination of chert rick, massive, bryozoan boundstone, and introduction of non-resistant, very thinly bedded, tan and yellow shale. The Fleanor Member at the Stanley Farm Section is similar to the maroon shales, thin gray limestones, and siltstones described by Cooper and Cooper (1946) for exposures near Fleanor Mill, Tennessee.

UNIT 12. Unit 12 is a non-resistant unit composed primarily of calcareous terrigenous shale and siltstone which are sporadically interbedded with medium to coarse grained biosparites. This interbedded nature is prevalent and probably is due to fluctuations in local terrigenous sediment influx or tidal variation, yielding small scale interfingering of the beds.

Lower intervals of unit 12 (1-12 m) consist of very thin to thin bedded (1-6 cm), fine to medium grained, whiteish tan to yellowish brown and light gray shaly dismicrite (mudstone and wackestone). Beds weather into small (1-15 cm), thin (0.5-2 mm) chips. Algal oncolites and small scale cross laminations are present on weathered surfaces of less shaly wackestone. Constituents include Givanella clasts (11.8%), unidentifiable fossil material (9.5%), Girvanella and Spongiostroma oncolites (9%), detrital quartz (7.2%), Hedstroemia (4.6%), encrusting Spongiostroma (3.2%), and (< 1%) each of peloids, ostracodes, gastropods, brachiopods, Solenopora and corals. Micrite, spar, and microspar account for 37.9%, 12.7% and 1.4% volume, respectively. Girvanella is present as isolated tubules, eroded clumps, and as oncolites. Many oncolites exhibit multialgal encrustations (e.g. gastropod nuclei) Girvanella-Spongiostroma, and Hedstroemia-Spongiostroma oncolites. Allochems exhibit little fragmentation and abrasion, and articulation is common. Disarticulated nested ostracode valves are present but rare. Additional allochems include several unidentified gastropods in addition to Raphistoma staminea Hall, and the tabulate coral Tetradium of the form T. syringoporoides (classification of Webby and Semeniuk, 1971). Horizontal (85-90%) and vertical burrows are present and most are filled with peloids. The percentage of quartz silt steadily increases upward throughout the interval.

Middle intervals of the unit (12-22 m) are characterized by thin bedded (4 cm), medium gray, fine to medium grained, well sorted calcareous siltstone and silty pelsparite (silty packstone). Subangular quartz silt (~0.2 mm) constitutes 35-45% volume of these siltstones;

small scale (10 mm) trough cross beds with an apparent dip of 15°-25° are prominent. Vertical burrows and oncolites are present, and fossils are severely abraded. Glauconite is rare.

Upper intervals of unit 12 (22-42 m) consist of yellow to maroon, fine grained, thick to very thick bedded (0.5-2 m), calcareous shale, quartz siltstone, and silty biomicrite (silty packstone) interbedded with white to gray, medium to coarse grained, medium to very thick bedded (0.2-1.5 m), biosparite (packstone and grainstone) (Fig. 2-4F, p. 28). Soft sediment deformational features are abundant in the siltstones. Biogenic activity is characterized by vertical burrows, and physical deformation is evidenced by disrupted laminae (Fig. 2-4G, p. 28). Well sorted, subangular to subrounded quartz silt accounts for as much as 55% volume; peloids are rare. Biomicrites and dismicrites exhibit little abrasion of allochems. Point counts of packstones from low and high horizons in the upper interval (22.5 m and 33.3 m) show constituents (Fig. 2-2, p. 22; Fig. 2-3, p. 23) to include Girvanella encrusting (9% - U) and as spherical oncolites (4.1% - U), Nuia (1.3% - U), echinoderms ($\sim$24%), detrital quartz (17.3% - L), unidentifiable material (12.5-5.6%), cryptostomes ($\sim$6%), trepostomes (2.1% - L), (1%) each of gastropods and brachiopods, and ($<$1%) each of peloids, ostracodes, and trilobites. Micrite constitutes 34% (L), spar constitutes 3.6-20.5%, and microspar accounts for 24.6% (U). Boring is prevalent and most peloids consist either of eroded algal clumps or algal encrusted grains. Large (12.7 mm x 4.4 mm) tabular shaped micrite clasts isolated within grainstone (Fig. 2-4H, p. 28) indicate severe water agitation and mud removal. Thin birdseye stringers

indicate desiccation; most interstitial micrite shows evidence of aggradational neomorphism (Bathurst, 1975). Glauconite is abundant in the upper intervals.

PALEOENVIRONMENTAL INTERPRETATION OF THE FLEANOR MEMBER

The Fleanor Member represents shallow, subtidal, sedimentation in agitated, commonly turbid waters with a continuous supply of terrigenous silt and clay. Oncolites are prevalent in the lower intervals of the Fleanor with the major encrusters being Girvanella, Hedstroemia, and Spongiostroma. Ginsburg (1960) stated that modern oncolites form in shoal waters of 0 to 6 meters depth. Furthermore, the presence of Solenopora (type P) suggests moderate to strong current activity. Vertical and horizontal burrows, and soft sediment deformation features are also present in these lower intervals. Water depths for these indicators, compiled by Benedict and Walker (1978), range between mean water level and 10 meters.

The middle and upper intervals feature greater terrigenous input than the lower interval. Sudden physical changes in the sediments suggest rapid energy fluctuations. Well sorted, laminated quartz silts and small scale crossbedding (Fig. 2-5A) reflect slight to intense water movement, as is often found on beach ramps or in tidal channels. Intense current activity, indicative of tidal channels, is suggested by the large tabular-shaped micritic intraclasts (Fig. 2-4H, p. 28). Rotated clasts of laminated sediment indicate storm wave activity (Fig. 2-4G, p. 28). Fossils present in the unit are severely abraded and oriented parallel to bedding; birdseyes suggest infrequent desiccation. These conditions indicate shallow, agitated, terrigenous

Figure 2-5. Photomicrographs, thin section photographs, and field photographs of the Lincolnshire Formation (Fleanor and Hogskin Members) and the Rockdell Formation.

A. Thin section showing cross-laminations of a siltstone in the Fleanor Member (F-39).

B. Outcrop of the Hogskin Member (unit 13) showing trough crossbeds. Key is 4.5 cm long.

C. Thin section of an overturned siltstone in the Hogskin Member (F-44).

D. Thin section showing dismicrite containing interlaminar birdseyes in the Hogskin Member (F-50B).

E. Thin section showing vertical burrows which exhibit geopetal fabrics in the Hogskin Member (F-49).

F. Outcrop of massive Rockdell Formation. Lens cap is 55 mm wide.

G. Photomicrograph of (?) Spongiostroma and (?) Hedstroemia algal structures of unit 14 in the Rockdell Formation (R-7). 20X.

H. Thin section showing grainstone of unit 15 in the Rockdell Formation. Dark allochems are micrite intraclasts and algal coated grains (R-31.5).

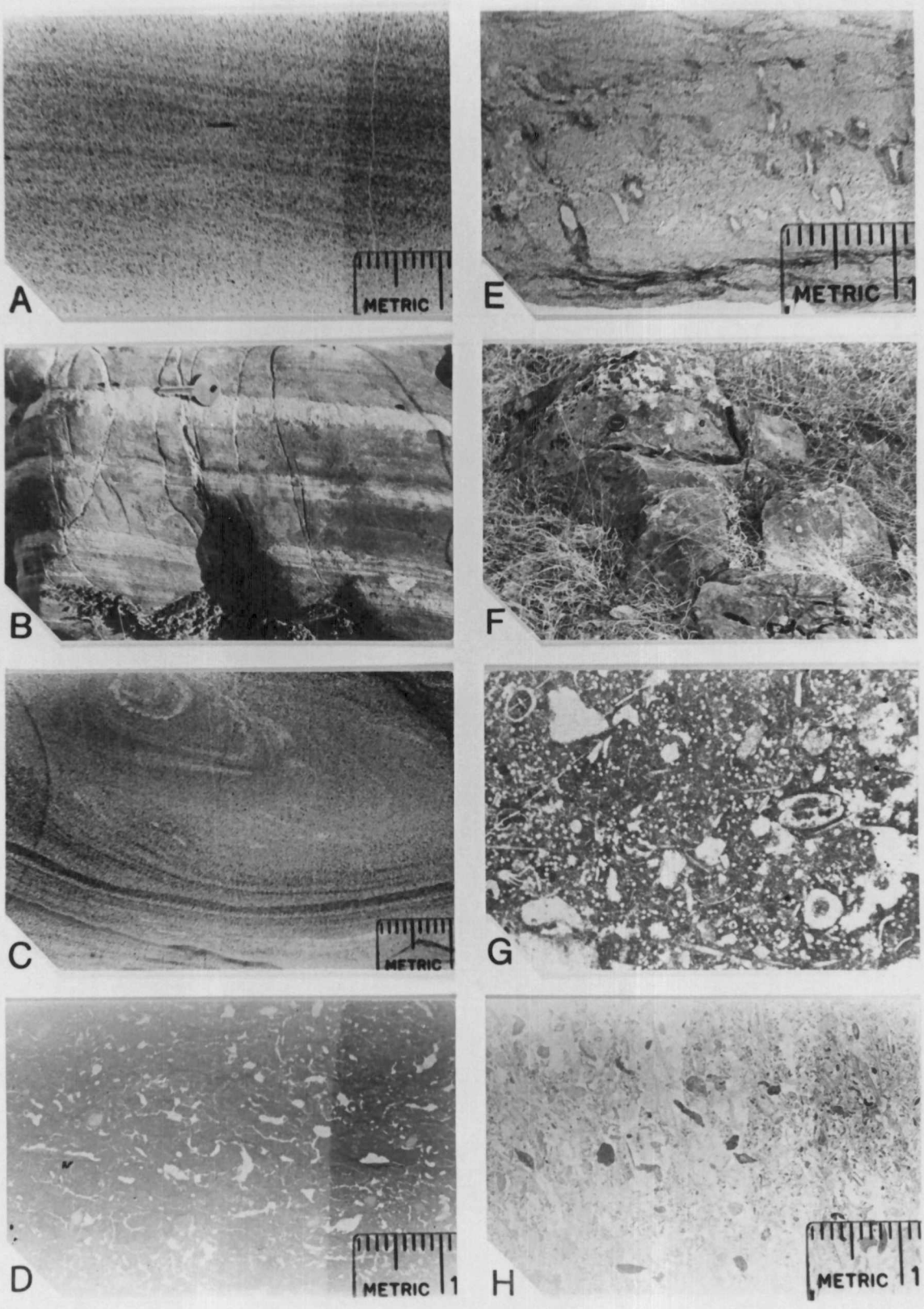


Figure 2-5.

clastic (deltaic) influenced deposition in an energy-fluctuating carbonate environment. These conditions are often found in shallow, shoaling regimes such as tidal channels and restricted shelf beach ramps, where storm waves and wave base are active depositional parameters. The introduction of the terrigenous clastic material may have occurred through migrating fluvial channels. Deposition of the Fleanor Member and its stratigraphic relationship with the Eidson and Hogskin members of the Lincolnshire Formation are discussed further in Chapter 3.

C. HOGSKIN MEMBER

The Hogskin Member of the Lincolnshire Formation overlies the Fleanor Member and represents one unit (13) with a total thickness of 20.7 meters. The contact of the Hogskin with the underlying Fleanor is denoted by the sudden appearance of massive and resistant beds of calcareous siltstone, wackestone, and packstone. Furthermore, the percentage of terrigenous silt and clay decreases to the point that shale drapes and thin mud layers replace the thick shale and siltstone beds characteristic of the Fleanor Member.

UNIT 13. Unit 13 consists of 20.7 meters of light to dark gray, fine to coarse grained, well sorted, thin to thick bedded (0.02 - 0.6 m), quartz siltstone, wackestone, and packstone interbedded with greenish yellow, light brown, and maroon, fine grained, very thin to very thick bedded (0.5 cm - 2.2 m), siltstone and calcareous shale. The shales commonly erode out on outcrop; consequently, the

siltstones, wackestones, and packstones often appear cobbly, especially in the upper part of the unit.

Well sorted, subangular, calcareous quartz-siltstone occurs throughout the unit. Peloids (0.2 mm) and silt grains compose the dominant constituents of these rocks. Quartz grains comprise 45%-50% volume and occur in structures ranging from gentle small scale cross laminations (~10° dip), to small (1-5 cm) trough crossbeds (Fig. 2-5B) and overturned beds (Fig. 2-5C), which collectively exemplify various stages of physical energy and soft sediment deformation.

Yellow and maroon shales of unit 13 contain approximately 25% detrital quartz. Even though opaque (hematite ?) grains are present in these silty mudstones, the brownish-red color is due largely to ferruginous stain in calcite mud and spar. Vertical burrows are common, and the most representative fossils are phosphatic inarticulate brachiopods. Dismicrites within this unit contain interlaminar birds-eyes which are characteristic of desiccation of algal mats (Fig. 2-5D, see Shinn, 1968). Mudcracks are common throughout the shaly intervals, whereas vertical burrows, which exhibit geopetal fabrics, are especially prevalent in the silty pelsparites (packstones) (Fig. 2-5E).

Biomicrites and pelbiomicrites (wackestones and packstones) are well exposed and give off a strong sulfurous odor. Fragmentation and abrasion of fossils are minimal and articulation is high (ostracodes range from 75% to 90% articulated). Constituents (derived from point counts at two intervals; 42 and 43 meters (counted as one interval), and 53 meters above the unit base) include Girvanella (2.5-1.7%),

Solenopora (type R) (2.2% - L), Hedstroemia (~ 2%), Nuia (< 1%), Kazakhstanelia (1.7% - L), echinoderms (21.4-14.6%), unidentifiable material (8.1-11%), cryptostomes (8.7-2.8%), trepostomes (~ 2.5%), peloids (3.8-6.2%), trilobites (0.5-2.5%), ostracodes (1.1-2.5%), bivalves (3.6-0.8%), brachiopods (~ 2%), and (< 1%) intraclasts and dolomite. Micrite decreases in volume (29.3-17.1%), while microspar increases (11.1-29.2%). Spar accounts for ~2% in each interval. Girvanella occurs as oncolites, especially on trilobite, gastropod, and trepostome fragments, and as unabraded clumps. Girvanella is also present in minor amounts as matrix tubules. Unit 13 marks the first appearance of Kazakhstanelia (Fig. 2-2, p. 22, Plate E), and abraded Nuia grains and Girvanella-encrusted fossil fragments comprise the majority of small peloidal-like grains. Micritization is extensive in the lower intervals, principally on ostracode valves, gastropod fragments, echinoderm debris, and cryptostomes. Articulated ostracodes contain either mud or neomorphic microspar centers; disarticulated valves are randomly oriented. Echinoderm columnals and plates are numerous. Large (5.1 mm) angular intraclasts (some hematite? coated) contain fine abraded fossil fragments.

Anastomosing stylolites, especially abundant in the upper part of the unit, are chiefly parallel to bedding. Thick (up to 9 mm) bright orange stylocumulates are composed of micrite, terrigenous clays, inarticulate brachiopod fragments, and small (< 0.01 mm) quartz grains. Echinoderm fragments exhibit a strong preference for chertification and syntaxial overgrowths. Spar cement, where present, displays pronounced triple junctions (Bathurst, 1975); radiaxial cement is present within the spar filling of some brachiopods.

PALEOENVIRONMENTAL INTERPRETATION OF THE HOGSKIN MEMBER

The Hogskin represents a shallow water, terrigenous clastic-influenced environment where wave action was an important parameter. This is evidenced by various syndepositional sedimentary structures such as crossbeds and overturned beds. The abundance of concentrically laminated Girvanella oncolites likewise implies shallow, agitated water sedimentation. Logan et al. (1964) stated that oncolites are a product of low intertidal areas exposed to waves and agitated shallow water below low-water mark. Algal diversity is high in this unit (Fig. 2-2, p. 22), burrowing is common, and mudcracks, birdseyes, and soft sediment deformation are prevalent; Benedict and Walker (1978) reported that these conditions fall within water depths ranging from -10 meters below to +10 meters above mean low water level. Micritization is prominent in the upper intervals of the unit. Mørk and Worsley (1980) determined that both Girvanella and micritization are common in environments of water depths above normal wave base, with micritization indicating slightly more shallow water than Girvanella. The Hogskin represents subtidal, shallow water, wave-active to intertidal environments, which were interrupted by influxes of terrigenous clastic material.

Plummer and Gostin (1981) stated that shrinkage cracks can form either through subaerial desiccation or on the sediment water interface via the synaeresis process; however, the mudcracks and birdseyes present in the Hogskin most likely reflect infrequent subaerial exposure. Consequently, the Hogskin may represent deposition in

terrigenous clastic influenced tidal flats or shallow near shore restricted shelf (lagoonal) facies.

V. ROCKDELL FORMATION

The Rockdell Formation overlies the Lincolnshire Formation and underlies the Benbolt Formation; it crops out between Loyston Road to the southwest and Raccoon Valley Road to the southeast. The contact is denoted by the sudden appearance of massively bedded, stylolitized, cherty wackestone and packstone above the cobbly and easily erodable siltstone, wackestone and packstone of the upper Lincolnshire. In addition, the Rockdell lacks the terrigenous clastic components that are characteristic of the Hogskin Member of the Lincolnshire Formation. The 34 meter-thick Rockdell was divided into 2 units; unit 14 consists of the lower 28.5 meters of the formation, and unit 15 consists of the upper 5.5 meters.

UNIT 14. Unit 14 consists of 28.5 meters of medium gray, medium to coarse grained, poorly to moderately sorted, massively bedded (>1 meter) biomicrite and biosparite (packstone and occasional grainstone) (Fig. 2-5F, p. 42). The rocks have a sugary texture, and dark gray oval to lensoid chert pods are common on outcrop. Constituents (point counts at the base of unit, at 11 meters, and at 25.5 meters) include Girvanella clumps and tubules (1.2, 1.9, 9.6%) and oncolites (3.4% L to 0.3% U), (<1%) Nuia, Hedstroemia, Kazakhstanelia, Spongiostroma, and Sphaerocodium, echinoderms (3, 13.4, 22.5%), bryozoans (4.7, 3.4, 0.6%), unidentifiable skeletal debris (2.4, 3.7, 0.6%), gastropods (2.4, 0.6, 1.9%), trilobites (1.9 L to 0.8% H), peloids (3.3, 2.2, 1.4%),

brachiopods (0.6% M), sponge spicules (1.4% U), and (< 1%) intraclasts and bivalves. The percentage of microspar and micrite decreases (48.4, 35.8, 16%; 25.8, 7.2, 3%, respectively) while percent spar increases (4.2, 20.9, 34.1%) (see Fig. 2-2, p. 22; Fig. 2-3, p. 23, and Appendix B).

Girvanella oncolite nuclei consist of cryptostomes, Kazakhstanelia grains, gastropods, brachiopods, echinoderms, trilobites, ostracodes, intraclasts, and fossil hash rich mud lumps. Spongiostroma also forms small oncolites. Girvanella and Nuia are commonly eroded and abraded to peloidal sizes. Kazakhstanelia occurs "in life" position and Sphaerocodium first appears in the section in unit 14 (Fig. 2-2, p. 22). Possible (?) Spongiostroma and (?) Hedstroemia algal structures are abundant throughout the unit (Fig. 2-5G, p. 42). Micritization, though extensive in the lower intervals, is rare in the upper intervals. Rinds in the lower intervals are produced by borers (with subsequent micrite infill); algal encrustation, chiefly Girvanella is also heavy.

Articulation is high within the unit; ostracodes range from 35-100% and brachiopods virtually 100%. Center fills consist of micrite. Most curved fragments such as brachiopod valves, curved echinoderm plates, cryptostome fragments, ostracode valves, and some algal filaments display a convex-up attitude. Abrasion and fragmentation intensities are medium to high (i.e. all allochems exhibit moderate to severe degrees of abrasion and fragmentation, terminology used hereafter) in the poorly washed lower intervals, and of low intensity in the upper intervals. Furthermore, the lower intervals tend to be micrite- and microspar-rich whereas the upper intervals of the unit contain large spar crystals with well developed triple junctions.

UNIT 15. Unit 15 consists of 5.5 meters of medium to dark gray, coarse grained, poorly to well sorted, massively bedded (>1 m) biosparite (packstone and grainstone) (Fig. 2-5H, p. 42). The rocks lack the sugary texture characteristic of unit 14, and are thinner bedded as a result of a greater amount of terrigenous clastic sediment. Constituents include echinoderms (12.6%), intraclasts (8.5%), peloids (5.9%), trilobites (4.1%), brachiopods (2.8%), (1.8%) of cryptostomes, ostracodes and Kazakhstanelia, and (<1%) trepostomes, molluscs, and unidentifiable material. Spar, micrite, and microspar account for 47.2%, 6.4% and 1%. Girvanella encrusts echinoderms and cryptostomes. Common allochems include echinoderms (Carabocrinus plates), well preserved articulate brachiopods, and micrite intraclasts which contain finely abraded fossil debris.

Unit 15 contains the most extensive micritization observed thus far in the section. Essentially all allochems are micritized and many are bored to the extreme of masking abrasion. Carbonate mud is prominent in the centers of brachiopods, ostracodes, in the porous network of echinoderm plates, and as coatings on cryptostomes and trepostomes. Whereas the majority of brachiopods have mud filled centers, a few show drusy mosaic spar fill. In contrast, mud is lacking in the interstices. Allochems of the lower part of unit 12 exhibit little abrasion and fragmentation, and medium to high articulation. Virtually 100% of the articulate brachiopods and 35-45% ostracodes are articulated. Cryptostomes exhibit little abrasion or fragmentation, which may be attributed to a "cushioning" effect caused by the mud coatings. Conversely, the upper intervals of the unit (top 2.5 meters) exhibit highly abraded

and fragmented echinoderms and cryptostomes. Chert and chalcedony are abundant in the unit, but do not exhibit any preference for specific allochems.

PALEOENVIRONMENTAL INTERPRETATION OF THE ROCKDELL FORMATION

The Rockdell Formation represents deposition in a shallow, subtidal, current-active environment. Unit 14 reflects slightly deeper, or quieter water deposition than unit 15. The presence of micrite in interstitial areas and in fossil centers, algal diversity and high articulation, reflects water energy not quite capable of winnowing mud. The high degree of abrasion may be due to biological breakdown, as opposed to mechanical breakdown. Swinchatt (1965) reported that reduction of the smaller carbonate fraction usually occurs by biological, rather than mechanical, breakdown. In contrast, the upper intervals of unit 14, and unit 15, suggest deposition in more current-active shoaling waters. Extensive micritization, the presence of oncolites, and the lack of interstitial micrite suggest shallow, agitated-water sedimentation. These conditions normally would cause moderate to severe abrasion in fossil allochems, however, the excellent preservation of fragile allochems in the Rockdell may be explained either by the "cushioning effect" resulting from heavy algal encrustations and micritic coatings, or by a lack of transportation. The presence of these grainstones interbedded with terrigenous rich layers suggests depositional conditions similar to that expected in near shore shoaling areas.

VI. BENBOLT FORMATION

The Benbolt Formation overlies the Rockdell Formation and based on field exposures and thin section analysis has been divided into 7 units (16-22) for a total thickness of 95.4 meters. The formation is well exposed along both sides of Raccoon Valley Road, and on the north flank of Bullrun Ridge (Fig. 1-3, p. 5). The rocks consist primarily of interbedded shale and packstone (biomicrite and biosparite) and in thin section closely resemble the lithologies of the upper Rockdell Formation (Unit 15). In outcrop, however, the rocks exhibit a much more cobbly appearance than the more massively bedded Rockdell, which reflects the large percentage of shale drapes and shale layers dispersed between the Benbolt limestones. As the surrounding shales weather away, only the limestone cobbles remain. The contact between the Rockdell and Benbolt formations, therefore, was chosen at the first appearance of the cobbly weathering pattern.

UNIT 16. Unit 16 consists of 4 meters of light to medium gray, medium grained, thinly bedded (2-10 cm), biomicrite (packstone) and cherty biomicrite (cherty packstone) interbedded with thin (1-8 mm) hummocky shale drapes. Constituents include unidentifiable fossil material (14.2%), cryptostomes (3.6%), echinoderms (3%), ostracodes (1.2%), and (< 1% each) trepostomes, bivalves, trilobites, Nuia, Girvanella, and brachiopods. Interstitial areas consist of microspar (41.8%), micrite (29.7%), and spar (3.9%). Girvanella occurs as isolated tubules in matrix, clasts, and encrustations, especially on gastropods. Nuia is more abundant than Girvanella and occurs as

abraded grains. Abrasion, fragmentation, and articulation are moderate for most fossils. Recrystallized sponge spicules and trilobite spines are common debris constituents. Micritization is uncommon and occurs principally on mollusc and echinoderm fragments. Chert and chalcedony replace many grains.

UNIT 17. This unit consists of 45 meters of interbedded shale and light to medium gray, medium to coarse grained, poorly sorted, thin to medium bedded (7-30 cm) biomicrite and biosparite (packstone and grainstone). The unit is characterized by cobbles (average size = 4 cm x 30 cm, Fig. 2-6A). Thin (1 mm - 2 cm) shale drapes combined with abundant stylolites yield a hummocky appearance to the exposures. Fossils common on outcrop include algal oncolites, the alga Receptaculites, the sponge Allosaccus, sponge spicules, articulate brachiopods (Dinorthis transversa Willard, Sowerbyella compacta Cooper, Hesperorthis sp. A (= Hesperorthis sp. 2 of Cooper, 1956, p. 360 , pl. 50 C, Fig. 8-13), and Mimella globosa (Willard), echinoderms (Crinoidea: Archaeocrinus peculiaris (Miller and Gurley), Diabolocrinus vesperalis (White), Acolocrinus hydraulicus Kesling & Paul, Apodasmocrinus punctatus (Brower & Veinus), Hybocrinus punctatus (Miller & Gurley), Palaeocrinus avondalensis Brower & Veinus, Paleocrinus planobasalis Brower & Veinus, Triboloporus cryptoplicatus Kesling & Paul, and Carabocrinus micropunctatus Brower & Veinus; Paracrinoidea: Canadocystis tennesseensis Parsley and Batherocystis appressa Bassler; Rhombifera: Coronocystis angulatus (Wood), Amecystis sp., and Regulaecystis pyriformis (Parsley); Eocrinoidea: Ulrichocystis eximia Bassler; Parablastoidea: Meristochisma hudsoni Sprinkle; and Blastoidea:

Figure 2-6. Photomicrographs, thin section photographs, and field photographs of the Benbolt Formation.

A. Typical cobbly exposure of the Benbolt Formation. Located along Raccoon Valley road. The book is 26 cm long.

B. Thin section showing uncrushed Girvanella oncolites (Bn-41).

C. Photomicrograph showing Girvanella encrusted cryptostomes in packstone/grainstone (biomicrite/biosparite) of unit 17 (Bn-11.5). 20X.

D. Photomicrograph of packstone exhibiting mud filled gastropods (Bn-61). 10X.

E. Thin section of echinoderm grainstone of unit 18 (Bn-49).

F. Outcrop of massively bedded echinoderm grainstone of unit 18. Lens cap is 55 mm wide.

G. Field photograph exhibiting shaly nature of unit 21. Lens cap is 55 mm long.

H. Thin section of packstone of unit 22 showing mud filled brachiopod valves aligned parallel to bedding (Bn-95).

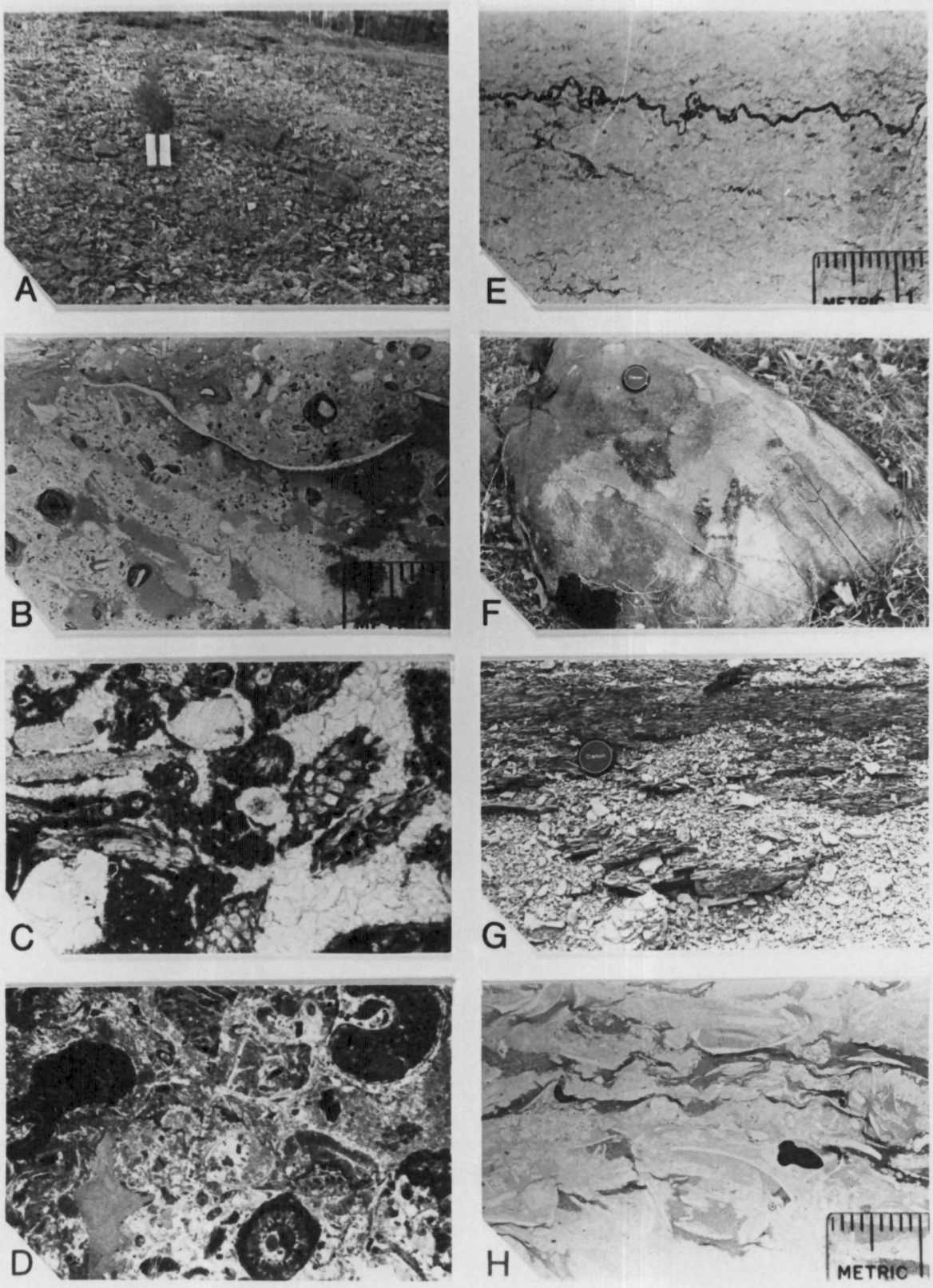


Figure 2-6.

Macurdablastus uniplicatus Broadhead, T. W. Broadhead, pers. comm., 1982), trilobites (Isotelus, Bumastus, Nanillaenus, Ceraurinella, Cybeloides, Dolichoharpes, Sphaerexochus, Encrinurus, and Calyptaulax, Maitland, 1979), trilobite fragments, ostracode valves, and braching (up to 6 cm) and encrusting bryozoans. Thin sections from the base and the top of the unit were point counted and allochems (in ascending stratigraphic order) consist of echinoderms (15.3 - 10%), unidentifiable material (4 - 15.6%), Girvanella (1.6 - 9%), cryptostomes (7.1 - 3.6%), trepostomes (5.3 - 3.3%), brachiopods (0.8 - 4.8%), trilobites (2.4 - 0.9%), bivalves (0.8 - 2.1%), gastropods (1.2%, upper interval only), ostracodes (1.1 - 0.6%), and ($<1\%$) Solenopora (type R), Nuia, Contexta, Kazakhstanelia, and Hedstroemia. Micrite accounts for 23.5 - 14.7%, microspar accounts for 15.3 - 29%, and spar constitutes 21.4 - 3.3%.

Girvanella is extremely prominent and occurs as oncolites ($\sim$3.1 mm, Fig. 2-6B), spheroidal clasts (up to 5.3 mm), lens shaped laminations (up to 5.3 mm) and muddy-appearing laminations which trapped other allochems and sediment. Oncolite nuclei include mollusc, echinoderm, brachiopod and trilobite fragments, and even other algae such as Girvanella clasts, Nuia and Hedstroemia. By far, the greatest preference for nucleation is with bryozoan debris; approximately 85% of cryptostomes are encrusted (Fig. 2-6C). The percentage of Girvanella increases substantially throughout the upper 2.8 meters of the unit and reaches a maximum ($\sim$15%) approximately 41 meters above the base of the Benbolt. Contexta and Kazakhstanelia (in probable life position) are also sparsely present. Fragmentation and abrasion are minimal in this unit; cryptostomes, echinoderm plates, trilobite pleura and spines

and impunctate brachiopod valves are well preserved. Only Kazakhstanelia exhibits minor abrasion. Approximately 40% of the brachiopods and 75-95% of the ostracodes are articulated. Gastropods are represented by low spired, high spired, and planispired shell morphologies with shells filled with fine grained mud and fossil hash (Fig. 2-6D). Bryozoans show the strongest preference for chertification, although echinoderms and brachiopods are commonly chertified. Subhedral to euhedral dolomite rhombs are concentrated within stylocumulates.

UNIT 18. Unit 18 consists of 3.1 meters of medium gray, medium to coarse grained, moderately sorted, massively bedded (up to 1.4 m) and resistant, packstone and grainstone (Fig. 2-6E, F). This resistant unit weathers similar to the massive-resistant Rockdell Formation. Stylolites (maximum amplitude = 2.9 mm) are abundant on outcrop surfaces. These pressure solution features are similar to the well lithified, non-fitted fabric, type 1A stylolites described by Buxton and Sibley (1981) in the Alpena Limestone.

Point count percentages include echinoderms (52.6%), Girvanella clasts (10.3%), cryptostomes (5%), stylocumulate (1.8%), brachiopods (1.1%), and (< 1%) ostracodes and trilobites. Interstices consist of spar (27.4%) and microspar (1.1%). Echinoderm plates exhibit low to moderate abrasion, while ostracode articulation remains in the 45-65% range. Micrite, absent in the interstitial areas, effectively coats and replaces as micrite envelopes ostracodes and cryptostomes.

UNIT 19. Unit 19 consists of 8.9 meters of shaly calcareous mudstone. Field exposure of this unit is poor and the shales weather

much in the same manner as the shales of the Fleanor Member of the Lincolnshire Formation. Rarely, small (2 x 30 cm) fossiliferous cobbles weather out. Fossils include braching and encrusting bryozoans, brachiopods, and echinoderms. Most of the unit is covered; no thin sections were made.

UNIT 20. Unit 20 consists of 21.5 meters of medium to dark gray, medium to coarse grained, poorly sorted, biomicrite (packstone) slabs (1-4 cm) interbedded with shale. The weathering of the shale produces the tabular packstone sets ($\sim$17.5 cm wide by several meters length) which becomes progressively more cobbly near the top of the unit. Constituents include algal clasts (23.9%), cryptostomes (12.7%), echinoderms (8.8%), unidentifiable material (8.1%), trilobites (3.4%), gastropods (2.3%), (2.1% each) bivalves, brachiopods, Kazakhstanelia and Girvanella oncolites, Contexta (1.6%), (1.3%) ostracodes and isolated Girvanella tubules, and ($<$1%) sponge spicules and Vermiporella. Stylocumulate account for 2.3% volume while micrite and spar constitute 22.1% and 2.3% volume, respectively.

Girvanella commonly encrusts fossil allochems, as well as other algae such as Hedstroemia, Kazakhstanelia, Contexta and Girvanella. Hedstroemia and Nuia, although not abundant, are present as small clumps and single unabraded grains, respectively. Both Kazakhstanelia and Vermiporella were observed in thin section in both longitudinal and oblique views with elongation perpendicular to bedding (probably life position), and Contexta occurs in thin section as transverse cuts. Algal derived peloids are common throughout the unit and generally are compacted sufficiently to yield a grumuleuse fabric. Furthermore,

many oval peloids (~0.48 mm x 0.2 mm) which are concentrated into thin layers suggest fecal pellet origins.

Sponge spicules (largest = 1.1 mm x 0.03 mm) are sporadically present whereas articulate brachiopods, represented by impunctate, pseudopunctate, and punctate varieties, are abundant. Ostracode articulation varies from ~40% in the lower intervals to virtually 100% in the upper intervals. Gastropods are mud filled, and trilobites consist of spines and unbroken doublures. Fragmentation and abrasion intensities vary throughout the unit; however, abrasion tends to be minimal in the lower intervals of the unit and greatest in the upper. The only non-abraded allochems of the upper intervals are those "cushioned" by Girvanella encrustation.

UNIT 21. Unit 21 consists of 4.5 meters of tan to light brown, well sorted, fine grained, very thinly bedded (2-3 cm), calcareous shale and dismicrite. The shale weathers easily into thin chips (1 x 6 mm, Fig. 2-6G, p. 54). Peloids (0.01 mm) and horizontal burrows characterize the lithology. Small scale compaction is indicated by the misalignment of terrigenous clay drapes.

UNIT 22. Unit 22 consists of 8.4 meters of medium gray, medium to coarse grained, cobbly (3 x 30 cm), interbedded calcerous mudstone, and biomicrite and biosparite (packstone). The cobbly weathering pattern is similar to that of units 17 and 20. Constituents include cryptostomes (13.7%), trepostomes (12.6%), echinoderms (9.9%), brachiopods (6.7%), dolomite rhombs (6.2%), and trilobites (4.3%). Interstices contain micrite (36.7%), spar (7.5%), and microspar (2.4%).

Fragmentation and abrasion are low for the unit; cryptostomes are delicately preserved. Furthermore, bryozoan apertures and the interior of convex up brachiopod valves contain fine grained mud fills (Fig. 2-6H, p. 54). Compaction of allochems is indicated by crosscut (stylolitized) brachiopod valves. Matrix consists of pure micrite with hummocky layers (0.5-4.7 mm thick) of terrigenous clay. Subhedral and euhedral dolomite rhombs are common throughout the unit.

PALEOENVIRONMENTAL INTERPRETATION OF THE BENBOLT FORMATION

The Benbolt Formation represents deposition in a shallow subtidal environment which was occasionally interrupted by influxes of terrigenous clastic sediments and migration of tidal channels. The lower units of the formation reflect shallow, but rather quiet water sedimentation. This is evident in units 16 and 17 by the presence of matrix forming Girvanella tubules, which Moore (1978) stated are a common component of restricted water, lagoonal mudflats. Micrite is prominent both in interstitial areas, and in mud filled fossils (e.g. gastropods). The fact that most fossil fragments are severely abraded in such "quiet water" micrite rich environments, may be attributed to biological, as opposed to mechanical, breakdown (Swinchatt, 1965). These quiet lagoonal muds were subject to migrating tidal channels and shoaling periods however.

The middle units (17 and 18) reflect deposition in agitated water. Oncolites are pervasive in unit 17 and are similar to the concentrically and randomly stacked spheroidal (type Ss; modes "C"

and "R") structures described by Logan et al. (1964) which are a product of low intertidal, agitated, depositional regimes. These shoaling conditions are similar to those found in near reef areas, nearshore shoaling areas, patch reefs, or tidal channels.

Unit 18 is distinctive in field exposures as a result of its resistance to weathering; it corresponds to Member "a" of Harris and Mixon (1970) and has also been recognized at Evans Ferry (Sickafoose, 1979, p. 58). This echinoderm grainstone reflects washing of the sediment that removed micrite, and may reflect tidal channel sedimentation. Furthermore, Sickafoose (1979, p. 67) observed bidirectional cross-bedding in the Evans Ferry grainstone which implied deposition by tidal currents; depositional features such as cross-bedding are not evident in unit 18 at Stanley Farm.

Units 19-21 reflect the influx of fine grained terrigenous clastic sediments. For the most part, the environmental conditions of these mudstones were probably too harsh for most macrobiota, however, a few interbedded horizons of biosparite exhibit prolific brachiopod and echinoderm assemblages. Horizontal burrows indicate the presence of detritus feeders. The upper unit (22) of the Benbolt once again exhibits quiet water sedimentation as is evidenced by micrite in interstitial areas, bryozoan apertures and beneath convex up brachiopod valves. In addition, low levels of fragmentation and abrasion suggest little water movement. Furthermore, the lack of algae in these intervals probably reflects turbid water conditions. Minor compaction is indicated by the presence of stylolitized brachiopod valves. As a result, the Benbolt Formation is interpreted to reflect terrigenous

clastic influenced restricted shelf (lagoonal) sedimentation which was locally interrupted by migration of tidal channels and shoaling areas.

VII. WARDELL FORMATION

The Wardell Formation overlies the Benbolt Formation, underlies the Bowen Formation, and represents 4 units (23-26) for a total thickness of 56.4 meters. The formation is exposed along the southeast side of Raccoon Valley Road on the lower northern slope of Bullrun Ridge (Fig. 1-3, p. 5). The Wardell is the most poorly exposed formation in the Stanley Farm Section; consequently, the division of the formation into units was achieved primarily through thin section analysis, and secondarily by means of available outcrops. The contact of the Wardell is marked by the abrupt absence of the cobbly limestones and shales characteristic of the Benbolt, and by the appearance of more massive, evenly bedded micrite mudstones. The mudstones are resistant to weathering; consequently, a prominent low ridge marks the contact. Neither the Gratton Limestone (Prouty, 1946), located between the Benbolt and Wardell Formations, nor the 40 cm thick Girvanella oncolite bed used by Sickafoose (1979) to delineate the Benbolt-Wardell contact is present at the Stanley Farm Section.

UNIT 23. Unit 23 consists of 29 meters of light to medium gray, fine to coarse grained, medium bedded (15-30 cm) biomicrite (mudstone), and biosparite (packstone and grainstone). Fossils observed on outcrop include recrystallized orthoconic cephalopods and gastropods, large (up to 6.5 cm) trepostome bryozoans, and trilobite fragments. Also visible in outcrop are stylolites and shale drapes.

Thin section constituents include unidentifiable fossil material (20%), echinoderms (6.8%), bivalves (5.6%), brachiopods (2.1%), cryptostomes (1.5%), Girvanella clumps (1.2%), and (<1%) trilobites and ostracodes. Micrite (41.8%) and microspar (19.7%) fill the interstices. Though algae are present at the base of the Wardell, they are absent a few meters above the contact. This trend is probably a reflection of very rapidly changing water energy and turbidity. Girvanella is primarily present as oncolites and single layered encrustations, although it is also secondarily present as clumps and isolated tubules. The dominant oncolite nuclei consist of brachiopod fragments and cryptostomes. Single Nuia and Hedstroemia grains are rarely present. Sponges are represented by spicules, and by complete recrystallized specimens with mud filled interiors (Fig. 2-7A). Curved disarticulated valves, such as ostracodes and brachiopods, are oriented concave up and contain mud fills.

The upper 17.6 meters of the unit exhibit an increase in both the percentage and size of peloids. The lower most 11.6 meters contain 5-10% micropeloids ($\sim$0.05 mm) while the upper 6 meters include up to 45% peloids, approximately twice the size of the micropeloids, arranged in thin ($\sim$1 mm) sparry bands. The combination of these sparry bands, concentrated peloids, and small incipient stylolites produces a faint lamination.

Fragmentation and abrasion are of extremely low intensity in the middle and upper intervals of the unit; trilobites, sponges, and cryptostomes are exquisitely preserved. In contrast, 70-95% of fossil allochems near the base of the unit are abraded, indicative of increasing

Figure 2-7. Photomicrographs, thin section photographs, and field photographs of the Wardell and Bowen Formations.

A. Thin section showing mudstone/wackestone of unit 23 in the Wardell Formation. Large allochems are a recrystallized sponge, trilobite fragment, and a mollusc fragment (W-6).

B. Photomicrograph showing Tetradium colony in unit 24 of the Wardell Formation. Large allochem in the upper left of the photograph is the red alga Solenopora (type R of Moore, 1978) (W-29). 10X.

C. Thin section showing current or storm produced rotated laminae in unit 25 of the Wardell Formation (W-50).

D. Typical exposure of shale and wackestone of the Bowen Formation. Located on Bullrun Ridge.

E. Thin section showing burrowed wackestone containing fossil allochems in the Bowen Formation (B-3).

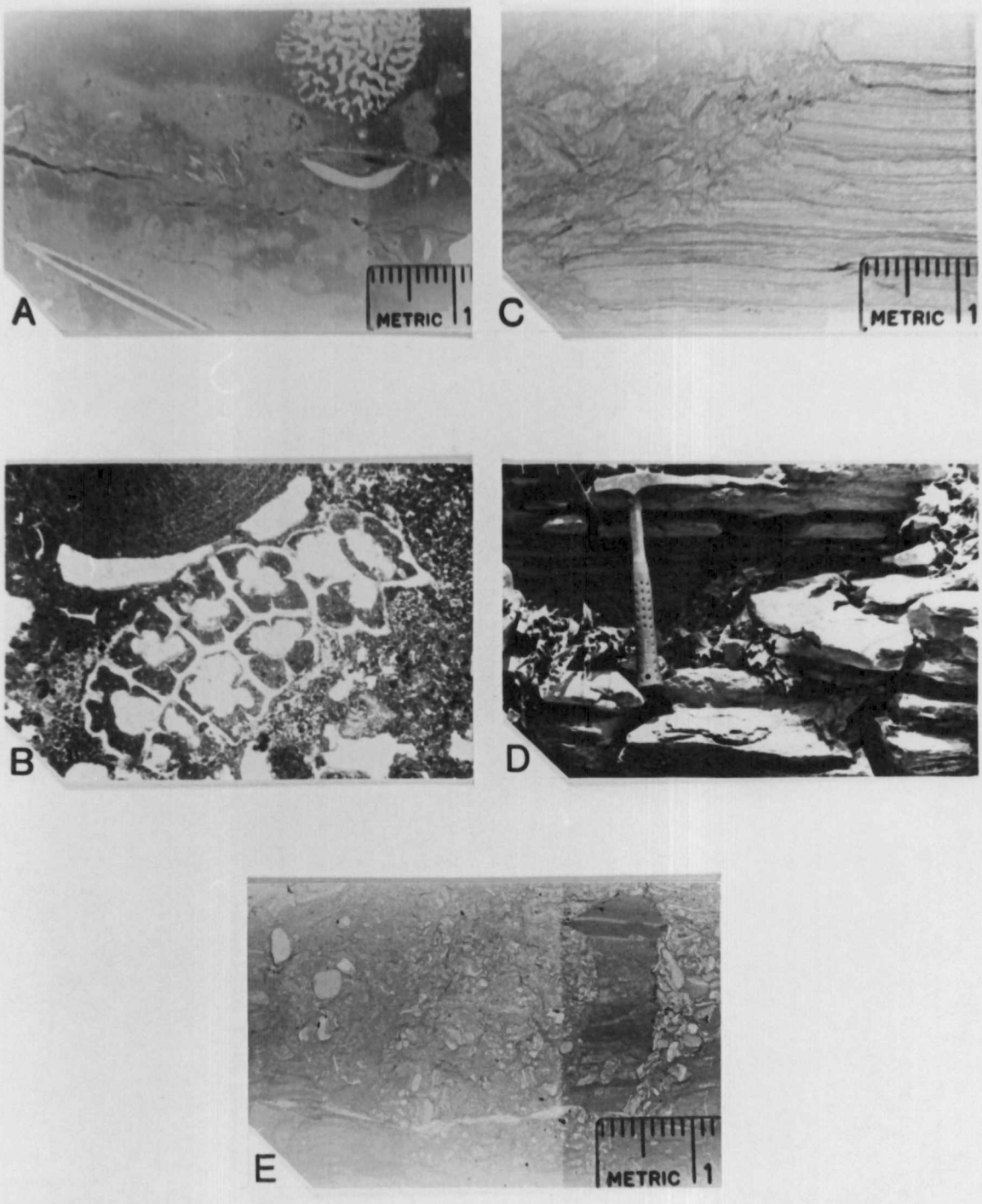


Figure 2-7.

water energy or biotic degradation from Benbolt to Wardell deposition. The only unabraded allochems present in the lower intervals consist of brachiopods and gastropods which have been protected by Girvanella encrustation. Bioturbation of the micrite has produced a mottled appearance.

UNIT 24. Though mostly covered, unit 24 contains 11 meters of light gray, medium to coarse grained, poorly to medium sorted, very thin to thin bedded (2-7.5 cm), algal pelmicrite (wackestone). Constituents include peloids (15.3%), Girvanella (8.8%), Solenopora (type R) (7.5%), Tetradium (4%), unidentifiable fossil material (2.7%), ostracodes (2.4%), Hedstroemia (2%), and (< 1%) trilobites, echinoderms, and molluscs. Microspar, micrite, and spar constitute 31.5%, 15.7% and 8.8% volume. Solenopora (up to 5.1 mm), Hedstroemia (~ 3.8 mm), and Contexta (~ 0.6 mm) all appear as well preserved grains, while Girvanella occurs as clumps and oncolites. Tetradium colonies (? Tetradium cellulosum; growth form I. syringoporoides of Webby and Semeniuk, 1971) occur throughout the unit and are apparent in both transverse (Fig. 2-7B) and longitudinal views. The colony walls are recrystallized (solution-redeposition of calcite after aragonite) and, in some cases, are replaced with chalcedony. Calices are usually filled with both mud and spar. Also common are gastropods, and sponges with mud filled interiors. Peloids (~ 0.3 mm) are common and suggest derivation from both larger micrite intraclasts (up to 1.5 mm) and abraded algal clumps. In addition, the compaction of some peloids has produced a fabric which is similar in appearance to the encrusting alga Spongiostroma. Ostracodes generally exhibit high levels of

articulation (75-85%). Also common are detrital quartz grains (15-25%, average size = 0.03 mm) and dolomite rhombs (~0.1 mm).

UNIT 25. Unit 25 consists of 14 meters of light gray, fine grained, very thin to medium bedded (2.5-15 cm), peloidal dismicrite which weathers dominantly as small (4-8 cm) shaly chips. This unit is as poorly exposed as unit 24; consequently, lithologic differentiation of the two units was achieved primarily through thin section analysis. Unit 24 consists basically of algal pelmicrites whereas unit 25 consists largely of peloidal dismicrites. Solenopora (type R?) is present but due to intense abrasion and lack of algae in sufficient quantities is most likely exotic. The combination of peloids, micrite, and small incipient stylolites produces a faint lamination. In addition, a slight coarsening upward texture is present. Laminae are crinkled suggesting a cryptalgal origin. Though biogenic activity (vertical burrowing) is common throughout the unit, physical deformation is the dominant property of the rocks. Rotated, though virtually unabraded, mud clasts indicate either brief but intense current activity or storm deposition (Fig. 2-7C). Small (< 0.01 mm) dolomite rhombs are rare.

UNIT 26. Unit 26 consists of 2.4 meters of light gray, coarse grained, extremely poorly sorted, thin to medium bedded (3-25.5 cm), biomicrite (mudstone and wackestone). Like units 24 and 25, unit 26 was mainly differentiated on the basis of thin section analysis; each unit consisted, respectively, of algal pelmicrite, peloidal dismicrite, and biomicrite. Constituents include bivalves (10.5%), unidentifiable

material (5.8%), brachiopods (3.8%), ostracodes (2.6%), (1.5% each) trilobites and gastropods, and (< 1% each) echinoderms, cryptostomes, and trepostomes. Micrite (64.5%) and microspar (7.8%) comprise the remainder. Articulation is extremely high in this unit and many brachiopod valve interiors exhibit geopetal fabrics. Fragmentation and abrasion intensities are low.

PALEOENVIRONMENTAL INTERPRETATION OF THE WARDELL FORMATION

The Wardell Formation represents sedimentation in shallow, subtidal environments which were subject to fluctuations in tidal energy (causing fluctuations in water agitation), storm activity, and terrigenous clastic influx. Unit 23 exhibits a restricted shelf, less agitated regime, evidenced by the abundance of micrite, concave up (hydrodynamically unstable), mud-filled fossil shells, and presence of a well preserved biota, including sponges. The lack of algae in this unit may be attributed to either turbid water, or the biological breakdown of algae (Swinchatt, 1965), so that algae become the major source for micrite.

Unit 24 exhibits evidence of more agitation than unit 23. Oncolites, and abundant diverse algae reflect shallow, turbulent water. The presence of in situ Tetradium colonies likewise suggests fairly active water circulation. These corals, providing they were dense and abundant enough, acted as a potential baffle on the agitated water in a manner similar to modern marine rooted plants. Scoffin (1970) pointed out that dense plant roots serve as effective sediment trappers

and binders in Bimini Lagoon, Bahamas. He stated that, although macroscopic green algae and algal mats are not dense enough to trap large volumes of sediment appreciably, the roots of many marine grasses are. Furthermore, Ginsburg and Lowenstam (1958) reported that marine grasses (1) form a thin layer of "semi-motionless" water and (2) the root system acts as a sediment binder. Since density is the important factor, a large mass of Tetradium, or numerous closely associated small colonies, could effectively baffle marine currents and trap sediment. Hill (1981) reported that Ordovician Tabulata are found in shallow, subtidal, level bottom communities on carbonate platforms. Moore (1978) stated that the concentration of algae, described here, along with pelletal muds are often indicative of (restricted shelf) lagoonal mudbanks. The detrital quartz present in unit 24 most likely reflects sediments derived from the infringing southeastern terrigenous clastic source, described by Benedict and Walker (1978).

Units 25-26 further exhibit shallow, subtidal, wave active regimes. Cryptalgal laminations, storm produced soft sediment deformation (Walker, 1974), and vertical burrows (Rhoads, 1975), all indicate shallow water, above tide level down to $\sim$10 meters water depth (Benedict and Walker, 1978), near shore, fairly restricted water environments.

VIII. BOWEN FORMATION

The Bowen Formation overlies the Wardell Formation, underlies the Witten Formation, and represents one unit (27) with a total

thickness of 5.8 meters. The formation is poorly exposed on the north side of Bullrun Ridge (Fig. 1-3, p. 5) southeast of Raccoon Valley Road, however, it is well exposed along a small gully which runs perpendicular to the ridge. The contact of the Bowen is denoted by the change upward from purer micritic, peloidal rich, mudstone and wackestone of the Wardell to tan to yellow brown calcareous mudstone and shale.

UNIT 27. Unit 27 consists of 5.8 meters of tan to yellow brown, thin to medium bedded (2-15 cm), calcareous shale and silty wackestone (Fig. 2-7D, p. 64). Bioturbation is slightly evident on outcrop but especially so on cut slab surfaces. Exotic allochems in this unit consist of Solenopora (type P) (up to 3.4 mm), Girvanella oncolites (6.7 mm), and fragments of inarticulate phosphatic and articulate brachiopods, cryptostomes, trepostomes, gastropods, echinoderms, ostracodes, trilobites, intraclasts, peloids, and detrital quartz grains. All of the quartz grains occur in vertical burrows (Fig. 2-7E, p. 64). They apparently filtered down into the burrows subsequent to biogenic activity. Previous workers have also observed that the Bowen is virtually fossil free (except for burrows). Fine grained detrital quartz (10-15%), small clay drapes, and small incipient stylolites produce faint lamination.

PALEOENVIRONMENTAL INTERPRETATION OF THE BOWEN FORMATION

The Bowen Formation represents shallow water, terrigenous clastic-influenced deposition in the Middle Ordovician which reflects the encroaching southeastern sediment basin infill described by Benedict

and Walker (1978). The presence of vertical burrows implies shallow water (Rhoads, 1967, 1975) such as in intertidal to shallow subtidal areas. Furthermore, the lack of an indigenous calcareous biota implies that carbonate deposition was deterred by the presence of terrigenous clastic detrital quartz and clays.

The allochems present in the vertical burrows probably were derived from a nearby environment and transported into Bowen regimes by storms and intense tidal activity. Infill of the burrows most likely occurred during the burrowing process, or very soon afterwards. The environment from which the allochems were derived consisted of a subtidal, shallow, current active area as evidenced by the presence of Solenopora (type P) biscuits and Girvanella oncolites, both of which indicate agitated water (Moore, 1978). Peloids and a diverse eurytopic biota are also present and, according to Laporte (1967), indicate a subtidal facies.

IX. WITTEN FORMATION

The Witten Formation overlies the Bowen Formation, underlies the Moccasin Formation, and represents 4 units (28-31) for a total thickness of 93 meters. The formation is fairly well exposed in a gully which runs perpendicular to, and up the north side of, Bullrun Ridge (Fig. 1-3, p. 5). The rocks cocsist of dismicrite and biopelsparite (mudstone, wackestone, and packstone). The contact of the formation with the lower Bowen is denoted by the change from tan to yellow brown terrigenous clastic mudrocks of the lower unit, to the light brown gray to medium gray carbonate rocks of the Witten. The Moccasin

Formation, which overlies the Witten, is characterized by red and yellow terrigenous clastic mudrocks (Cooper, 1956). At the actual contact, the rocks exhibit a greenish color, and are represented by medium to thick bedded (0.25 - 0.6 m) carcareous shales and silty calcarenites. The position of the contact was chosen at the first appearance of these red and green mudrocks. The Moccasin Formation, truncated to the southeast by the Copper Creek Fault, comprises the remainder of the Middle Ordovician sequence on Bullrun Ridge, however, the formation was not measured and described in this study.

UNIT 28. Unit 28 consists of 12 meters of light to medium gray, fine (near the base only) to very coarse grained, thinly bedded (2-5 cm), dismicrite, biomicrite, and pelbiosparite (wackestone and grainstone). Fossils are extremely prevalent on outcrop. Constituents of unit 28 include peloids (26%), brachiopods (10.7%), unidentifiable fossil material (5.2%), echinoderms (2.4%), (1.8% each) ostracodes and trilobites, and ($<$1% each) cryptostomes and Hedstroemia. Interstitial areas contain spar (39.5%), micrite (9.8%), and ($<$ 1%) microspar. Unit 28 contains the most abundant brachiopod fauna observed in the entire section. Essentially all brachiopods are well preserved (non-abraded and nonfragmented), are rather large (up to 20.8 mm), but are disarticulated, and oriented parallel to bedding ($\sim$70% convex up); many are replaced by chalcedony. 75-80% of the ostracodes are disarticulated.

Desiccation cracks are common and most exhibit a subsequent infilling of fossil fragments. Although micrite mud is abundant in

the unit, much of the "muddy material" is "pseudomatrix" formed through close packing and compaction of peloids. Differentiation between the two is often impossible.

UNIT 29. Unit 29 consists of 31 meters of medium gray, fine to coarse grained, thick bedded (up to 1 m) and resistant dismicrite and biomicrite (mudstone and wackestone, Fig. 2-8A). The lower intervals (12-28 m) are predominantly thick bedded (up to 1 m) while the upper intervals (28 to 43 m) are thinly bedded (2.5 to 10 cm). Constituents include peloids (12.5%), trilobites (2.6%), trepostomes (2%), and (< 1% each) bivalves, brachiopods, echinoderms, ostracodes, cryptostomes, and gastropods. Micrite (70.2%) and spar (9.9%) fill the interstices.

Bioturbation is the most prominent feature of unit 29, evidenced by mottling. Horizontal burrows are characterized by two zones; an inner mud zone delineates the actual zone of burrowing, while an outer peripherial microspar zone delineates changes in the chemistry of mud matrix surrounding the burrow (Fig. 2-8B, see Rhoads, 1975). Most burrows contain euhedral dolomite rhombs. Although these rocks are basically dismicrites, well preserved fossil-rich zones are prevalent, and are set off from the fine grained mud zones by stylolites. The allochems of unit 29, especially the bryozoans and trilobites, are the least abraded and fragmented, and best preserved in the entire section. Molluscs generally are recrystallized (solution-reprecipitation of calcite after aragonite), and ostracodes are highly (75-85%) articulated.

Figure 2-8. Thin section photographs and field photographs of the Witten Formation.

A. Outcrop of unit 29 of the Witten Formation. Located on Bullrun Ridge.

B. Thin section showing mottled biomicrite, produced from bioturbation (Wi-36).

C. Thin section showing scoured surface, fining upward peloidal sequence, and transverse sections through four horizontal burrows in unit 30 of the Witten Formation. Large allochem at the bottom center of the photograph is a gastropod (Wi-44).

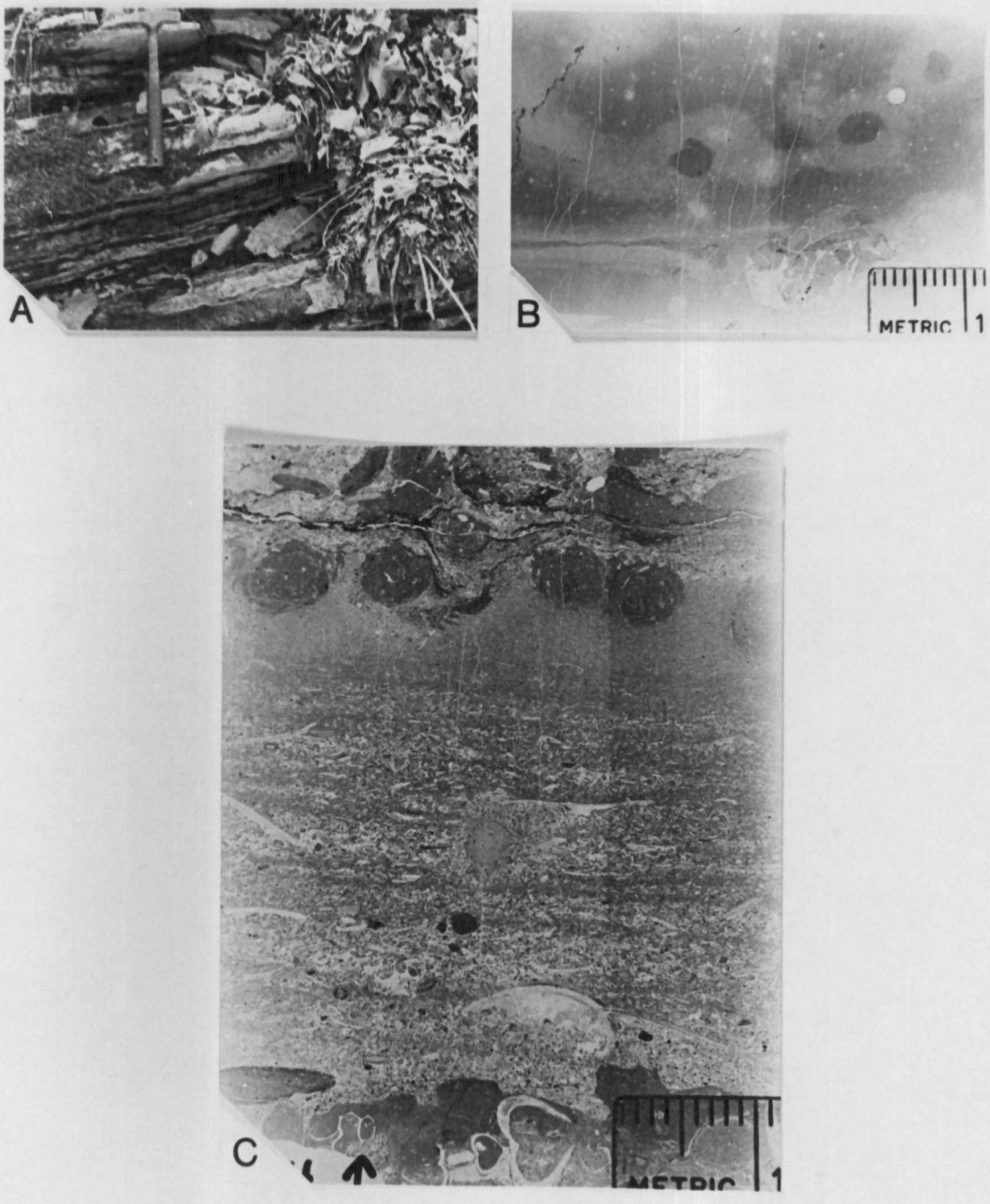


Figure 2-8.

UNIT 30. Unit 30 consists of 44 meters of medium gray, fine to very coarse grained, extremely poorly sorted, thinly bedded (~ 5 cm), cobbly, interbedded dismicrite and biopelsparite (mudstone and packstone). The lower 17 meters of the unit are poorly exposed along a path on Bullrun Ridge, however, the upper 27 meters of the unit are well exposed in a gulley along the north side of the ridge (Fig. 1-3, p. 5). Point counts of thin sections from the lower (~ 44 m) and upper (~ 78 m) intervals of the unit show constituents of peloids (61.1 - 27.5%, in ascending stratigraphic order), echinoderms (3.5 - 10.2%), brachiopods (3.5 - 8.8%), bivalves (6.5%, U), unidentifiable material (3.5 - 5.4%), dolomite rhombs (5.1 - 2.5%), trilobites (3.2 - 2.3%), and (< 1% each) ostracodes, bryozoans, intraclasts, and Solenopora (type R). Spar is the dominant interstitial component (11.3 - 34%), while micrite (7.4 - 0.6%) and microspar (< 1%) are rare. Small (1.3 mm) Solenopora (type R) grains and small incomplete micrite rinds are rarely present. Bioturbation in the dismicrites is almost as intense as that found in unit 29; both vertical and horizontal burrows are present. Abrasion and fragmentation are low; cryptostomes reach lengths of 10.3 mm displaying virtually no breakage or abrasion. Peloids constitute as much as 90% of the allochems in some samples, and may be represented by one size (~ 0.2 mm), or by a spectrum of sizes from intraclasts (up to 2.4 mm) down to the smallest peloids (< 0.03 mm). Possible peloidal precursors include eroded algal grains, eroded intraclasts, and fecal pellets. Fining upward sequences of peloids are also common.

One sample (Fig. 2-8C) exhibits a horizon of large fossils (~ 7.2 mm) sharply overlain by smaller fossils and peloids (0.2 - 0.4

mm). These peloids gradually fine upward to a minimum size of approximately 0.03 mm. Within this upper micropeloidal horizon are horizontal mud filled burrows. The entire sequence is sharply overlain by much larger (up to 13.6 mm) fossil fragments, burrows, and interclasts.

Fine layering in some samples results from the concentration of brachiopods (~22.5 mm) in planar layers (~2 mm thick) between the more peloidal horizons. Most (75 - 80%) have a concave-up orientation. Dolomite is abundant in the upper intervals of the unit and seems to be prevalent within, or very near, well preserved brachiopod shells. Its formation appears to have been by secondary replacement, as many of the euhedral rhombs are located within the syntaxial spar overgrowths of echinoderm fragments.

UNIT 31. Unit 31 consists of 6 meters of light gray to medium gray to green, extremely fine grained, thin to medium bedded (2 - 20.5 cm) dismicrite (calcareous mudstone). These fenestral mudstones contain both horizontal (planar) birdseyes, which follow relict bedding planes, and vertical (vuglike) birdseyes. It is not possible to determine whether the fenestrae of these dismicrites formed as a result of cryptalgal activity, bioturbation, or desiccation. At the contact with the Moccasin Formation, red and green calcareous mudstones and red terrigenous clastic mudstones become prevalent.

PALEOENVIRONMENTAL INTERPRETATION OF THE WITTEN FORMATION

The Witten Formation reflects subtidal, shallow water deposition in the lower units (28 - 30), and subtidal to shallow intertidal conditions at the top (31). Units 28, 29, and the lower intervals of 30 exhibit evidence of subtidal deposition, such as abundant micrite, horizontal burrows (which Rhoads (1967, 1975) stated are more common in shallow, subtidal environments), and lack of fragmentation and abrasion. Fossils filling the desiccation cracks are also well preserved. Furthermore, the lack of birdseyes, restricted biota, and other fabrics indicative of subaerial exposure, suggest subtidal deposition. Shallowing conditions do occur, however, near the Witten-Moccasin contact.

The upper intervals of unit 30, and unit 31 exhibit fluctuations in current energy, as evidenced by fining upward peloidal mudstones, scoured surfaces, increased intensities of abrasion and fragmentation, increased abundance of vertical burrows, lack of algae, and numerous fenestral features, including both planar and vuglike birdseyes (Shinn, 1968). These conditions indicate environments subject to fluctuations in water energy such as shallow subtidal to intertidal regimes.

CHAPTER III

STRATIGRAPHIC RELATIONSHIPS OF THE LINCOLNSHIRE FORMATION

Cooper and Prouty (1943) named and described the Lincolnshire Formation for 40 to 100 feet of dark, granular, cherty limestone in the quarry on Lincolnshire Branch, west of Five Oaks, Virginia. In Tennessee, within Clinch Valley, Beaver Valley, and Hogskin Valley, the Lincolnshire Formation can be differentiated into two members: Eidson cherty limestone and Hogskin shale (Cooper, 1956). The Eidson Member (Cooper and Cooper, 1946) is characterized by thin bedded, dark limestone containing black chert underlying the Hogskin Member (Cooper and Cooper, 1946) which consists of yellow-weathering shale and cobbly limestone. Cooper (1956) stated that the Hogskin Member was correlative to the Lincolnshire Formation of Cooper and Prouty (1943) and represented it to the south and west.

The Stanley Farm Section is located in Raccoon Valley (also referred to as Hogskin Valley; Hunter Valley Allochthon) and recognition of the Eidson and Hogskin Members is possible. The Eidson Member at Stanley Farm (Fig. 3-1A) is characterized by biomicrite and biosparite (packstone and grainstone), and algal-bryozoan boundstone interbedded with pods and lenses of red and black chert. The Hogskin Member (Fig. 3-1B) consists of dismicrite, quartz siltstone, biomicrite (wackestone), and pelbiomicrite (packstone) interbedded with thiner bedded terrigenous siltstone and calcareous shale.

Occurring between the Eidson and Hogskin Members at Stanley Farm is the Fleanor Member (Fig. 3-1C), a sequence of interbedded

Figure 3-1. Field photographs of the Lincolnshire Formation (Eidson Fleanor, and Hogskin Members).

A. Eidson Member showing interbedded biomicrite and biosparite, and pods and lenses of red and black chert.

B. Hogskin Member showing interbedded siltstone, dismicrite, biomicrite, and pelbiomicrite.

C. Fleanor Member showing interbedded yellow and maroon shale, thin shaly limestone, and siltstone.

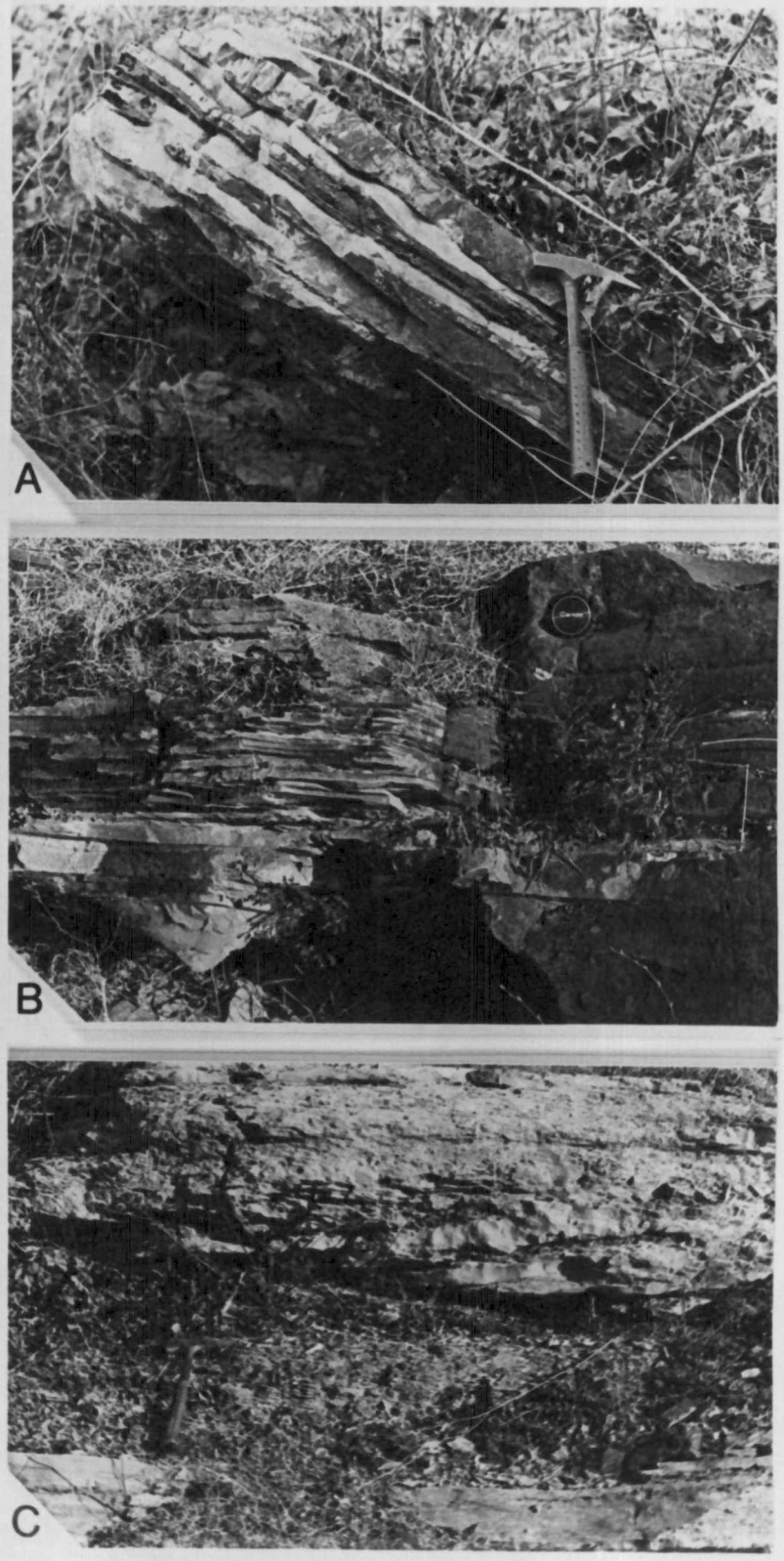


Figure 3-1.

yellow and red shale, thin shaly limestone and siltstone. The Fleanor was originally designated as a formation by Cooper and Cooper (1946) for about 200 feet of maroon and red shale, thin gray limestones, siltstone, and calcarenite on a farm lane along Foster Branch near Fleanor Mill, Tennessee (Cooper, 1956). The type section has subsequently been destroyed by highway construction. Cooper (1956) stated that the sparse fossil assemblage found in the Fleanor indicated correlation with the Hogskin Member of the Lincolnshire Formation.

The lithologies and sedimentary structures of the Fleanor and Hogskin Members are, in many respects, similar. Both members are characterized by interbedded siltstone, biomicrite and biosparite (wackestone and packstone), and light brown to maroon calcareous shale, thin bedded siltstone and dismicrite. Percentage detrital quartz ranges up to 45% in the Fleanor Member and up to 50% in the Hogskin although the Fleanor has a much higher terrigenous clay content. Syndepositional sedimentary features common to both members include small scale trough crossbedding (1-5 cm in the Hogskin Member and up to 10 cm in the Fleanor Member), overturned silt beds (most common in the Hogskin), and storm produced rotated micritic intraclasts (most common in the Fleanor). Vertical and horizontal burrows, interlaminar birdseyes, and subtidal, shallow water produced algal oncolites are also common in both members. Even though the Hogskin becomes less terrigenous rich near the top, lithologic similarities have almost certainly resulted in misidentification in many areas (e.g. Breland, 1980; Weiss, 1981) where these upper members are poorly exposed.

In contrast, the lithologies of the Fleanor and Eidson Members differ completely. The upper 4.4 meters of the Eidson consist of algal-bryozoan boundstone which, at the Eidson-Fleanor contact, is effectively smothered by the introduction of Fleanor terrigenous silt and clay. Consequently, the onset of Fleanor terrigenous clastic deposition most likely occurred very rapidly.

As a result of the stratigraphic position of the Fleanor relative to the underlying Eidson Member and overlying Hogskin Member, and because of the lithologic similarity between the Fleanor and Hogskin, the Fleanor at the Stanley Farm Section is regarded as a member of the Lincolnshire Formation and not as a separate formation as originally suggested by Cooper (1956).

Lithologies similar to the Lincolnshire Formation have been described by previous workers in the Hunter Valley Allochthon. Unit 2 of Harvell (1954) Causey (1956), and Lomenick (1958) consist of buff to maroon, calcareous shale and silty shale, which most likely corresponds to the Fleanor and Hogskin Members at Stanley Farm. Furthermore, Unit 1 of these workers is a pure gray limestone interbedded with chert and shale, representing the Five Oaks Formation and Eidson Member of the Lincolnshire Formation, and Unit 3, massively bedded gray limestone, is equivalent to the Rockdell Formation.

At Evans Ferry, 61 km northeast of the present study area, the Lincolnshire Formation is easily differentiated into the Eidson and Hogskin Members (Sickafoose, 1979, p. 34, 44); the cobbly bedded wackestone and shale of the Hogskin directly overlies the interbedded cherty mudstones, wackestone, and grainstone of the Eidson. Formational

contacts are sharp and the lithologies do not intergrade. Furthermore, the Fleanor is not present at Evans Ferry.

At the Solway Bridge Section, 40 km southwest of the present study area (Weiss, 1981, p. 20-22), the Eidson and Hogskin Members are present and distinguishable. However, most (41.9 m) of the Lincolnshire Formation is covered; only 8.7 meters of the Eidson Member and 2 meters of the Hogskin Member are exposed. The covered 41.9 meters occur in the same relative stratigraphic position as the Fleanor Member and the lower intervals of the Hogskin Member; consequently, the Fleanor is possibly present, although covered, at Solway Bridge.

Fleanor-like (?) lithologies (yellow to yellow brown shales) are present at the Lay School Section, 30 km northeast of the present study area (Ewing, in prep., pers. comm., 1982, also measured by Carnes, 1975), however, the section is complicated by faulting (Ewing, pers. comm., 1982), resulting in possible repeated intervals. As a result, thickness of theFleanor at the Lay School Section is estimated to range from 1 to 42 meters, using the Evans Ferry and Stanley Farm Sections as (along strike) range limits.

The thickness of theFleanor varies along strike (southwest to northeast: Weiss = covered, inferred thickness = 15 m (minimum to 42 m (maximum), Harvell = 50 m, Causey = 42 m, Fleanor Mill (type section) $\sim$ 61 m, Lomenick = 32 m, Ashworth = 42 m, Ewing = unknown because of stratigraphic faulting, inferred thickness = 1 to 42 m (maximum), Sickafoose = Fleanor absent) and exhibits a lens shaped stratigraphic appearance (Figs. 3-2, 3-3). This appearance coupled with the lithologic character suggests that Fleanor deposition occurred

Figure 3-2. Fence diagram of the Lower Middle Ordovician of East Tennessee. Vertical exaggeration = 59X.

(W) Weiss (1980)
(H) Harvell (1954)
Five Oaks = "lower 1/4 of unit I"
Eidson = "upper 3/4 of unit I"
Fleanor = unit II
Hogskin = "lower portion of unit III"
Rockdell = "upper portion of unit III"
Benbolt = unit IV
Cs) Causey (1956)
Five Oaks = "lower 1/4 of unit I"
Eidson = "upper 3/4 of unit I"
Fleanor = "lower 3/4 of unit II"
Hogskin = "upper 1/4 of unit II"
Rockdell = unit III
Benbolt = unit IV
(FM) Fleanor Mill - type section
(L) Lomenick (1958)
Five Oaks = "lower 1/3 of unit I"
Eidson = "upper 2/3 of unit I"
Fleanor = "lower 2/3 of unit II"
Hogskin = "upper 1/3 of unit II = subunit IIA"
Rockdell = unit III
Benbolt = unit IV
(A) Ashworth (1982)
(E) Ewing (in prep.)
(Ca) Carnes (1975)
(S) Sickafoose (1979)
(B) Breland (1980)
dg = Dry Gap Section
hc = Halls Crossroads Section
g = Graveston Section

Blackened intervals represent covered intervals.

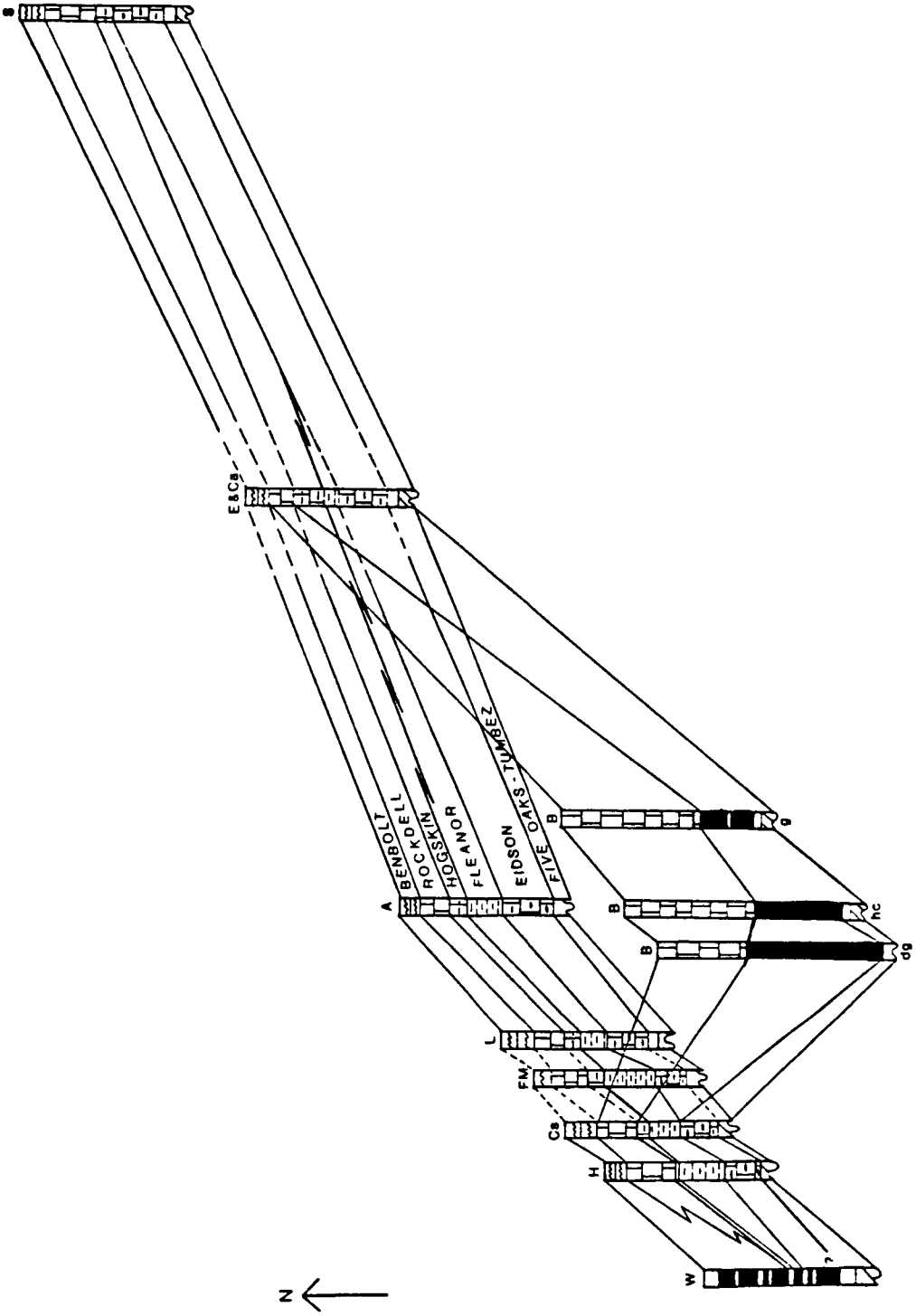

E&Ca
BENBOLT
ROCKDELL
HOGSKIN
FLEANOR
EIDSON
FIVE OAKS-TUMBEZ
A
B
B
B
hc
dg
L
FM
Ca
H
W
N

Figure 3-2.

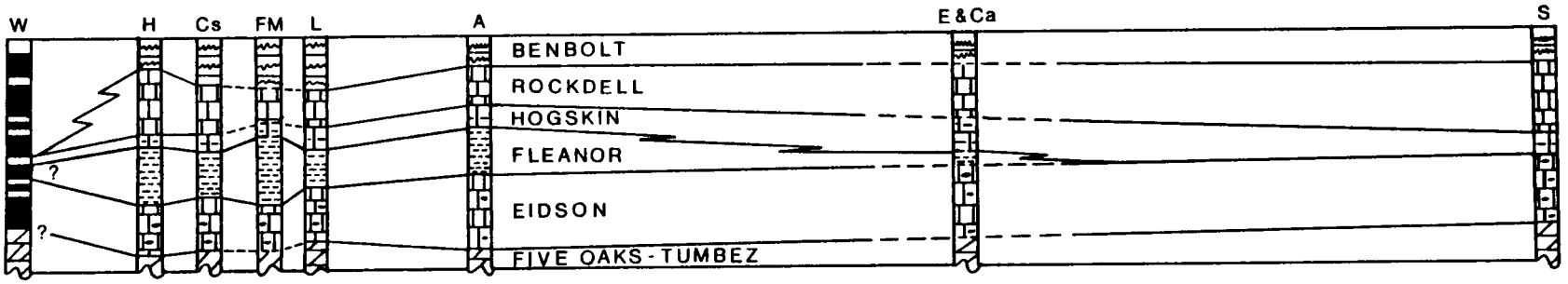


Figure 3-3. Stratigraphic cross-section of the Lower Middle Ordovician, Hunter Valley Allochthon. Blackened intervals represent covered intervals. Vertical exaggeration = 59X.

(W) Weiss (1980)
(H) Harvell (1954)
(Cs) Causey (1956)
(FM) Fleanor Mill-type section
(L) Lomenick (1958)
(A) Ashworth (1982)
(E) Ewing (in prep.)
(Ca) Carnes (1975)
(S) Sickafoose (1979)

in a carbonate regime which was periodically interrupted by influxes of terrigenous clastics via a delivery mechanism such as migrating fluvial channels in a deltaic setting. Breland (1980) reported Fleanor lithologies in Beaver Valley (covered thicknesses ranging from 154 m at Dry Gap Section to 99 m at Halls Crossroads Section; much of the covered intervals may correspond to the Hogskin Member, Fig. 3-2). Breland stated that based on the shaly nature and stratigraphic position of the lithologies with respect to the Lincolnshire Formation, the terrigenous source was to the southwest and northwest. However, the lack of Fleanor-like lithologies in the Kingston Allochthon (Borowski, in prep., and Ghazizadeh, in prep., Fig. 1-1, p. 2) suggests that either the sediment source may have been only from the northwest, or that the delta channel mouth was farther to the southeast, near the Stanley Farm area.

A similar depositional (though not climatic) setting occurs in Eastern Shark Bay, Western Australia. Davies (1970) reported that the Gascoyne and Wooramel rivers drain into Shark Bay forming small deltas. These rivers are intermittent and flow largely after heavy rainfall caused by infrequent summer cyclones or abnormal winter conditions. Terrigenous quartz and feldspar on the carbonate bank is derived from marine reworking of the river sediments. Davies reported that the percentage of terrigenous grains decreased (32-19%) from inner intertidal-zone sediments to outer intertidal-zone samples. Furthermore, some samples from terminal fans contained very high (up to 67% of total grain volume) percentages of terrigenous grains. The presence of similar terrigenous clastic quartz grains in shallow water

Fleanor siltstones, rapid deposition of the terrigenous clastic sediment over the underlying Eidson Member, lens-shaped stratigraphic configuration, and local setting suggests that Fleanor deposition may have occurred under similar conditions.

CHAPTER IV

PALEOECOLOGY OF THE BENBOLT FORMATION

I. INTRODUCTION

The Benbolt Formation consists of 95.4 meters of interbedded shale and packstone (biomicrite and biosparite), and occasional grainstone (biosparite). The weathering of the thin (1-2 cm) shale drapes around the thicker (3-6 cm) carbonate beds produces cobbly appearing outcrops. The Benbolt Formation was chosen for fossil assemblage analysis primarily because (1) the cobbly weathering pattern facilitates bedding plane sampling and (2) bedding plane exposures are extremely fossiliferous. Ten bedding planes were sampled from the formation: 7.6 m (181.9 m), 10.9 m (185.2 m), 20 m (194.3 m), 31 m (205.3 m), 39 m (213.3 m), 56 m (230.3 m), 63 m (237.3 m), 81.2 m (255.5 m), 89.1 m (263.4 m), and 95 m (269.3 m), above the base of the formation, and Knox-Five Oaks contact, respectively. No fossiliferous slab was thicker than 10 cm (average 4 cm) and bedding planes were easily traced; consequently, rocks representing very precise time intervals could be sampled in order to observe environmentally related biotic changes throughout Benbolt deposition.

A total of 52 fossiliferous slabs were collected; the number of slabs from each bedding plane varied from two (bed at 20 m) to ten (bed at 7.6 m), depending on the availability of slabs. When possible, enough slabs were collected from each bedding plane to cover an area of 0.5-1 m^2. Two acetate peels perpendicular to bedding were made of

different slabs from each bedding plane to supplement paleoenvironmental interpretations and fossil identifications. The ten bedding planes are located in four of the seven units (Chapter 2, Fig. 4-1, and Appendix A) of the Benbolt Formation: unit 17 contains the beds from 7.6 m - 39 m, unit 19 contains the bed from 56 m, unit 20 contains the beds from 63 m and 81.2 m, and unit 22 contains the beds from 89.1 m and 95 m.

Fossils were identified primarily from slab surfaces, and rarely from individual specimens, acetate peels, and thin sections. Lists of fossil assemblages from the ten bedding planes are presented in Appendix C.

Fossils on slab surfaces and individual specimens (Appendix E: Plates) were identified by the author using information in the literature, with additional assistance from T. W. Broadhead and R. E. McLaughlin. The taxonomic level to which fossils were identified depended largely on the availability of current literature and quality of preservation. Echinoderms were identified to generic and specific levels using Brower and Veinus (1974) and Breland (1980) as sources. Brachiopods and algae were identified to generic and specific levels using Cooper (1956) and Moore (1978) as references, respectively. Trilobites were identified to the generic level according to Maitland (1979). Bryozoans were identified on outcrop only by growth form and in acetate peel to ordinal level using standard paleontology texts (e.g. Beerbower, 1968, and Clarkson, 1979) as sources. Gastropods were identified as genus A, B, C, ...; each most likely represents one species of one genus. The remaining fossil specimens were identified as precisely as possible (to very broad taxonomic levels) using the

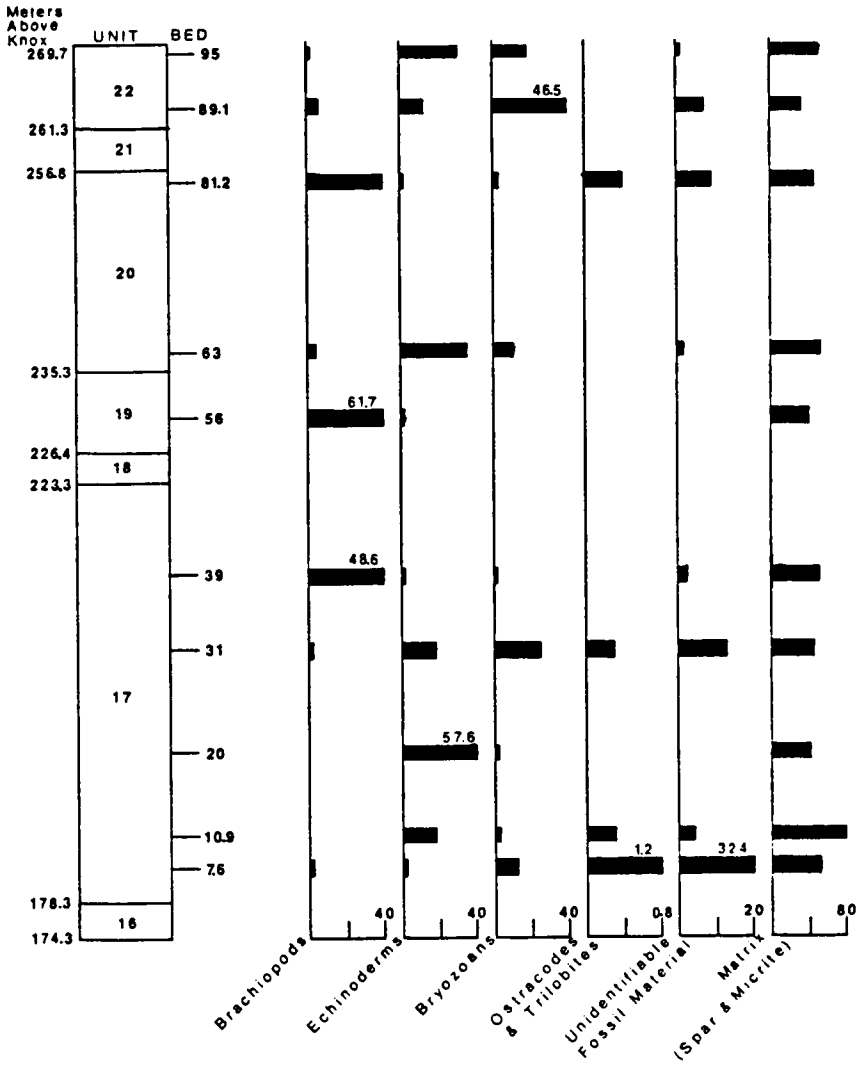


Figure 4-1. Slab surface constituent analyses of the Benbolt Formation.

available pertinent literature, including the Treatise On Invertebrate Paleontology and paleontology texts.

Interpretations of the assemblages required information on taxonomic dominance; consequently, biovolume percentages (see Walker, 1972; Ausich, 1981) were determined for each bedding plane. An acetate grid (1 cm grid spacing) was used to point count slab surfaces (described in Ausich, 1981). A total of 8,386 points was counted; the number of points for each bedding plane ranged from 287 (bed 56) to 1,266 (bed 63) with an average of 850 points per slab. Biovolume percentages were determined largely at the phylum level, and rarely at the generic level for brachiopods. Percentages for bryozoans were determined for growth form. Abundance percentages at the generic and specific level for all taxa, other than point counted brachiopods, were determined by careful visual estimation. All data are presented in Appendix D (Table D-1 and D-2). Slab surface constituent analyses, biovolume percentages, and fossil diversity are plotted in Figures 4-1, 4-2, and 4-3, respectively.

II. BEDDING PLANE

FOSSIL ASSEMBLAGE ANALYSIS

As interpreted in Chapter 2, the interbedded shale, packstone, and grainstone of the Benbolt Formation represents deposition in fairly quiet, shallow, subtidal water (restricted shelf-lagoonal regime), which was periodically interrupted by influxes of terrigenous clastic sediment and migration of tidal channels or shoaling environments.

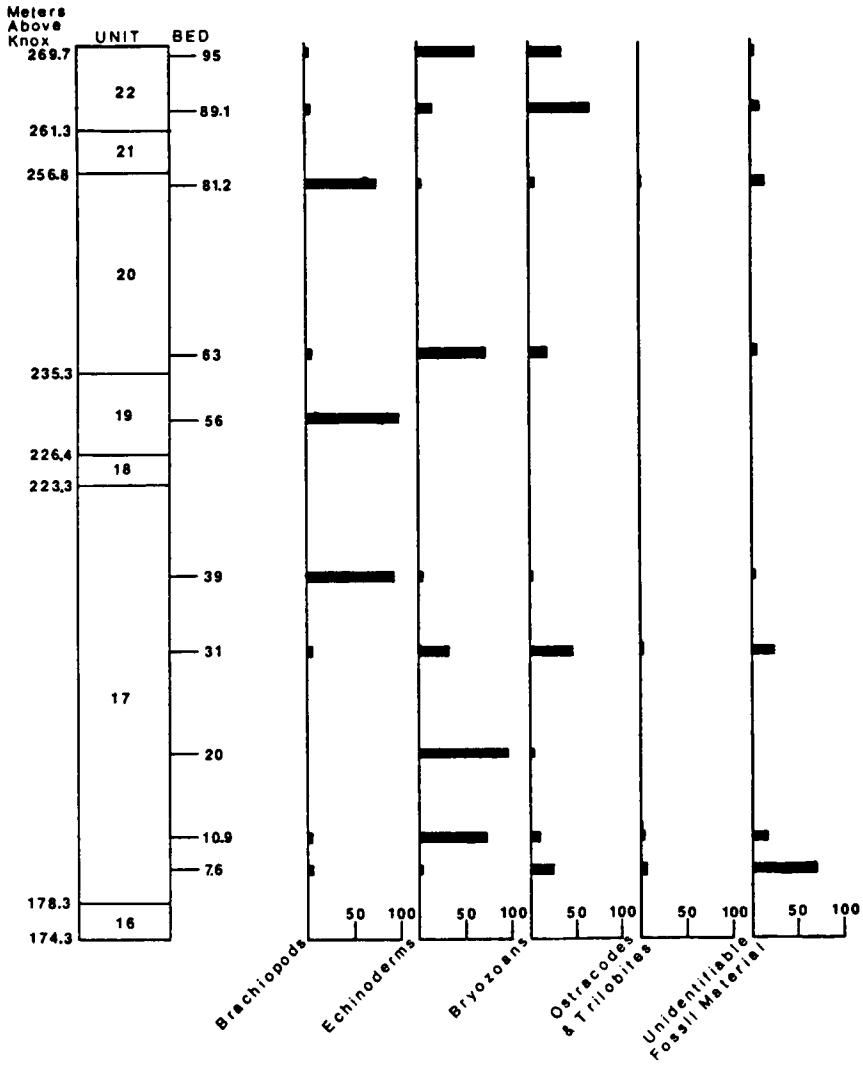


Figure 4-2. Biovolume percentages of the Benbolt Formation.

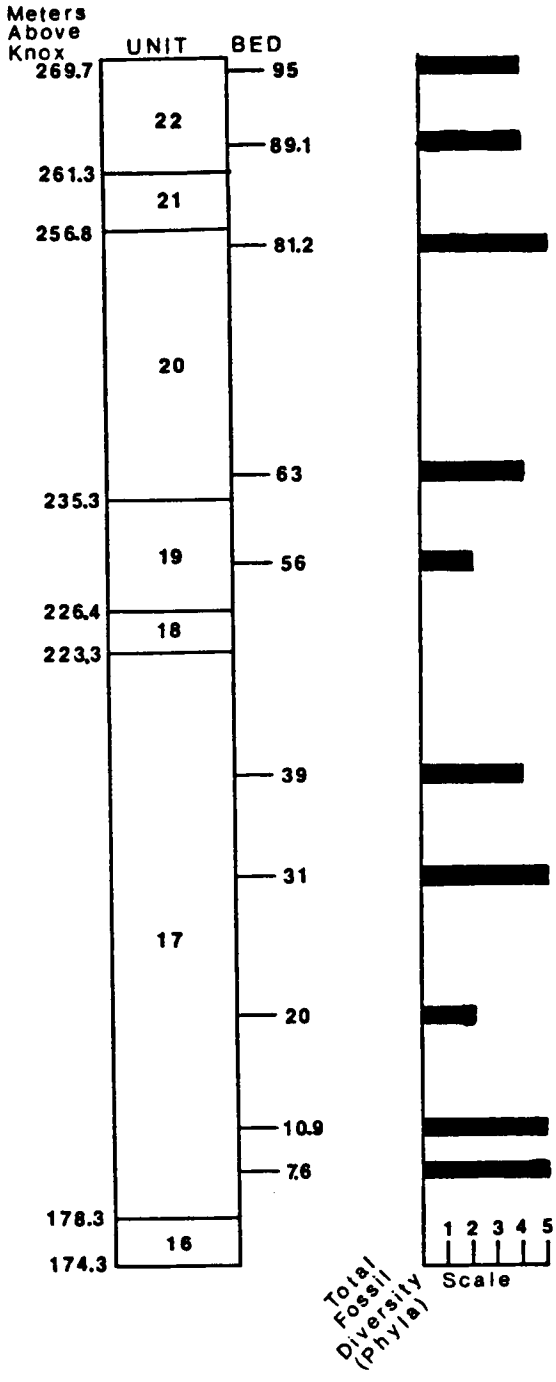


Figure 4-3. Fossil diversity of the Benbolt Formation.

To determine if the fossil assemblages represented "life" or "death assemblages", each bedding plane sample was examined using the criteria described by Johnson (1960); allowing each assemblage to be identified as a representative of Model I, II, or III ("in situ" assemblage, moderate exposure and transportation of fossils, and extreme exposure and transportation of fossils, respectively). In order to plot the assemblages on Johnson's graph (1960, p. 1079), the technique described by Weiss (1981, p. 137) was employed. The assemblages plotted on the graph are shown in Figure 4-4.

Bed 7.6. Bed 7.6 is located in unit 17 and consists of biomicrite (wackestone, Plate E-1). Slab surface constituents, based on 1,257 slab points, include matrix (53.3%), unidentifiable fossil material (32.4%), bryozoans (10.7%), brachiopods (1.4%), ostracodes (1.2%), and echinoderm debris (1%). Biovolume percentages recalculated to eliminate matrix include unidentifiable fossil material (69.3%), bryozoans (23%), brachiopods (3.1%), ostracodes (2.6%), and echinoderm debris (2%).

Brachiopods (Plate E-2) are represented by Strophomena medialis (~80%) and Hesperorthis sp. A (~20%, = Hesperorthis sp. 2 of Cooper, 1956). Brachiopods (up to 4.5 cm) are oriented both concave up (~66%) and convex up (~34%) with larger shells usually the latter; virtually all shells (~95%) are disarticulated. Abrasion and fragmentation are minimal, and minor bryozoan encrustation occurs infrequently.

Echinoderms (Plates E-3, E-4) are present on slab surfaces as well preserved columnals (~59%) and isolated plates (~41%).

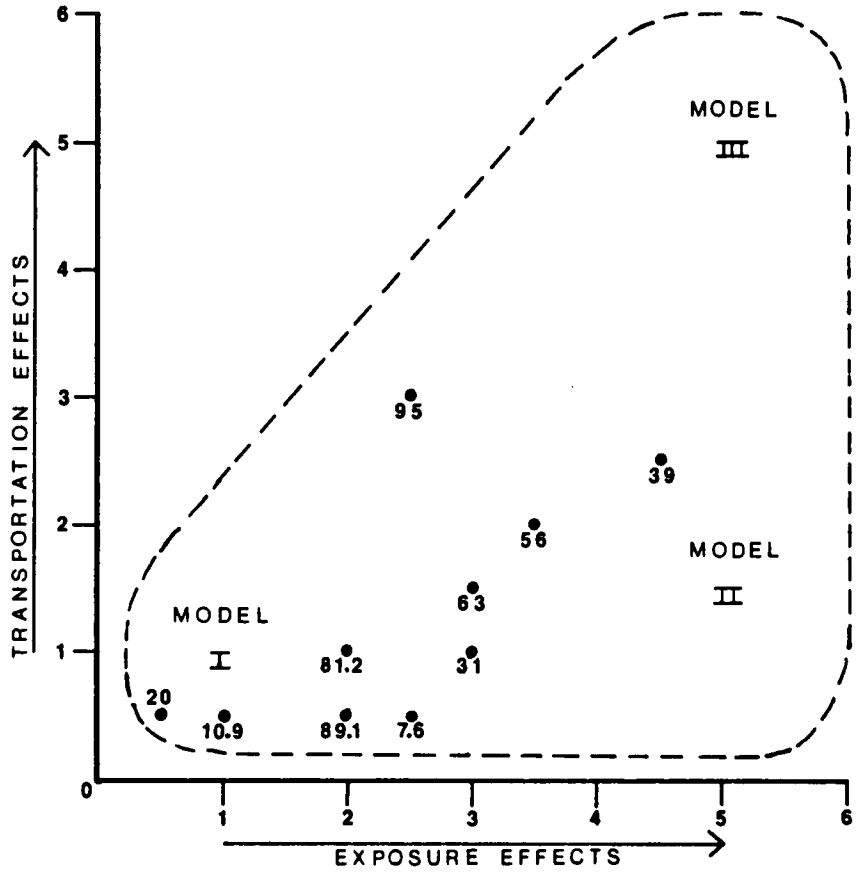


Figure 4-4. Fossil assemblages plotted on Johnson's (1960) graph. (Modified after Weiss, 1981).

Crinoids include Hybocrinus punctatus, Carabocrinus sp., Carabocrinus micropunctatus, and Paleocrinus planobasalis. Rhombiferans and blastoids include Regulaecystis pyriformis and Macurdablastus uniplicatus, respectively. All echinoderm plates are present in approximately equal percentages and are oriented parallel to bedding. Most (75-85%) columnals are disarticulated, however, articulated ones occur in all orientations: parallel, oblique, and perpendicular to the bedding surface.

Trilobites (Plate E-5) present in bed 7.6 include fragments (in most cases either pygidia or cephalons) of Isotelus, Illaneus, Calyptaulax, cf. Bumastus, and unidentifiable debris. All genera are present in approximately equal percentages and occur with the ventral side on the bedding surface (i.e. right side up).

Bryozoan growth forms (Plate E-5) include branching (up to 2.7 cm, ~60%) cup shaped (up to 0.5 cm) (~ 30%), encrusting (~8%), phyloproinnid (up to 1.6 cm, ~ 2%), and cylindrical (< 1%). All bryozoans are parallel to bedding but do not exhibit any evidence of current alignment. Fragmentation and abrasion for bryozoans, as well as virtually all allochems, are minimal.

Acetate peels of bed 7.6 reveal that much of the unidentified fossil material present on slab bedding surfaces is actually echinoderm debris. Echinoderm fragments (up to 4 mm) are well preserved and exhibit a crude bedding parallel orientation. Trilobite fragments (~ 6 mm) consist primarily of spines. Ostracodes (~1 mm) are 55-65% articulated; disarticulated valves are randomly oriented. Bryozoans consist principally of well preserved cryptostomes (~ 6 mm) and rare

trepostomes. Additional acetate peel constituents include sponge spicules (~2 mm) and encrusting Girvanella (Plate E-6). Fragmentation and abrasion are very low for all allochems. Matrix consists of micrite and rare microspar. Acetate peels do not exhibit any vertical faunal or depositional changes.

Conditions reflected on slab surface and in acetate peels indicate relatively quiet water deposition as evidenced by hydrodynamically unstable fossil orientations (shells concave up) and minimal exposure effects. Furthermore, branching and phyloporinnid bryozoans occur parallel to bedding, and cuplike bryozoans are present with the base up which suggests death and toppling of the colony before burial. These conditions indicate an assemblage intermediate between Johnson's Model I and II (Fig. 4-4). The diverse faunal assemblage of bed 7.6 suggests a stable, stress free, environmental setting (Sanders, 1969).

Bed 10.9. Bed 10.9 is located in unit 17 and consists of biomicrite (wackestone). Slab surface constituents, based on 881 slab points, include matrix (77.3%), echinoderm debris (16.8%), unidentifiable fossil material (3.8%), branching bryozoans (1.5%), and ostracodes and brachiopods (each 0.3%). Biovolume percentages recalculated to eliminate matrix include echinoderms (74%), unidentifiable fossil material (16.5%), branching bryozoans (6.5%), and ostracodes and brachiopods (1.5% each).

Echinoderms are present almost entirely in the form of "in situ" holdfasts and disarticulated and articulated columnals. Only one

well preserved plate, Rhombiferan A (undescribed, Broadhead, pers. comm., 1982) was observed on the slab surface. The concentration of "in situ" holdfasts produces small mounds or topographic highs (1-2 cm) on the bedding surface.

Brachiopods are represented in bed 10.9 by one disarticulated brachial valve of cf. Dinorthis transversa. The small size (6 mm), and the absence of brachiopod shells in acetate peels suggests that this specimen may not be indigenous to this environmental regime. Branching bryozoans (up to 2.7 cm) are present perpendicular, oblique, and parallel to bedding which most likely reflects life positions. Trilobites are rare and are represented by one crushed, unidentifiable molt. Abrasion and fragmentation are minimal for all allochems.

Acetate peels of bed 10.9 exhibit additional allochems of cryptostomes (~9 mm), trepostomes (~7.7 cm), ostracodes (~1 mm), sponges (~9 cm x 4 cm) and spicules, and encrusting Girvanella. Cryptostomes are well preserved in all orientations: parallel, oblique, and perpendicular to bedding. Anastomosing echinoderm fragments are present throughout the peels and represent "in situ" holdfasts. Many echinoderms are encrusted by the alga Girvanella. Large encrusting trepostomes, "in situ" sponges reaching lengths of 9 cm, and sponge spicules (largest = 3 mm) are pervasive throughout the rocks. Articulated (~85%) ostracodes are also well preserved. Matrix, of the biomicrites, is composed of micrite, and rarely, microspar. Acetate peels do not exhibit any vertical depositional changes; matrix remains homogeneous and appears to have been deposited around the "in situ" fossils.

Bed 10.9 exhibits a period of rapid carbonate and terrigenous accumulation, similar to that of bed 20. The faunal assemblages were constantly subjected to rapid accumulations of carbonate mud and infrequently smothered by influxes of terrigenous sediment. Echinoderm holdfasts and bryozoans were commonly buried in life position. In addition, exposure effects are virtually non-existant. Because Diabolocrinus vesperalis was the only crinoid observed in bed 20, it may be likely that many of the holdfasts and columnals in bed 10.9 belong to that species. Furthermore, many columnals similar to those of Diabolocrinus are present in bed 10.9. The rapid burial found in bed 10.9 reflects environmental conditions similar to those described in Johnson's (1960) Model I (Fig. 4-4).

Bed 20. Bed 20 is located in unit 17 and consists of biomicrite (packstone). Slab surface constituents, based on 314 slab points, include echinoderms (57.6%), matrix (41.4%), and branching bryozoans (1%). Corrected biovolume percentages include echinoderms (98.4%), and branching bryozoans (1.6%).

Echinoderms are represented solely by Diabolocrinus vesperalis; disaggregated calyces, plates, pinnules, and columnals constitute virtually the entire slab surface. Fragmentation and abrasion are extremely low, and most fossils are articulated. Columnals reach continuous lengths of 12 cm, calyx bases are intact, and articulated pinnules lie on the bedding surface. Very rare branching bryozoans are oriented parallel to the bedding surface.

Acetate peels of bed 20 exhibit well preserved, though rare, cryptostomes ($\sim$ 2 mm) and trepostomes (up to 1.6 cm). In contrast to

slab surfaces, many echinoderms evident in peels are disarticulated; however, this may be a result of the plane of observation of the peel. Very rare though well preserved trilobite fragments (up to 4 mm) are present. Matrix consists dominantly of (neomorphic) microspar and rare micrite. Echinoderm debris is dispersed homogeneously throughout the acetate peels; no vertical depositional changes were observed.

Lewis (1980, p. 29) stated that echinoderms disarticulate very quickly upon death, or even before death. Furthermore, he reported that some species of modern comatulid crinoids lose the pinnules within two days after death, and the calyx disarticulates within six days (p. 31, 29, respectively). Since these disintegration rates occurred in nonagitated regimes, agitated water would only hasten the disarticulation process. Consequently, the preservation of the pinnules and calyces of Diabolocrinus vesperalis in bed 20 suggests that terrigenous deposition (forming the thin shale beds between the thicker biomicrites) at this horizon occurred very rapidly. Moreover, deposition was rapid enough to prevent colonization of branching, and encrusting bryozoans. Many stem segments are oriented parallel to bedding; these may have been knocked over by turbid water in the burial process. As a result, bed 20 is interpreted to represent a depositional model similar to Johnson's Model I (rapid burial of the assemblage).

Bed 31. Bed 31 is located in unit 17 and consists of biomicrite (packstone). Slab surface constituents, based on 1,199 slab points, include matrix (44.2%), branching bryozoans (17.9%), echinoderms (17.3%), unidentifiable fossil material (12.4%), encrusting bryozoans (5.4%), phyloporinnid bryozoans (1.5%), brachiopods (0.8%), and

ostracodes (0.3%). Biovolume percentages recalculated to eliminate matrix include branching bryozoans (32.1%), echinoderms (31.1%), unidentifiable fossil material (22.3%), encrusting bryozoans (9.7%), phyloporinnid bryozoans (2.7%), brachiopods (1.5%), and ostracodes (0.6%).

Branching (up to 2.9 cm), encrusting (up to 1.7 cm), phyloporinnid (up to 1.2 cm), and cylindrical (< 1%, up to 8 mm) bryozoans are prevalent on slab surfaces and all are oriented parallel to bedding; none exhibit any evidence of current orientation. Most are well preserved with mud filled apertures. Abrasion is minimal although weathering effects are prominent.

Echinoderms are represented by plates of the rhombiferan Coronocystis angulatus and the eocrinoid Ulrichocystis eximia, and by disarticulated and articulated columnals. Plates and columnals account for ~ 5% and ~ 95% of the echinoderms, respectively.

Brachiopods are represented by small (7 mm) specimens of (?) Hesperorthis, oriented parallel to bedding with the pedicle valve exterior upward. Abrasion and fragmentation are minimal. Trilobites (< 1%) are present as abraded, unidentifiable fragments.

Acetate peels of bed 31 exhibit lithologies similar to bed 7.6. Well preserved cryptostomes (~ 8 mm) are oriented parallel to bedding; many contain mud filled apertures while others are Girvanella encrusted, forming oncolites. Trilobites are represented by 1.7 cm unbroken spines while ostracodes are 60-75% articulated. Gastropods are represented by unabraded, mud-filled specimens. Trepostomes have encrusted many allochems and mud clasts to effectively form trepostome biscuits. Small (1 mm) sponge spicules are present throughout the

peels. Abrasion and fragmentation for all allochems are very low. Elongate and planar allochems (i.e. long cryptostomes, echinoderm grains, and brachiopods) are oriented parallel to bedding which suggests some current activity. However, allochems are well preserved and may have been protected from current produced abrasion by mud coatings and Girvanella encrustation. Deposition was most likely a fairly rapid event, although the presence of algal oncolites, trepostome biscuits, and planar orientation of elongate allochems indicates moderate current activity. Consequently, bed 31 probably represents a Model I to Model II intermediate (Fig. 4-4, p. 97).

Bed 39. Bed 39 is located in unit 17 and consists of biomicrite and biosparite (packstone). Slab surface constituents, based on 770 slab points, include matrix (49%), brachiopods (48.6%), echinoderm debris (1%), unidentifiable fossil material (0.8%), and branching bryozoans (0.7%). Biovolume percentages recalculated to eliminate matrix include brachiopods (95.2%), echinoderm debris (2%), unidentifiable fossil material (1.5%), and branching bryozoans (1.3%).

Brachiopods are composed dominantly of Sowerbyella compacta. Articulated ($\sim$68%) and disarticulated ($\sim$32%) shells are present; most disarticulated shells are oriented convex up. The articulated shells are predominantly (75-85%) oriented convex up with the brachial valve down; 85-95% of the shells are oriented parallel to bedding but exhibit no current alignment. Shells not oriented parallel to bedding are usually oriented with the anterior upward (away from the bedding surface). Most brachiopods ($\sim$ 75%) range in size from 0.3-1.6 cm length (measured along the hingeline).

Echinoderms, although rare, are represented by the crinoid Diabolocrinus vesperalis, the rhombiferan Coronocystis angulatus, and articulated and disarticulated columnals. Coronocystis angulatus is represented by isolated thecal plates while Diabolocrinus vesperalis is represented by a calyx base. The remaining echinoderm debris is present as (unidentifiable) columnals oriented parallel to bedding. All echinoderms occur in approximately equal percentages. Branching bryozoans (up to 1.8 cm) are oriented on slab surface parallel to bedding.

Acetate peels of bed 39 exhibit rare fragmented cryptostomes and trilobites (~5 mm) oriented parallel to bedding, and very rare articulated ostracodes (2.5 mm) and sponge spicules. Micrite intraclasts (~1.9 cm) are present oriented parallel to bedding and contain small abraded echinoderm fragments, disarticulated ostracode valves, and sponge spicules. Girvanella encrustation is quite heavy on both the concave and convex surfaces of many brachiopod shells. Brachiopods are pervasive in bed 39 on slab surface and in acetate peel. Virtually all (68-70%) are oriented parallel to bedding and most are articulated. The disarticulated valves (and most articulated shells) invariably are oriented in hydrodynamically stable positions (concave down) signifying moderate current activity. Many concave down shells exhibit geopetal structures in the shell concavity. Abrasion is common. This pattern is constant throughout the vertical extent of the peel, indicating fairly prolonged washing of the substrate. Matrix consists of micrite, microspar, and spar.

The presence of Girvanella coated grains, elongate allochems, especially brachiopods, oriented parallel to bedding in hydrodynamically stable positions, and intraclasts, indicate current activity and probable transportation of allochems. Abrasion and fragmentation are common, further indicating either "in situ" exposure, transportation, or both. Consequently, bed 39 represents a definite Model II assemblage (Fig. 4-4, p. 97). According to Sanders (1969), the dominance of one species (in this case Sowerbyella compacta, 95.2%), and lack of a diverse complimentary biota, suggests deposition in a stressful environmental setting.

Bed 56. Bed 56 is located in unit 19 and consists of biomicrite (wackestone). Slab surface constituents, based on 287 slab points, include brachiopods (Sowerbyella) (61.7%), matrix (38%), and (< 1%) echinoderm debris. Biovolume percentages recalculated to eliminate matrix include brachiopods (99.4%), and echinoderms (0.6%).

Sowerbyella compacta was the only brachiopod observed in bed 56. Shells (ranging from 2-10 mm) are both articulated (~ 60%) and disarticulated (~ 40%). Most (65-75%) shells are oriented parallel to bedding on outcrop, and both brachial valves (~ 68%) and pedicle valves (~ 32%) are exposed. Fragmentation and abrasion are minimal, however, erosion of the shells is evident on slab surfaces. Bed 56 is similar in biotic content to bed 39. Echinoderms are rare in this horizon; only one columnal, oriented parallel to bedding, was observed on slab surface.

Acetate peels of bed 56 include constituents of brachiopods (~ 1.2 cm), ostracodes (~ 1 mm), echinoderm debris (~ 3 mm), trilobites

(~5 mm), and cryptostomes (~4.5 mm). All fossils with the exception of brachiopods are very rare. Brachiopods are present in various orientations: parallel, oblique, and perpendicular to bedding. Unlike bed 39 where virtually all (85-95%) shells were parallel to bedding, bed 56 contains 65-75% parallel to bedding brachiopods. This greater percentage of odd orientations (i.e. vertical and oblique to bedding) may reflect either "in life" shell orientations or possible biogenic reworking (Salazar-Jiménez, Frey, and Howard, 1982). Fossils exhibit less evidence of abrasion and fragmentation than the allochems of bed 39; bed 56 represents a Model II assemblage (Fig. 4-4, p. 97). Matrix consists of micrite and microspar.

As in bed 39, bed 56 is dominated by one species: Sowerbyella compacta. According to Sanders (1969), this lack of a diverse biota suggests a stressful physical environment. As a result, the environmental constraints were probably similar for the two beds. However, the brachiopods of bed 56 assume more inclined orientations relative to the bedding surface that those of bed 39 which suggests that current activity may have been slightly less. The decrease in current activity may have resulted from either a slight deepening of the water or possible current baffling in the area of deposition. Decreased current activity should accompany greater diversity in the biota, although this is not evident in bed 56. However, unit 19 (includes bed 56) is characterized by terrigenous clastic input; outcrops consist of shaly calcareous mudstone (Chapter 2). Consequently, the lack of a diverse biota in bed 56 may reflect physical stress due to terrigenous clastic turbidity rather than current agitation.

Bed 63. Bed 63 is located in unit 20 and consists of biomicrite (packstone). Slab surface constituents, based on 1,266 slab points, include matrix (51.8%), echinoderms (34.6%), branching bryozoans (9.5%), brachiopods (2.9%), unidentifiable fossil material (1.2%), and (< 1%) encrusting and cylindrical bryozoans, and gastropods (Gastropod A). Biovolume percentages recalculated to eliminate matrix include echinoderms (71.8%), branching bryozoans (19.7%), brachiopods (6.1%), unidentifiable fossil material (~ 2.5%), and (< 1%) encrusting and cylindrical bryozoans and gastropods.

Echinoderms are prevalent on slab surface, and are represented by columnals (~ 66%), abraded and well preserved plates (~ 32%), and calyx bases (~ 2%). Species present include Archaeocrinus peculiaris (~ 65%), Paleocrinus planobasalis (~ 32%), and (?) Carabocrinus stellifer (~ 3%). Plates are commonly oriented parallel to bedding and convex up (hydrodynamically stable). Columnals are present both as small (longest column length = 1.2 cm) articulated columns (with the column lying parallel to bedding) and as disarticulated columnals (with each columnal lying flat on the bedding surface). Columnals are predominantly (85-95%) disarticulated. Furthermore, except for a few calyces, plates are disarticulated. Fossils exhibit minimal fragmentation and abrasion.

Brachiopods on slab surfaces include specimens of small (~ 1.3 cm, hingeline length) Sowerbyella compacta, and larger (~ 1.7 cm, beak to anterior) Mimella. Brachiopods tend to be oriented parallel to bedding with the brachial valve down. All shells are predominantly (~ 85%) articulated. Exposure effects (abrasion and fragmentation) are minimal, however, weathering (erosion) has destroyed many shells.

Branching (largest length = 3 cm), encrusting (up to 3 cm), and cylindrical (~1.4 cm length) bryozoans are fairly well preserved on outcrop, with little weathering. All are oriented parallel to bedding, and are assumed to have fallen over after death, or toppled by muddy turbid influx. Apertures are commonly mud filled. Gastropods are represented by a small (3 mm) mud filled, low spired, involute, dextral form (Gastropod A) with the apex pointing upward from the bedding surface.

Fossils present in acetate peels are well preserved and include mud coated cryptostomes (~1.2 cm), trepostomes (~2.4 cm), elongate echinoderm fragments (5.5 cm) oriented parallel to bedding, brachiopods (~1 cm), rare gastropods (~2 mm) and trilobite spines and cross-sections of pleural lobes (~2.5 mm), ostracodes (dominantly articulated, ~1 mm), and rare Kazakhstanelia (~3 mm). Matrix consists of micrite and rare microspar.

Exposure effects are minimal in bed 63 and carbonate mud is dominant, completely coating many allochems. The mud coatings may have, in fact, been the agent responsible for the lack of severe abrasion. These conditions suggest that bed 63 was deposited in a fairly quiet (or protected) water environmental setting. Furthermore, Lewis (1980) stated that echinoderms usually disarticulate very quickly upon death. Consequently, the echinoderms present in this bed may have been exposed for a short time (several days or longer) on the sediment water interface before being buried, evidenced by the abundance of disarticulated columnals and plates. These conditions are similar to those found in a setting such as an assemblage intermediate between Johnson's (1960) Model I and Model II (Fig. 4-4, p. 97). Bed

63 contains a diverse faunal assemblage. According to Sanders (1969) this diversity reflects a low-stress environment.

Bed 81.2. Bed 81.2 is located in unit 20 and consists of biomicrite (packstone). Slab surface constituents, based on 814 slab points, include matrix (46.2%), brachiopods (40.1%), unidentifiable fossil material (8.5%), branching bryozoans (3.3%), echinoderm debris (1.6%), and ostracodes (0.4%). Biovolume percentages recalculated to eliminate matrix include brachiopods (74.4%), unidentifiable fossil material (15.8%), branching bryozoans (6.2%), echinoderm debris (3%), and ostracodes (0.7%).

Brachiopods are extremely prevalent on outcrop and are represented by Sowerbyella compacta ($\sim$99%, size range 0.5 - 1.4 cm), and ($<$1% each) Dinorthis transversa, Mimella, and cf. Hesperorthis. Shells occur in virtually all orientations: concave or convex up (in approximately equal percentages), perpendicular to the bedding surface, and articulated ($\sim$62%) and disarticulated ($\sim$38%) shells randomly oriented. Exposure effects (abrasion and fragmentation) range from low to medium in intensity. In addition, weathering effects on slab surfaces are moderate to severe. The shells do not exhibit any current alignment.

Branching (largest = 2.8 cm) and rare ($<$1%) phyloporinnid bryozoans are parallel to bedding. The exposed surfaces of many Sowerbyella pedicle valves are covered by encrusting bryozoans. Echinoderms are represented by rare, unidentifiable plates and columnals.

Acetate peels of bed 81.2 exhibit numerous brachiopods which are both concave and convex up (in approximately equal percentages) parallel to bedding. Trilobites (~1.5 cm) and ostracodes (~90% articulated) are rare. Matrix consists of micrite and microspar (in approximately equal percentages) trapped under the concave down side of brachiopod shells and in cryptostome zooecia. All elongate and planar fossils exhibit a strong bedding parallel orientation.

The presence of micrite and lack of intense abrasion suggests that bed 81.2 represents fairly quiet water deposition, and corresponds to a Model I to Model II intermediate (Fig. 4-4, p. 97).

Bed 89.1. Bed 89.1 is located in unit 22 and consists of biomicrite (wackestone). Slab surface constituents, based on 731 slab points, include branching bryozoans (42%), matrix (32%), echinoderms (11.2%), unidentifiable fossil material (6.6%), phyloproinnid bryozoans (4.5%), and brachiopods (3.8%). Biovolume percentages recalculated to eliminate matrix include branching bryozoans (61.8%), echinoderm debris (16.5%), unidentifiable fossil material (9.7%), phyloporinnid bryozoans (6.6%), and brachiopods (5.4%).

Branching bryozoans (largest = 2 cm) are pervasive on slab surface. All are oriented parallel to bedding and are interpreted to have fallen over or were knocked down by turbid water. Exposure and weathering effects are minimal; preservation is good. Phyloporinnid bryozoans are flat on the bedding surface; the largest zooarium is 2.5 cm x 4 cm.

Brachiopods are represented by Sowerbyella compacta (largest = 1.7 cm), Mimella globosa (largest = 2.7 cm), Mimella sulcata (largest =

1.6 cm), and Hesperorthis (largest = 8 mm). Virtually all (~98%) specimens of Mimella and Sowerbyella are articulated and oriented parallel to bedding, with the brachial valve down. Hesperorthis is represented by several concave up disarticulated pedicle valves, oriented parallel to bedding. All three genera are well preserved (virtually no effects of abrasion, transportation, or fragmentation), however, Mimella exhibits effects of severe (post-lithification) weathering. The shells do not exhibit any current alignment.

Echinoderms are represented by plates (~65%), columnals (~25%), and stems (~10%). Species present include Hybocrinus punctatus and Archaeocrinus peculiaris (represented by plates in approximately equal percentages), and Diabolocrinus vesperalis (represented by arm and radial plates, and a crushed calyx). A pentamere stem (~9.4 cm long) on the bedding surface is crushed but well preserved.

In acetate peels, bed 89.1 contains well preserved, bedding parallel, cryptostomes (~6 mm). Abrasion and fragmentation are rare. Virtually all ostracodes (~1.5 mm) are articulated; trilobites (~7 mm) are present as spines and assorted fragments. Concave down disarticulated brachiopod shells exhibit geopetal fabrics. Matrix consists of micrite and microspar (present in approximately equal percentages).

The lack of moderate to severe abrasion and presence of a diverse biota reflect an intermediate Model I to Model II assemblage (Fig. 4-4, p. 97).

Bed 95. Bed 95 is located in unit 22 and consists of biomicrite (packstone). Slab surface constituents, based on 885 slab points, include matrix (50%), echinoderms (30.6%), branching bryozoans (15.6%),

encrusting bryozoans (2%), brachiopods (1%), and unidentifiable fossil material (0.9%). Biovolume percentages recalculated to eliminate matrix include echinoderms (61%), branching bryozoans (31.1%), encrusting bryozoans (4.1%), brachiopods (2%), and unidentifiable fossil material (1.8%).

Echinoderms are present largely as columnals (~ 85%) and abraded plates (~ 15%). Crinoids are represented by Carabocrinus stellifer. Columnals are both articulated (~ 35%) and disarticulated (~ 65%), and are oriented both parallel and perpendicular to the bedding surface. Many articulated columnals stick up from the bedding surface and appear to be "in situ". Disarticulated plates are oriented both parallel to, and perpendicular to the bedding surface. Exposure effects (abrasion and fragmentation) are minimal.

Branching bryozoans (~ 1.5 cm) are prevalent on outcrop and assume many orientations: parallel, oblique, and perpendicular to bedding. Encrusting bryozoans (~ 6 cm x 2.9 cm) are also common. Abrasion and fragmentation for both types of bryozoans are minimal.

Brachiopods (largest = 2.3 cm) are rare in bed 95 and occur primarily oriented obliquely (possible "in life" position) to the bedding surface; only small portions of the anterior part of the shell are exposed. As a result, brachiopods could not be identified on slab surfaces.

Constituents are oriented parallel to bedding in acetate peels. Cryptostomes (~ 6 mm), echinoderm debris (~ 6.5 mm), trilobites (~ 1.1 cm), brachiopods (~ 2 cm), and gastropods (Gastropod A, ~ 3 mm) are all fairly well preserved. Many gastropods are Girvanella encrusted and contain centers of microspar and spar. Large (~ 5.1 cm) well

preserved, encrusting trepostome bryozoans are prevalent. Possible bioturbation is evidenced by an abundance of peloids (resembling fecal pellets ~0.3 mm), and current agitation and possible transportation is evidenced by fragmented trilobites, Girvanella encrusted oncolites, and well rounded micrite intraclasts (~1.3 cm long). Matrix consists predominantly of micrite and microspar, and rare spar cement.

Conditions favorable for the formation of bed 95 are found in environments subjected to fairly rapid deposition (for "in situ" allochems) and moderate agitation (for transportation of allochems and intraclasts); these are similar to those found in Johnson's (1960) Model I to Model III assemblage (Fig. 4-4, p. 97).

III. DISCUSSION

Recent studies in paleoecology have concentrated largely on either the descriptive or functional aspect of fossil assemblages. These include size analyses (Craig and Hallam, 1963; Hallam, 1972), ecologic successions (Walker and Alberstadt, 1975; Alberstadt and Walker, 1976; Walker and Parker, 1976), trophic analyses (Turpaeva, 1957; Walker, 1972; Walker and Bambach, 1974; Stanton and Dodd, 1976; Scott, 1978; Ausich, 1980), and biotic-environmental stability analyses (Bretsky and Lorenze, 1969; Sanders, 1969; Johnson, 1972).

Food availability, sedimentation rate, substrate stability, turbidity, water energy, salinity, and dissolved oxygen govern the distribution and composition of benthic communities (Rhoads, Speden, and Waage, 1972). The Benbolt Formation was deposited under relatively constant environmental constraints; salinity and dissolved oxygen

content are assumed to have remained fairly constant throughout deposition, with only minor undetectable fluctuations occurring. With this in mind, the major factors affecting Benbolt deposition include food availability and changes in the sedimentation rate and its affect on the substrate. These latter factors will be analyzed in this study.

Turpaeva (1957) and other Russian workers, and Walker (1972) in particular have discussed the role of food produced niche differentiation in benthic communities. They observed, in recent and ancient communities that, in general, (1) one trophic group dominates the community, (2) if the most dominant species belongs to one trophic group, the next dominant species belongs to a different group, and (3) a single species within a particular trophic group dominates that group in terms of biomass (or biovolume) (Walker, 1972). These workers used broadly defined groups in their classifications: suspension feeders (low and high level), collectors, and swallowers.

This niche stratification has been applied at an even more detailed scale by Ausich (1980) for suspension feeders only. He reported that tiering among Lower Mississippian crinoids was determined by height above the sea floor. Three levels (low = 0 to 15-20 cm, intermediate = 15-20 to 50 cm, and high = 50 to 100 cm above the substrate) categorized feeding. Minor niche differentiation occurred by food-size selection (i.e. ambulacral width).

On a very large scale, Ausich and Bottjer (1982) proposed a pattern of tiering history of suspension-feeding communities throughout the entire Phanerozoic. They recognized four tier subdivisions in

epifaunal suspension feeding communities: approximately 5 cm, 10 cm, 50 cm, and 1 m above the substratum. In addition, 3 tier subdivisions were reported for infaunal suspension feeders.

Figures 4-1 and 4-2 (pp. 92 and 94) display slab surface constituent analyses and biovolume percentages of the Benbolt slab surfaces. A definite interaction existed among the fossil groups present; brachiopods and echinoderms almost never co-occur throughout the formation and bryozoans usually co-occur with the echinoderms. The fossil assemblages present at Stanley Farm reflect Turpaeva and Walker's generalizations in that one fossil group (either brachiopods, echinoderms, or bryozoans) dominates the assemblage in terms of biovolume; in this case however, all of the dominant fossil groups belong to the same trophic group, namely suspension feeders. This presence or lack of co-occurrence may reflect either feeding or substrate and water turbidity relationships of the organisms with their environment. For example, the virtual mutual exclusion of brachiopods and echinoderms and the co-occurrence of echinoderms and bryozoans may result from competition in feeding or tiering of suspension feeding (e.g. bed 7.6, Fig. 4-5) as described by Turpaeva (1957) and Walker (1972), and Ausich (1980), respectively. Mutual exclusion of fossil groups may result from substrate relationships and water turbidity rather than competition for food (e.g. beds 39 and 56).

Figure 4-4 (p. 97) exhibits the relative position of each bedding plane on Johnson's (1960) graph. Most of the assemblages plot either as a Model I representative or as a Model I to Model II intermediate; each bedding plane contains either an "in situ" fossil

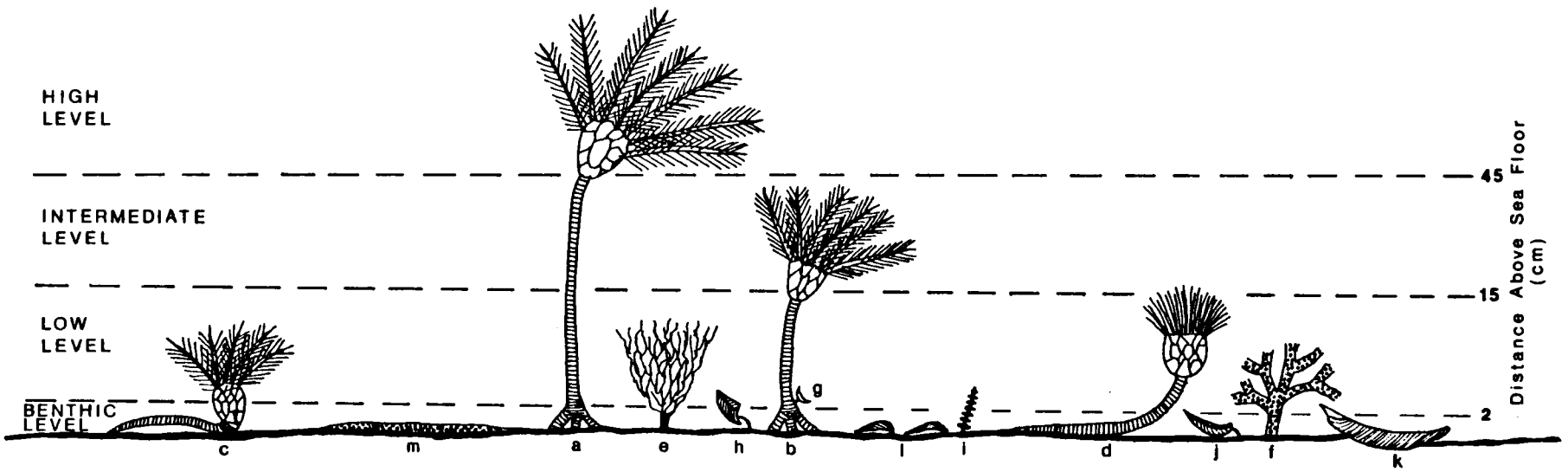


Figure 4-5. Tiering of suspension feeders in the Benbolt Formation. Modified after Ausich (1980).

a = High level suspension feeders; Camerates, e.g. Diabolocrinus, Archaeocrinus.
b = Intermediate suspension feeders; Inadunates, e.g. Carabocrinus, Paleocrinus. Blastoids, e.g. Macurdablastus.
c = Low level suspension feeders; e.g. Hybocrinus.
d = Low level suspension feeders; e.g. Rhombiferans.
e-i = Low level suspension feeders; e.g. (in alphabetical order) phyloporinnid bryozoan, branching bryozoan, cuplike bryozoan, Hesperorthis, cylindrical bryozoan.
j-m = Benthic level suspension feeders; e.g. (in alphabetical order) Dinorthis, Strophomena, Sowerbyella, encrusting bryozoan.

assemblage or one subjected to minimal to moderate degrees of exposure, fragmentation, and abrasion. As a result, the fossil assemblages sampled from the Benbolt Formation were probably indigenous to the depositional area. Furthermore, if the Benbolt fossils represent indigenous assemblages, Sanders' (1969) stress-diversity approach may be used as an approximation of the degree of stress in each depositional area; i.e. low-stress environments should yield high fossil diversity while high-stress environments should yeild low fossil diversity. The reaction of each fossil assemblage to the environmental stress (i.e. substrate stability, water agitation, and water turbidity) is evident in each bed (or group of beds).

Bed 7.6 contains both brachiopods (3.1%) and echinoderm debris (2%). Acetate peels reveal that much of the unidentifiable fossil material (69.3%) was actually echinoderm debris; thus, echinoderms constitute a slightly higher biovolume percentage than brachiopods, although the biovolume difference is still not appreciable. The biotic diversity of bed 7.6 may have reflected a low stress environmental setting (Sanders, 1969); the low environmental stress allowed many groups to colonize the substrate. As a result, bed 7.6 represents a biologically accommodated assemblage. Any biovolume diversity probably resulted from niche stratification (e.g. tiering in crinoids by differing columnal lengths and food size selection, Fig. 4-5) and not from environmental constraints (substrate relationships, water energy and turbidity).

In contrast, beds 10.9 and 20 exhibit exclusion of fossil groups probably resulting from unfavorable environmental parameters,

rather than food availability. Beds 10.9 and 20 represent an assemblage subject to rapid carbonate and terrigenous deposition; this rapid accummulation of sediment most likely produced a high stress environmental setting. The dominance of echinoderms may be attributed to their ability to rapidly colonize the soft substrate ("in situ" holdfasts are pervasive); brachiopods would most likely be rapidly buried. Echinoderms also have an advantage in that the columnal supports the calyx above the sediment water interface for feeding. Diversity of bed 10.9 is less than the diversity of bed 7.6.

Bed 31 marks the transition from a rapid "in situ" depositional setting (beds 10.9-20) to a more current agitated, terrigenous influenced setting (beds 39-56). The fossil diversity of bed 31 is similar to bed 7.6 except for the larger percentage of echinoderms. Some current washing is evidenced by the presence of small Girvanella coated grains, trepostome biscuits, and bedding parallel elongate allochems.

Beds 39 through 56 (upper portion of unit 17, 18, and part of 19) exhibit harsh environmental conditions. This is supported by the presence of a non-diverse biota, represented chiefly by brachiopods. Echinoderms were present in this environmental setting; thin sections of unit 18 (chapter 2) consisted of echinoderm (52.6%) grainstone which was interpreted as representing a shoaling regime or migrating tidal channel. However, unit 18 contained virtually no brachiopods (1.1%). The presence of a non-diverse biota suggests harsh environmental constraints; environmental factors such as substrate mobility, water turbidity, and current agitation controlled the assemblage by

reducing the potential for colonization. Such physical constraints are often favorable for the colonization of opportunists, however. Levinton (1970) stated that opportunistic species are not resource limited and often rapidly increase in numbers in short time periods in environments subjected to high physiological stress. He further stated that such populations are short-lived, and great densities of shells are left in the death assemblage. The abundance of Sowerbyella compacta in beds 39-56 most likely reflected the introduction of this opportunist following terrigenous clastic influxes. Successions (see Walker and Alberstadt, 1975) often result from the introduction of opportunistic species. Walker and Parker (1976) described an ecological succession in which the pioneer species Strophomena basilica paved the soft substrate for later colonization by other benthic fossil groups. Episodic terrigenous sedimentation in the Benbolt Formation at Stanley Farm may also have favored opportunistic substrate colonization by Sowerbyella compacta and the possible formation of later-stage successions.

Beds 63 through 81.2 reflect minor fluctuations in current energy. Though both beds exhibit features indicative of fairly quiet water deposition (e.g. presence of micrite mud, and lack of abrasion and fragmentation), bed 63 appears to represent a slightly less agitated environment. This interpretation is supported by the presence of partially articulated Archaeocrinus bases. Bed 81.2 also represents quiet water deposition, supported by the large diversity of brachiopods, not present in beds representing more terrigenous-influenced or agitated regimes (39-56). The upper intervals of unit

20 (including bed 81.2) were effectively smothered by the terrigenous clastic rich lithologies of unit 21. The lack of sedimentary structures (only minor laminations are present) and the presence of very fine grained sediment suggests fairly quiet water deposition. Furthermore, the presence of horizontal burrows suggests that the sediment rich waters were conducive only to detritus feeders.

Beds 89.1 and 95 represent the re-establishment of the benthos by suspension feeders subsequent to the terrigenous influx. Ostracodes are predominantly articulated and crinoids are represented by crushed, but articulated calyces and stems (up to 9 cm). A stress free environment is suggested by a diverse faunal assemblage. The biota is dominated by bryozoans, echinoderms, and finally brachiopods. The dominance hierarchy of this assemblage may be a result of either tiering among the fossil groups or the ability of each group to recolonize the substrate subsequent to the terrigenous deposition. Bed 95 again marks a return to agitated conditions, evidenced by Girvanella oncolites, fragmented trilobites, and rounded intraclasts; intraclasts and fragmented fossils in the unit may be transported. This bed reflects deposition in environments subjected to fairly rapid deposition and moderate agitation which may have created unfavorable substrate or water conditions. As a result, the ability to colonize and dominate the substrate probably resulted from environmental constraints rather than tiering.

Biotic changes reflect general depositional changes throughout Benbolt deposition. Petrographic analysis of units 16 and 17 indicated a muddy bottom, quiet water environment in the lower intervals of the

unit, as evidenced by the abundance of micrite and Girvanella matrix forming tubules. The upper intervals of the unit reflect more agitated, shoaling water, as evidenced by fragmented allochems and oncolites. Acetate peels and slabs of the unit indicate quiet water though rapid deposition in the lower intervals (beds 7.6-20). This is supported by diverse biotic assemblages, probably reflective of stress free environments (Sanders, 1969), and "in situ" echinoderm assemblages. The peels of the upper intervals (beds 31 and 39) indicate more shoaling regimes as evidenced by fragmented cryptostomes and trilobites, and oncolites and intraclasts. Furthermore, the presence of non-diverse, brachiopod dominated assemblages probably reflects stressful depositional environments.

Unit 19 on outcrop (no thin sections made) consisted of terrigenous clastic rich shales, and biomicrite cobbles which suggest fairly harsh environmental conditions. This is supported by the Sowerbyella dominated horizon of bed 56. Although current activity may not have been intense, evidenced by lack of abrasion and presence of micrite mud, the influx of terrigenous clastic material may have prevented colonization of many groups.

Units 20-22 reflect fluctuations of agitated and quiet water deposition. Petrographic analysis indicated a decrease in abrasion and fragmentation stratigraphically upward, and an increase in micrite content, which reflects a decrease in current energy. In peels and on slab surfaces, biotic diversity is highly variable, resulting from the sporadic influxes of terrigenous clastic material. However, the diversity increases overall to a maximum at bed 89.1.

Bryozoans become the dominant fossil group, with most oriented in life positions. Abrasion intensities are low, while crinoid stems and columnals are commonly articulated. Finally, the environment became slightly agitated during deposition of the upper intervals of the formation, as bed 95 exhibits oncolites and rounded intraclasts which are indicative of current activity (Benedict and Walker, 1978).

Brower and Veinus (1974, p. 14-16) discussed echinoderm paleoecology of the Benbolt Formation throughout southwestern Virginia and eastern Tennessee. They concluded that the high faunal diversity in the lower intervals indicated fairly quiet water conditions of normal marine salinity. This corresponds to the high faunal diversity, low stress environments of beds 7.6-20 at Stanley Farm. Brower and Veinus reported that stratigraphically higher intervals contained many abraded brachiopod shell fragments and disarticulated crinoids which indicate water agitation. They stated that the water was intermittently quiet allowing for deposition of fine grained sediment. This corresponds to the fluctuating quiet to agitated, terrigenous clastic punctuated environments of beds 31-95 at Stanley Farm. Agitated conditions were indicated, according to Brower and Veinus, by (1) robust thick-plated crinoids, (2) the possession of a simple massive calyx by the hybocrinids, and (3) Diabolocrinus vesperalis being the most abundant camerate. Diabolocrinus vesperalis is also, by far, the most abundant crinoid at the Stanley Farm Section. Brower and Veinus also stated that examination of roots in matrix indicated that "Benbolt" crinoids were rooted in the sediment and not around rocks. The crinoid holdfasts of bed 20 at Stanley Farm may have likewise been soft substrate colonizers.

CHAPTER V

SUMMARY AND CONCLUSIONS

The Stanley Farm Section contains 424.9 meters of Middle Ordovician rocks which display a sequence from supratidal to offshore subtidal depositional regimes. The Five Oaks Formation represents tidal flat (supratidal-intertidal) deposition on the Knox karst surface. Lower and middle intervals of the formation (units 1-3) represent supratidal to intertidal deposition as evidenced by abundant dolomite and abraded allochems. Upper intervals (unit 4) represent intertidal to subtidal deposition, as indicated by the appearance of algae and a diverse biota. The Lincolnshire Formation (consisting of the Eidson, Fleanor, and Hogskin Members) represents an intertidal to subtidal-restricted carbonate shelf puncutated by episodes of terrigenous clastic sedimentation. The Eidson Member represents shallow subtidal environments as evidenced by a diverse algal assemblage, a diverse though rarely abraded biota, and algal and algal-bryozoan microboundstones and boundstones. The Fleanor Member exhibits biogenic and physical deformation features which suggest very shallow (wave-active) current influenced terrigenous clastic deposition; vertical burrows, rotated intraclasts, cross-laminations and current produced intraclasts are common. The Hogskin Member represents deposition in a Fleanor-like environment, however, the percentage of terrigenous material gradually decreases stratigraphically upward. Algal oncolites, burrowing, mudcracks, algal mats, trough crossbedding and overturned silt beds indicate shallow (intertidal to shallow subtidal) water, terrigenous clastic influenced deposition.

The Rockdell Formation represents shallow, subtidal deposition. The massive nature of the Rockdell reflects the lack of terrigenous clastic material. The Benbolt Formation represents subtidal, quiet to agitated deposition which was sporadically punctuated by influxes of terrigenous clastic sediments and migration of shoaling areas, and possibly tidal channels. The lower intervals (unit 16 and the lower intervals of unit 17) reflect non-agitated, stable deposition as evidenced by a high faunal diversity and quiet water constituents (e.g. Girvanella tubules). The middle intervals of the formation (upper intervals of unit 17 and unit 18) reflect agitated water deposition as indicated by the presence of numerous algal oncolites and abraded echinoderm grainstones. Units 19-21 reflect the influx of terrigenous clastic material. The presence of a low fossil diversity and lack of algae suggest turbid conditions. The upper intervals (unit 22) once again exhibits quiet water sedimentation.

The Wardell Formation reflects shallow water (wave-active) sedimentation, as evidenced by storm produced deformation and cryptalgal laminations. Tetradium colonies were also prevalent, indicative of active water circulation. The Bowen Formation represents a terrigenous clastic influenced depositional episode; fossils are absent. The Witten Formation reflects shallow water deposition in the lower units (28-30), as evidenced by horizontal burrows and lack of fossil abrasion, and subtidal to shallow intertidal deposition in the upper unit (31), as evidenced by scoured surfaces, abundant peloids, fenestral features, and lack of algae.

The Lincolnshire Formation, consisting at the Stanley Farm Section of the Eidson, Fleanor, and Hogskin members, represents shallow water, terrigenous clastic influenced deposition. Cooper (1956) divided the Lincolnshire into two members: Eidson limestone and Hogskin shale. Cooper and Cooper (1946) designated the Fleanor as a formation. However, at Stanley Farm, the Fleanor lies between the Eidson and Hogskin Members and grades into the Hogskin; consequently, all three units are considered members of the Lincolnshire Formation. The thickness of the Fleanor Member varies along strike and, in stratigraphic cross-section, exhibits a lens shaped configuration. This configuration, along with its rapid stratigraphic appearance and lack of lateral interfingering, suggests that the Fleanor may have been deposited in a deltaic setting similar to that reported by Davies (1970) in Shark Bay of Western Australia.

Ten bedding planes were sampled from the Benbolt Formation for purposes of paleoecological analysis. Biovolume percentages, derived from point counting slab surfaces, exhibit a general mutual exclusion of brachiopods and echinoderms, and a general co-occurrence of echinoderms and bryozoans in most horizons. Co-occurrence, or lack of co-occurrence may be explained either by niche stratification resulting from tiering (Turpaeva, 1957; Walker, 1972; Ausich, 1980; Ausich and Bottjer, 1982), or by substrate stability, water agitation and water turbidity. Low stress environments (beds 7.6, 31, 63-89.1) exhibit high diversity (Sanders, 1969); assemblage composition was most likely governed by tiering (e.g. differing crinoid columnal and filtration fan lengths, and overall food size selection). High stress environments

(beds 10.9-20 and 39-56) exhibit low diversity; assemblage composition was most likely governed by the organism's ability to adapt to environmental constraints (substrate and water turbidity) rather than food availability. Rapid sediment accummulation was most likely the factor controlling faunal composition in beds 10.9-20, while water turbidity was probably the controlling factor in beds 39-56. Furthermore, the abundance of Sowerbyella compacta in beds 39 and 56 possibly represents the colonization of the substrate by an opportunistic species following terrigenous clastic influx. Bed 95 differs from the other beds in that rapid sedimentation accompanied moderate water agitation, reflected in the reduced faunal diversity.

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APPENDICES

APPENDIX A

MEASUREMENT CONVENTIONS AND STRATIGRAPHIC DESCRIPTION OF THE STANLEY FARM SECTION

MEASUREMENT CONVENTIONS

The bed thickness measurement conventions used in field descriptions of this investigation are based on the suggestions of McKee and Weir (1953), modified by Ingram (1954). Grain size descriptions are modified after the terminology established by Wentworth (1922) and sorting criteria was developed by Folk (1974). The rock classifications used were proposed by Dunham (1962) and Folk (1962).

Bed Thickness

Very thick bedded (massive)	Greater than 1.0 m.
Thick bedded	0.3 - 1.0 m.
Medium bedded	0.1 - 0.3 m.
Thin bedded	0.03 - 0.1 m.
Very thin bedded	0.01 - 0.03 m.
Laminated	0.003 - 0.01 m.
Thin laminated	Less than 0.003 m.

Grain Size

Coarse grained	Greater than 1 mm.
Medium grained	0.25 - 1.0 mm.
Fine grained	0.1 - 0.25 mm.
Very fine grained	Less than 0.1 mm.

STANLEY FARM SECTION

The Stanley Farm Section is located near the Stanley Cemetery, along the intersection of Loyston and Raccoon Valley Roads (83°55'30" Long., 36°11'30" Lat.; Big Ridge Park Quadrangle). The Middle

Ordovician section is 424.9 meters thick and is bounded by the Knox/ Chickamauga contact to the northwest and by the Moccasin Formation (partially faulted by the Copper Creek Fault) to the southeast. The section was divided into 31 units which are described in ascending order from oldest to youngest. Thin section numbers are given with measured thickness from the base of the section.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
			KNOX GROUP unconformity CHICKAMAUGA GROUP
1	0.4	0.4	Five Oaks Formation - NEXT 4 UNITS: Light to medium gray, medium to coarse grained, cherty dolostone. Red and black angular chert clasts (restricted to 10 cm band), and dolomite intraclasts common. Fossils absent. Samples: K-5, 0.2 m.
2	0.8	1.2	Light to medium pinkish gray, thickly bedded, fine to medium grained, poorly sorted, nonlaminated to laminated, dolomitic mudstone. Angular chert clasts and tabular dolomite intraclasts common. Peloids concentrated in thin sparry bands. Macrofossils absent. Samples: K-6, 1.2 m.
	7.0	8.2	COVERED
2 (cont.)	0.6	8.8	Same as above. Samples: K-13, 8.2 m.
3	3.9	12.7	Light to medium gray, very fine to medium grained, thin to medium bedded pelmicrite. Less massive than Unit 2. Angular dolomite intraclasts common. Peloids concentrated in thin (0.2 - 0.4 mm) sparry bands. Fossils included phosphatic inarticulate brachiopods, trilobites, ostracodes (?). Samples: K-14.5, 9.7 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
4	3.3	16.0	Light to medium gray, medium to coarse grained, medium bedded, biopelsparite. Constituents include peloids, echinoderm debris, ostracodes, trilobites, inarticulate brachiopods, Hedstroemia, sponge spicules, red and black angular chert clasts, and micrite intraclasts. Birdseyes common. Samples: K-18, 13.2 m; K-21, 16.2 m. TOTAL FIVE OAKS = 16 meters
5	1.2	17.2	Lincolnshire Formation (Eidson Member) - NEXT 7 UNITS: White to light gray, fine grained, cherty biomicrite, interbedded with thin (~1 mm) shale drapes. Cobbles produced on weathering. Red and black chert nodules and lenses common. Allochems include trilobites, echinoderm debris, ostracodes, inarticulate brachiopods, and sponge spicules. Samples: K-22, 17.2 m.
6	1.2	18.4	Light gray, coarse grained, poorly sorted, biopelsparite, interbedded with thinner (1-6 mm) clay rich biosparite. Constituents include peloids, echinoderm debris, gastropods, trilobites, bryozoans, ostracodes, algae (Solenopora, Girvanella, Hedstroemia), inarticulate brachiopods, and intraclasts. Samples: K-23, 18.2 m.
	3.6	22.0	COVERED
6 (cont.)	0.4	22.4	Same as above. Samples: K-27, 22.2 m.
7	17.8	40.2	Fine to medium grained, thinly bedded, pinkish gray to pinkish blue biosparite, interbedded with fine grained, light maroon to blue, thin to thick bedded shale and siltstone. Lenses of red chert commonly interbedded with the shale and carbonate. Constituents include gastropods, peloids, echinoderms, trilobites, ostracodes, brachiopods, bryozoans, algae (encrusting Spongiostroma, Girvanella, Hedstroemia; and large

Unit #	Unit Thk(m.)	Cumul. thk(m.)	Description
			Solenopora biscuits) and micrite intraclasts. Upper 5.7 meters contains algal (Spongiostroma, Hedstroemia, Girvanella) microboundstone. Samples: K-30, 25.2 m; K-33, 28.2 m; K-34, 29.2 m; K-35, 30.2 m; K-37, 32.2 m; K-38, 33.2 m; K-40, 35.2 m; K-43, 38.2 m; K-45, 40.2 m.
	2.8	43.0	COVERED
7 (cont.)	2.7	45.7	Same as above. Samples: K-49.3, 44.5 m.
	2.5	48.2	COVERED
8	4.5	52.7	Light to medium gray, coarse grained, thin to medium bedded, poorly sorted biosparite and silty biosparite (up to ~44% quartz silt) interbedded with lenticular dark gray to black chert. Biosparites exhibit sugary texture upon weathering, and megascopic small fining upward sequences in some horizons. Allochems include quartz silt, echinoderms, peloids, bryozoans, trilobites, ostracodes, brachiopods, and algae (Solenopora and ?Nuia). Samples: E-0, 48.2 m; E-1.5, 49.7 m; E-3, 51.2 m.
9	0.4	53.1	Tan to light medium gray, very fine to fine grained, very thin bedded, silty dismicrite. Horizontal burrows prominent. Samples: E-4.5, 52.7 m.
	6.1	59.2	COVERED
10	1.6	60.8	Light gray, medium to coarse grained, poorly to moderately sorted, thick bedded, stylolitic, biomicrite. Allochems include sponges and spicules, gastropods, echinoderms, bryozoans, ostracodes, trilobites, and algae (Girvanella encrusting and as matrix tubules; Nuia). Samples: E-11, 59.2 m; E-12, 60.2 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
11	1.7	62.5	Light to medium gray, fine to coarse grained, poorly to well sorted, thin to medium bedded, biomicrite and cherty biopelsparite interbedded with pods and lenses of thin (2-5 cm) black chert. Weathering of irregularily spaced shale drapes produces cobbly/hummocky appearance. Many fossils silicified; allochems include brachiopods (e.g. Dinorthis holdeni (Willard)), ramose and encrusting bryozoans, gastropods, echinoderms (e.g. Carabocrinus), sponges and spicules, trilobites, ostracodes, orthoconic cephalopods, algal (Girvanella) oncolites, detrital quartz grains, peloids, and dolomite rhombs. Samples: E-12.6, 60.8 m; E-14, 62.2 m.
	3.0	65.5	COVERED
11 (cont.)	12.1	77.6	Same as above. Upper 4.4 meters of algal-bryozoan boundstone (Girvanella - trepostome biolithite). Samples: E-17.5, 65.7 m; E-18, 66.2 m; E-20.1, 68.3 m; E-22, 70.2 m; E-24.5, 72.7 m; E-25, 73.2 m; E-26, 74.2 m; E-28, 76.2 m. TOTAL EIDSON MEMBER = 61.6 METERS.
	5.8	83.4	COVERED
12	1.2	84.6	Lincolnshire Formation (Fleanor Member) - NEXT 1 UNIT: Whiteish tan to yellowish brown and light gray, fine to medium grained, very thin to thin bedded, shaly dismicrite. Beds weather into small (1-15 cm), thin (0.5 - 2 mm) chips. Small scale cross laminations present on weathered surfaces. Constituents include algae (Girvanella clasts and oncolites, Spongiostroma, Hedstroemia, Solenopora), detrital quartz, peloids, ostracodes, brachiopods, gastropods (e.g. Raphistoma staminea Hall) and corals (Tetradium, form T. syringoporoides). Horizontal burrows common and vertical burrows rare. Samples: F-6, 83.6 m; F-7A, 84.6 m; F-7B, 84.6 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
	5.0	89.6	COVERED
12 (cont.)	3.4	93.0	Thinly bedded, medium gray, fine to medium grained, well sorted, calcareous siltstone/silty pelsparite (up to 45% quartz silt). Small scale (10 mm) trough cross laminations and vertical burrows common. Samples: F-12 FL., 89.6 m; F-15, 92.6 m.
	7.1	100.1	COVERED
12 (cont.)	0.2	100.3	Same as above Samples: F-22.5, 100.1 m.
	6.3	106.6	COVERED
12 (cont.)	13.0	119.6	Yellow to maroon, fine grained, thick to very thick bedded, calcareous shale, siltstone, and silty biomicrite, interbedded with white to medium gray, medium to coarse grained, thin to medium bedded, biosparite. Vertical burrows, boudin shaped micrite intraclasts, and physical soft sediment deformation features are abundant. Constituents include echinoderms, detrital quartz grains, bryozoans, gastropods, brachiopods, peloids, ostracodes, trilobites and algae (Girvanella oncolites, and Nuia). Samples: F-29, 106.6 m; F-32.5A, 110.1 m; F-32.5B, 110.1 m; F-33, 110.6 m; F-33.3, 110.9 m; F 33.5, 111.1 m; F-36, 113.6 m; F-37, 114.6 m; F-38, 115.6 m; F-39, 116.6 m; F-40, 117.6 m; F-41.5, 119.1 m. TOTAL FLEANOR MEMBER = 42 METERS.
13	20.7	140.3	Lincolnshire Formation (Hogskin Member) - NEXT 1 UNIT: Light to medium dark gray, fine to coarse grained, well sorted, thin to thick bedded, quartz siltstone, biomicrite, and pelbiomicrite, interbedded with greenish yellow, light brown, and maroon, fine grained, very thin to very thick bedded, siltstone and calcareous shale. Shales erode producing a cobbly appearance to biomicrites and pelbiomicrites. Mudcracks,

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
			small (1 - 5 cm) trough crossbeds, vertical burrows, and interlaminar birdseyes common in siltstones and dismicrites. Massive biomicrites sulfurous. Fossil allochems include echinoderms, bryozoans, peloids, trilobites, ostracodes, bivalves, gastropods, inarticulate phosphatic brachiopods, algae (Girvanella, Solenopora, Nuia, Hedstroemia, Kazakhstanelia), and intraclasts. Samples: F 42 FL.A, 119.6 m; F-42 FL.B., 119.6 m; F-43, 120.6 m; F-44, 121.6 m; F-46.5, 124.1 m; F-49, 126.6 m; F-50A, 127.6 m; F-50B, 127.6 m; F-53, 130.6 m; F-55, 132.6 m; F-58, 135.6 m; F-59, 136.6 m. TOTAL HOGSKIN MEMBER = 20.7 METERS. TOTAL LINCOLNSHIRE FORMATION - 124.3 METERS.
14	28.5	168.8	Rockdell Formation - NEXT 2 UNITS: Medium gray, medium to coarse grained, poorly to moderately sorted, massively bedded, biomicrite and biosparite, interbedded with oval to lensoid, dark gray, chert pods. Weathering produces a sugary texture. Allochems include echinoderms, trilobites, gastropods, articulate brachiopods, phyloporinnid bryozoans, peloids, sponge spicules, algae (Girvanella clumps, tubules and oncolites, Nuia, Hedstroemia, Kazakhstanelia, Spongiostroma, and Sphaerocodium), and intraclasts. Anastomosing stylolites common. Samples: R-LC, 140.3m; R-2, 142.3m; R-4, 144.3 m; R-7, 147.3 m; R-9, 149.3 m; R-11, 151.3 m; R-13.5, 153.8 m; R-16, 156.3 m; R-19.5, 159.8 m; R-25.5, 165.8 m; R-28, 168.3 m.
15	5.5	174.3	Medium to dark gray, coarse grained, poorly to well sorted, massively bedded biosparite. Rocks thinner bedded than Unit 14 because of greater terrigenous clastic input. Constituents

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
			include trilobites, echinoderms, intraclasts, peloids, brachiopods, bryozoans, ostracodes, gastropods, Girvanella, and Kazakhstanelia. Samples: R-31.5, 171.8 m; R-UC, 174.3 m. TOTAL ROCKDELL FORMATION = 34 METERS
16	4.0	178.3	Benbolt Formation - NEXT 7 UNITS: Light to medium gray, medium grained, thinly bedded, biomicrite and cherty biomicrite, interbedded with small hummocky shale drapes. Bryozoans, bivalves, echinoderms, ostracodes, trilobites, brachiopods, Nuia and Girvanella prominent. Chert replaces locally. Samples: Bn-LC, 174.3 m; Bn-2, 176.3 m.
17	27.7	206.0	Shale interbedded with light to medium gray, medium to coarse grained, poorly sorted, thin to medium bedded, biomicrite and biosparite. Thin bedded shale drapes and abundant stylolites produces cobbly appearance. Constituents include echinoderms, bryozoans, trilobites, ostracodes, bivalves, gastropods, articulate brachiopods (Dinorthis transversa Willard, Sowerbyella compacta Cooper, Hesperorthis sp. A, and Mimella globosa (Willard)), sponges (Allosaccus) and spicules, algae (Nuia, Girvanella oncolites, Solenopora, Hedstroemia, Kazakhstanelia, Contexta, and Receptaculites), and algal mats. Samples: Bn-4, 178.3 m; Bn-7, 181.3 m; Bn-11.5, 185.8 m; Bn-15, 189.3 m; Bn-17, 191.3 m; Bn-20, 194.3 m; Bn-23.8, 198.1 m; Bn-26.5, 200.8 m; Bn-31.6, 205.9 m.
	6.5	212.5	COVERED (ROAD)
17 (cont.)	2.8	215.3	Same as above. Samples: Bn-38.2, 212.5 m; Bn-39, 213.3 m; Bn-40, 214.3 m; Bn-41, 215.3 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
	8.0	223.3	COVERED
18	3.1	226.4	Medium gray, medium to coarse grained, moderately sorted, massively bedded, and resistant, biomicrite and biosparite. Unit weathers similar to massive Rockdell Formation. Stylolites abundant on outcrop. Allochems include echinoderms (up to 50% volume), bryozoans, brachiopods, Girvanella clasts, and few ostracodes and trilobites. Samples: Bn-49, 223.3 m; Bn-50, 224.3 m.
19	8.9	235.3	Shaly calcareous mudstone. Mostly covered in outcrop. Rarely small cobbles weather out. Fossils include bryozoans, brachiopods and echinoderms. No samples.
20	21.5	256.8	Medium to dark gray, medium to coarse grained, poorly sorted, cobbly biomicrite interbedded with shale. Weathering produces tabular biomicrite sets (several m's long). Allochems include algae (Girvanella oncolites, Nuia, Contexta, Kazakhstanelia, Hedstroemia, and Vermiporella), bryozoans, echinoderms, trilobites, gastropods, bivalves, brachiopods, ostracodes, and sponge spicules. Many algal derived peloids and oval fecal pellets concentrated in thin spar rich bands. Samples: Bn-61, 235.3 m; Bn-66, 240.3 m; Bn-68, 242.3 m; Bn-70, 244.3 m; Bn-75, 249.3 m; Bn-78, 252.3 m; Bn-81, 255.3 m.
21	4.5	261.3	Tan to light brown, well sorted, fine grained, very thinly bedded, calcareous shale and dismicrite. Weathers into small, thin (1 x 6 mm) chips. Peloids and horizontal burrows common. Samples: Bn-86, 260.3 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
22	8.4	269.7	Medium gray, medium to coarse grained, cobbly interbedded calcareous mudstone, biomicrite and biosparite. Weathers into cobbles similar to units 17 and 20. Allochems include bryozoans, echinoderms, brachiopods, trilobites, molluscs and dolomite rhombs. Samples: Bn-91, 265.3 m; Bn-95, 269.3 m. TOTAL BENBOLT FORMATION = 95.4 METERS.
23	6.0	275.7	Wardell Formation - NEXT 4 UNITS: Light to medium gray, fine to coarse grained, medium bedded, biomicrite and biosparite. Stylolites and thin shale drapes common. Allochems include bivalves, echinoderms, brachiopods, bryozoans, trilobites, and ostracodes. Algae (Girvanella oncolites common, Nuia and Hedstroemia rare) present only at base of section. Lower 11.6 meters contains (5-10%) micropeloids; upper 6 meters contains (up to 45%) peloids. Samples: Bn-95.4, 269.7 m; W-6, 275.7 m.
	5.4	281.1	COVERED
23 (cont.)	0.6	281.7	Same as above Samples: W-11.4, 281.1 m.
	11.0	292.7	COVERED
23 (cont.)	6.0	298.7	Same as above Samples: W-23, 292.7 m.
24	0.3	299.0	Light gray, medium to coarse grained, poorly to medium sorted, thinly bedded, algal pelmicrite. Exposures limited. Constituents include peloids, algae (Solenopora, Girvanella oncolites, Hedstroemia, Contexta), ostracodes, trilobites, gastropods, echinoderms, and corals (Tetradium, form T. syringoporoides). Samples: W-29, 298.7 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
	10.7	309.7	COVERED
25	5.0	314.7	Few outcrops - mostly covered. No samples.
25 (cont.)	9.0	323.7	Light gray, fine grained, very thin to medium bedded calcareous peloidal dismicrite. Weathers as small chips. Vertical burrows common. Samples: W-45, 314.7 m; W-50, 319.7 m.
26	2.4	326.1	Light gray, coarse grained, thin to medium bedded extremely poorly sorted, biomicrite. Field exposures poor. Allochems include bivalves, brachiopods, ostracodes, trilobites, gastropods, and rare echinoderms and bryozoans. Samples: W-55, 324.7 m. TOTAL WARDELL FORMATION = 56.4 METERS.
27	5.8	331.9	Bowen Formation - NEXT 1 UNIT: Tan to yellow brown, thin to medium bedded, calcareous shale and silty dismicrite. Vertical burrows abundant. Exotic allochems include algae (Solenopora, Girvanella oncolites), inarticulate phosphatic brachiopod and articulate brachiopod fragments, bryozoans, gastropods, echinoderms, ostracodes, trilobites, intraclasts, peloids, and detrital quartz grains. Samples: B-0, 326.1 m; B-3, 329.1 m; B-5.2, 331.3 m. TOTAL BOWEN FORMATION = 5.8 METERS.
28	12.0	343.9	Witten Formation - NEXT 4 UNITS: Light to medium gray, fine to very coarse grained, thinly bedded, dismicrite, biomicrite, and pelbiosparite. Constituents include peloids, brachiopods, echinoderms, ostracodes, trilobites, bryozoans and Hedstroemia. Samples: Wi-LC, 331.9 m; Wi-6, 337.9 m; Wi-12, 343.9 m.

Unit #	Unit Thk(m.)	Cumul. Thk(m.)	Description
29	31.0	374.9	Medium gray, fine to coarse grained, massive and resistant, dismicrite and biomicrite. Allochems include peloids, trilobites, bryozoans, bivalves, brachiopods, echinoderms, ostracodes, and gastropods. Horizontal burrows prevalent. Samples: Wi-15.5, 347.4 m; Wi-27, 358.9 m; Wi-30, 361.9 m; Wi-36, 367.9 m.
30	44.0	418.9	Medium gray, fine to very coarse grained, extremely poorly sorted, thinly bedded, cobbly, interbedded dismicrite and biopelsparite. Constituents include peloids, echinoderms, brachiopods, bivalves, trilobites, ostracodes, bryozoans, Solenopora, intraclasts, and dolomite rhombs. Bioturbation intense. Peloidal fining upward sequences common. Samples: Wi-44, 375.9 m; Wi-60, 391.9 m; Wi-69, 400.9 m; Wi-78, 409.9 m.
31	6.0	424.9	Light to medium gray, to green, extremely fine grained, thin to medium bedded, dismicrite. Horizontal and vertical fenestral birdseyes prominent. Samples: Wi-87, 418.9 m; Wi-90.5, 422.4 m. TOTAL WITTEN FORMATION = 93 METERS.

The Witten is directly overlain by the Moccasin Formation which was not measured and is therefore of undetermined thickness. The Moccasin is truncated by the Copper Creek Thrust Fault.

APPENDIX B

PETROGRAPHIC CONSTITUENT ANALYSIS

Table B-1. Constituent particle analyses (rock volume percent) for selected thin sections.

Sample Numbers	Micrite	Microspar	Spar	Brachiopod Fragments	Bivalves	Bryozoans	Trilobite Debris	Gastropods	Ostracode Valves	Echinoderm Debris	Algae	Oncolites	Sponge Debris	Clay Laminae & Other Fossils	Unidentifiable Fossil Material	Intraclasts	Peloids	Detrital Quartz	Dolomite Rhombs
K-18	21.0	8.2	29.0	<1.0	0.0	0.0	0.7	0.0	1.0	1.4	<1.0	0.0	<1.0	3.4	8.2	<1.0	27.0	0.0	0.0
K-23	6.5	9.1	29.5	0.8	0.0	2.8	4.4	6.0	1.3	8.5	3.1	0.0	0.0	0.0	9.8	1.0	17.1	0.0	0.0
K-34	0.0	1.5	37.4	0.7	0.0	2.2	3.4	4.6	1.0	11.5	4.1	0.0	0.0	11.0	8.8	1.0	12.7	0.0	0.0
K-43	40.6	0.8	16.2	0.0	0.0	2.4	3.8	0.0	1.2	3.8	16.0	0.0	0.0	0.8	6.9	2.2	4.4	1.0	0.0
K-49.3	17.3	3.6	9.6	0.0	0.0	0.2	2.2	20.9	1.6	1.2	29.7	0.0	0.0	0.0	10.0	0.0	3.8	0.0	0.0
E-0	0.0	0.0	33.2	0.6	0.0	15.7	0.9	0.0	0.6	28.0	0.6	0.0	0.0	0.0	7.7	0.0	12.6	0.0	0.0
E-11	50.0	0.0	0.0	0.0	0.0	1.3	1.8	1.8	2.0	0.0	7.0	0.3	28.0	0.0	8.0	0.0	0.0	0.0	0.0
E-22	58.9	3.8	0.8	5.7	0.0	3.6	4.4	0.0	2.2	10.4	1.1	0.0	1.4	0.0	1.4	0.0	2.2	0.0	4.4
E-25	36.0	4.0	1.0	0.7	0.0	4.2	2.0	0.4	0.4	0.4	3.0	0.0	31.0	0.0	12.0	0.0	0.0	5.0	0.0
F-7B	37.9	1.4	12.7	0.3	0.0	0.0	0.0	0.6	0.9	0.0	19.6	9.0	0.0	<1.0	9.5	0.0	0.9	7.2	0.0

Table B-1 (continued).

Sample Numbers	Micrite	Microspar	Spar	Brachiopod Fragments	Bivalves	Bryozoans	Trilobite Debris	Gastropods	Ostracode Valves	Echinoderm Debris	Algae	Oncolites	Sponge Debris	Clay Laminae & Other Fossils	Unidentifiable Fossil Material	Intraclasts	Peloids	Detrital Quartz	Dolomite Rhombs
F-22.5 FL.	34.0	0.0	3.6	0.0	0.0	7.9	0.0	1.5	0.6	22.5	0.0	0.0	0.0	0.0	12.5	0.0	0.0	17.3	0.0
F-33.3	0.0	24.6	20.5	1.0	0.0	6.4	0.5	0.3	0.5	25.4	9.0	4.1	0.0	1.3	5.6	0.0	0.8	0.0	0.0
F-42 FL.A	29.3	11.1	2.7	1.9	0.0	11.4	0.5	0.5	1.1	21.4	0.8	0.0	0.0	0.3	8.1	0.5	3.8	6.5	0.0
F-43	6.4	9.9	13.0	0.6	3.6	29.1	2.8	1.9	1.9	8.3	7.3	0.0	1.1	3.6	4.7	0.0	5.8	0.0	0.3
F-53	17.1	29.2	3.1	2.0	0.8	5.3	2.5	0.3	2.5	14.6	3.5	0.8	0.0	0.0	11.0	0.0	6.2	1.1	0.0
R-LC	25.8	48.4	4.2	0.0	0.0	4.7	1.9	2.4	1.2	3.0	1.3	0.0	0.0	3.7	2.4	0.0	3.3	0.0	0.0
R-11	7.2	35.8	20.9	0.6	0.0	5.9	0.0	0.6	2.5	13.4	2.0	3.4	0.0	1.2	3.7	0.6	2.2	0.0	0.0
R-25.5	3.0	16.0	34.1	0.0	1.1	4.4	0.8	1.9	1.9	22.5	10.3	0.3	1.4	0.6	0.6	0.0	1.4	0.0	0.0
R-31.5	6.4	1.0	47.2	2.8	0.3	2.6	4.1	0.3	1.8	12.6	1.8	0.0	0.0	4.4	0.3	8.5	5.9	0.0	0.0
BN-2	29.7	41.8	3.9	0.3	0.6	4.5	0.3	0.0	1.2	3.0	0.6	0.0	0.0	0.0	14.2	0.0	0.0	0.0	0.0

Table B-1 (continued).

Sample Numbers	Micrite	Microspar	Spar	Brachiopod Fragments	Bivalves	Bryozoans	Trilobite Debris	Gastropods	Ostracode Valves	Echinoderm Debris	Algae	Oncolites	Sponge Debris	Clay Laminae & Other Fossils	Unidentifiable Fossil Material	Intraclasts	Peloids	Detrital Quartz	Dolomite Rhombs
BN-4	23.5	15.3	21.4	0.8	0.8	12.4	2.4	0.0	1.1	15.3	1.6	1.3	0.0	0.0	4.0	0.0	0.0	0.0	0.0
BN-40	14.7	29.0	3.3	4.8	2.1	6.9	0.9	1.2	0.6	10.0	9.0	1.5	0.0	0.0	15.6	0.0	0.6	0.0	0.0
BN-49	0.0	1.1	27.4	1.1	0.0	5.0	0.3	0.0	0.5	52.6	10.3	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0
BN-68	22.1	0.0	2.3	2.1	2.1	13.7	3.4	2.3	1.3	8.8	5.3	2.1	0.3	2.3	8.1	23.9	0.0	0.0	0.0
BN-95	36.7	2.4	7.5	6.7	0.0	26.3	4.3	0.0	0.0	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2
BN-95.4	41.8	19.7	0.0	2.1	5.6	1.5	0.9	0.0	0.6	6.8	1.2	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0
W-29	15.7	31.5	8.8	0.0	0.0	0.0	0.7	0.0	2.4	0.3	18.3	0.0	0.0	4.3	2.7	0.0	15.3	0.0	0.0
W-55	64.5	7.8	0.0	3.8	10.5	1.2	1.5	1.5	2.6	0.9	0.0	0.0	0.0	0.0	5.8	0.0	0.0	0.0	0.0
Wi-12	9.8	0.3	39.5	10.7	0.0	1.5	1.8	0.0	1.8	2.4	0.9	0.0	0.0	0.0	5.2	0.0	26.0	0.0	0.0
Wi-27	70.2	0.0	9.9	0.6	0.9	2.3	2.6	0.0	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	12.5	0.0	0.0

Table B-1 (continued).

Sample Numbers											
Micrite	7.4	0.6									
Microspar	0.6	0.0									
Spar	11.3	34.0									
Brachiopod Fragments	3.5	8.8									
Bivalves	0.0	6.5									
Bryozoans	0.0	1.7									
Trilobite Debris	3.2	2.3									
Gastropods	0.0	0.0									
Ostracode Valves	0.6	0.3									
Echinoderm Debris	3.5	10.2									
Algae	<1.0	<1.0									
Oncolites	0.0	0.0									
Sponge Debris	0.0	0.0									
Clay Laminae & Other Fossils	0.0	0.0									
Unidentifiable Fossil Material	3.5	5.4									
Intraclasts	0.0	0.3									
Peloids	61.1	27.5									
Detrital Quartz	0.0	0.0									
Dolomite Rhombs	5.1	2.5									
	Wi-44	Wi-78									

APPENDIX C

FOSSIL ASSEMBLAGES OF THE BENBOLT FORMATION

FOSSIL ASSEMBLAGES OF THE BENBOLT FORMATION

BED 7.6:

Brachiopods:
Strophomena medialis Butts
Hesperorthis sp. A (= *Hesperorthis* sp. 2 of Cooper, 1956)

Echinoderms:
Crinoids:
Hybocrinus punctatus (Miller & Gurley)
Carabocrinus sp.
Carabocrinus micropunctatus Brower & Veinus
Paleocrinus planobasalis Brower & Veinus

Rhombiferans:
Regulaecystis pyriformis (Parsley)

Blastoids:
Macurdablastus uniplicatus Broadhead

Columnals

Trilobites:
Isotelus sp.
Illaneus sp.
Calyptaulax sp.
cf. *Bumastus* sp.
unidentifiable debris

Bryozoans:
Branching
Cuplike
Encrusting
Phyloporinnid
Cylindrical

Algae:
Girvanella sp.

BED 10.9:

Brachiopods:
cf. *Dinorthis transversa* Willard

Echinoderms:
Crinoids:
(?) *Diabolocrinus vesperalis* (White)

Rhombiferans:
Rhombiferan A (undescribed)

columnals

Trilobites:
unidentifiable cephalon

Bryozoans:
Branching

Algae:
Girvanella sp.

BED 20:	Echinoderms:	Crinoids: Diabolocrinus vesperalis (White)
		columnals
	Bryozoans:	Branching
BED 31:	Brachiopods:	Hesperorthis (?)
	Echinoderms:	Eocrinoids: Ulrichocystis eximia Bassler
		Rhombiferans: Coronocystis angulatus (Wood)
		columnals
	Trilobites:	unidentifiable fragments
	Bryozoans:	Branching Cylindrical Encrusting Phyloporinnid
	Algae:	Girvanella sp.
BED 39:	Brachiopods:	Sowerbyella compacta Cooper
	Echinoderms:	Crinoids: Diabolocrinus vesperalis (White)
		Rhombiferans: Coronocystis angulatus (Wood)
		columnals
	Bryozoans:	Branching
	Algae:	Girvanella sp.
BED 56:	Brachiopods:	Sowerbyella compacta Cooper
	Echinoderms:	columnals

BED 63:	Brachiopods:	Sowerbyella compacta Cooper
		Mimella (?)
	Echinoderms:	Crinoids:
		Archaeocrinus peculiaris (Miller & Gurley)
		Paleocrinus planobasalis Brower & Veinus
		Carabocrinus stellifer Brower & Veinus
		Columnals
	Bryozoans:	Branching
		Encrusting
		Cylindrical
	Gastropods:	Gastropod A
	Algae:	Kazakhstanelia sp.
BED 81.2:	Brachiopods:	Sowerbyella compacta Cooper
		Dinorthis transversa Willard
		cf. Mimella
		cf. Hesperorthis
	Echinoderms:	columnals
	Bryozoans:	Branching
BED 89.1:	Brachiopods:	Sowerbyella compacta Cooper
		Mimella sulcata Cooper
		Mimella globosa (Willard)
		Hesperorthis
	Echinoderms:	Crinoids:
		Hybocrinus punctatus (Miller & Gurley)
		Diabolocrinus vesperalis (White)
		Archaeocrinus peculiaris (Miller & Gurlay)
		Pentamere stem
		columnals
	Bryozoans:	Branching
		phyloporinnid
BED 95:	Echinoderms:	Crinoids:
		Carabocrinus stellifer Brower & Veinus
		columnals
	Bryozoans:	Branching
		Encrusting

Algae: *Girvanella* sp.

Gastropods: Gastropod A

APPENDIX D

SLAB SURFACE CONSTITUENT ANALYSIS AND BIOVOLUME CONSTITUENT ANALYSIS OF THE BENBOLT FORMATION

Table D-1. Slab surface constituent analysis of the Benbolt Formation.

Bed Number	Matrix	Brachiopods	Echinoderms	Ostracodes & Trilobites	Branching Bryozoans	Encrusting Bryozoans	Phyloporinnid Bryozoans	Unidentifiable Material
7.6	53.3	1.4	1.0	1.2	10.7	0.0	0.0	32.4
10.9	77.3	0.3	16.8	0.3	1.5	0.0	0.0	3.8
20	41.4	0.0	57.6	0.0	1.0	0.0	0.0	0.0
31	44.2	0.8	17.3	0.3	17.9	5.4	1.5	12.4
39	49.0	48.6	1.0	0.0	0.7	0.0	0.0	0.8
56	38.0	61.7	0.4	0.0	0.0	0.0	0.0	0.0
63	51.8	2.9	34.6	0.0	9.5	0.0	0.0	1.2
81.2	46.2	40.1	1.6	0.4	3.3	0.0	0.0	8.5
89.1	32.0	3.8	11.2	0.0	42.0	0.0	4.5	6.6
95	50.0	1.0	30.6	0.0	15.6	2.0	0.0	0.9

Table D-2. Biovolume percentages for the Benbolt Formation.

Bed Number	Brachiopods	Echinoderms	Ostracodes & Trilobites	Branching Bryozoans	Encrusting Bryozoans	Phyloporinnid Bryozoans	Unidentifiable Material
7.6	3.1	2.0	2.6	23.0	0.0	0.0	69.3
10.9	1.5	74.0	1.5	6.5	0.0	0.0	16.5
20	0.0	98.4	0.0	1.6	0.0	0.0	0.0
31	1.5	31.1	0.6	32.1	9.7	2.7	22.3
39	95.2	2.0	0.0	1.3	0.0	0.0	1.5
56	99.4	0.6	0.0	0.0	0.0	0.0	0.0
63	6.1	71.8	0.0	19.7	0.0	0.0	2.5
81.2	74.4	3.0	0.7	6.2	0.0	0.0	15.8
89.1	5.4	16.5	0.0	61.8	0.0	6.6	9.7
95	2.0	61.0	0.0	31.1	4.1	0.0	1.8

APPENDIX E

PLATES

Plate E-1. Selected slabs from the Benbolt Formation.

A. Slab # 7.6: Biomicrite (Wackestone) located in unit 17.

B. Slab # 20: Biosparite (packstone) located in unit 17.

C. Slab # 39: Biomicrite/biosparite (packstone) located in unit 17.

D. Slab # 56: Biomicrite (wackestone) located in unit 19.

E. Slab # 63: Biomicrite (packstone) located in unit 20.

F. Slab # 81.2: Biomicrite (packstone) located in unit 20.

G. Slab # 89.1: Biosparite (wackestone) located in unit 22.

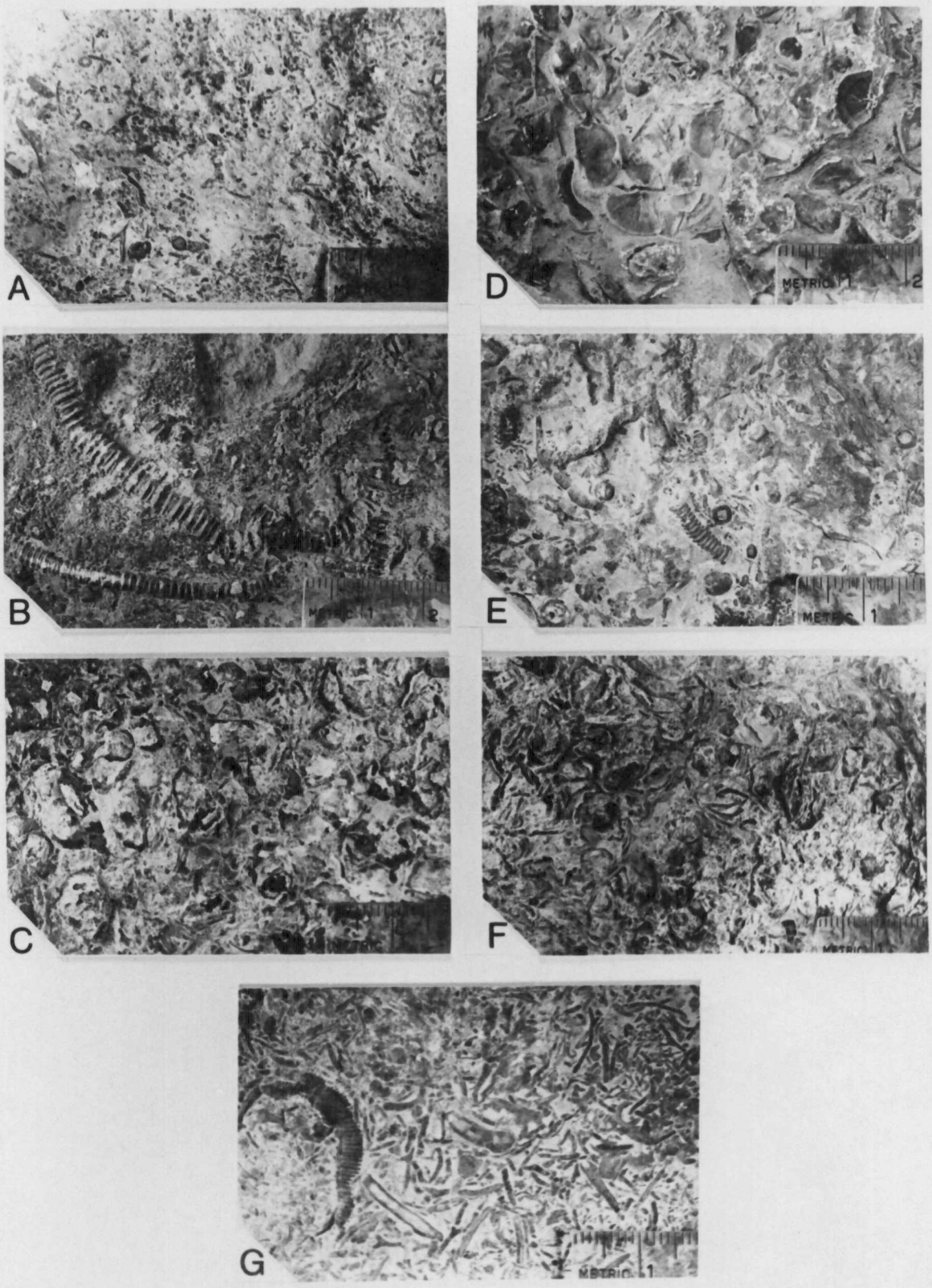


Plate E-1.

Plate E-2. Brachiopoda.

A, B, C. Dinorthis transversa, pedicle, brachial, and posterior views of the same specimen, 3X (bed 81.2).

D, E, F. Mimella sulcata, pedicle, brachial, and posterior views of the same specimen, 3X (bed 89.1).

G. H. I. Hesperorthis sp. A, pedicle, brachial, and posterior views of the same specimen, 3X (bed 7.6).

J. Strophomena medialis, pedicle view, 2X (bed 7.6).

K. Sowerbyella compacta, interior view of pedicle valves, 5X (bed 56).

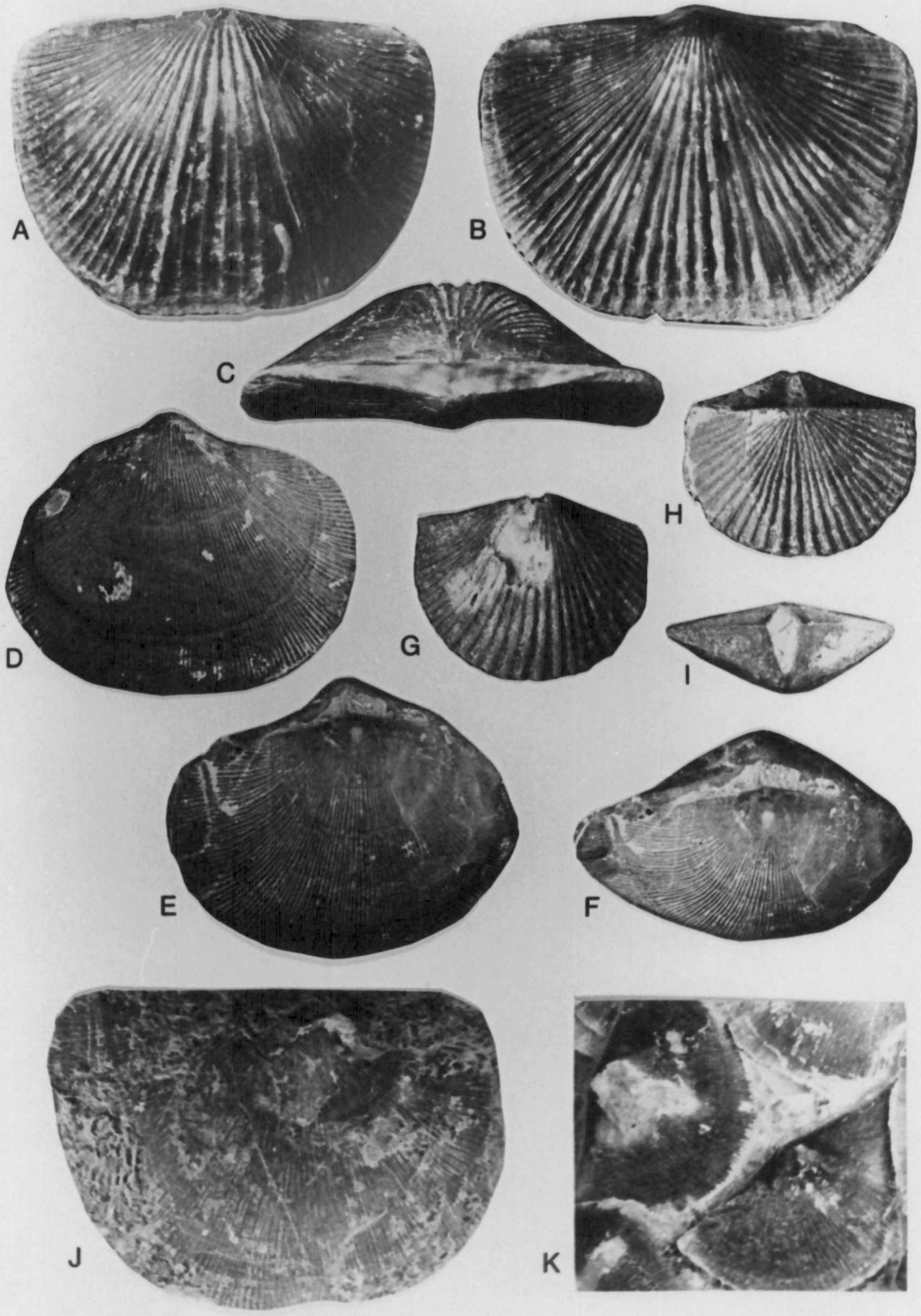


Plate E-2.

Plate E-3. Crinoidea.

A. Carabocrinus sp., radial plate, 5X, bed 7.6.

B. Carabocrinus stellifer, radial plate, 3X, bed 95.

C. Carabocrinus micropunctatus, (?) basal plate, 5X, bed 7.6.

D. Palaeocrinus planobasalis, plate, 5X, bed 7.6.

E. Hybocrinus punctatus, plate, 5X, bed 89.1.

F,G. Archaeocrinus peculiaris, plate, 10X, and base of calyx, 3X, bed 63.

H,I,J, Diabolocrinus vesperalis, base of calyx, 5X, bed 20, pinnules, 3X, bed 20, and arm plate, 3X, bed 89.1.

K. Pentamere stem, 3X, bed 89.1.

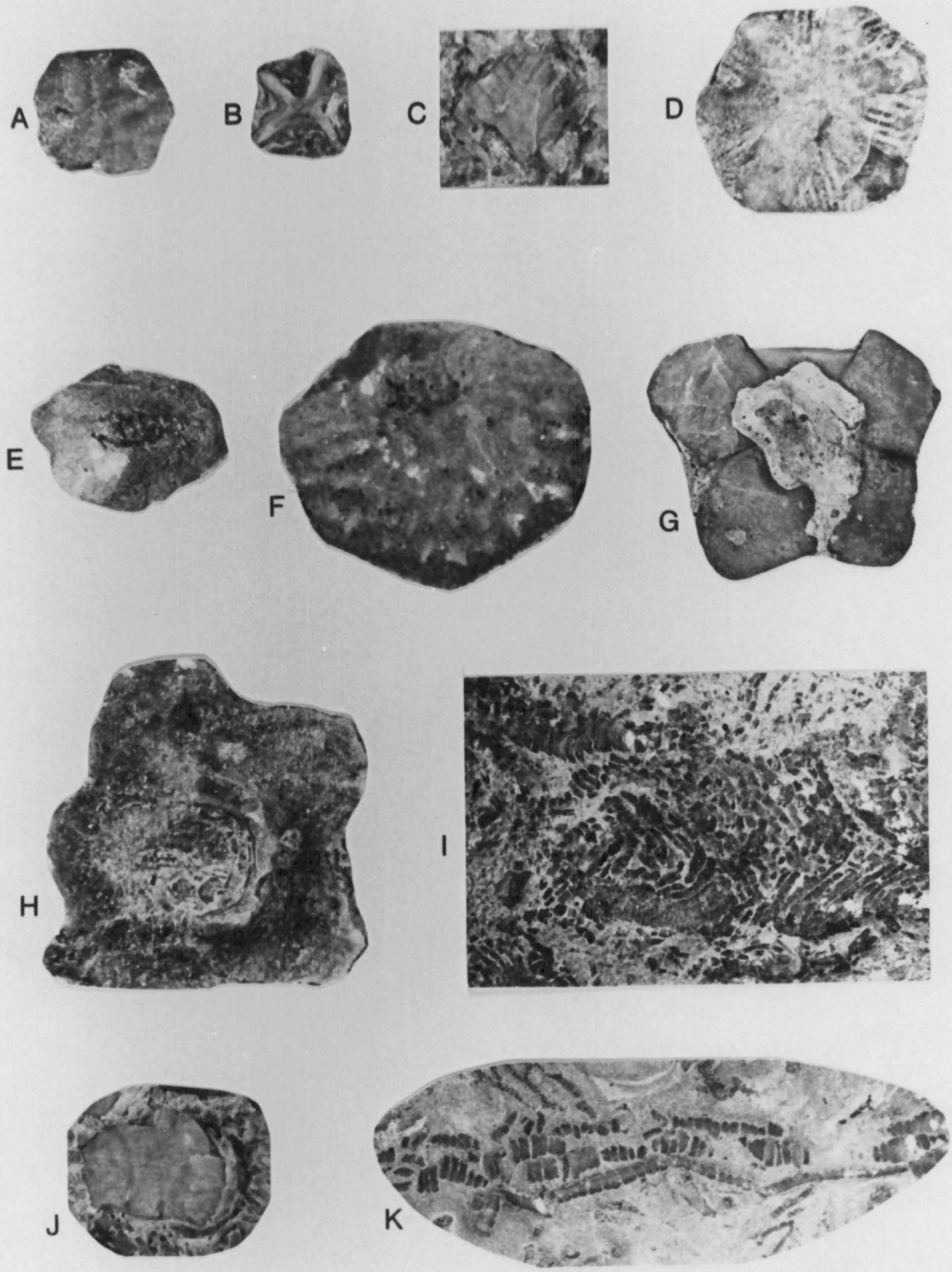


Plate E-3.

Plate E-4. Rhombifera (A-C), Blastoidea (D), Paracrinoidea (E), and holdfasts (F).

A. Coronocystis angulatus, plate, 10X, bed 39.

B. Regulaecystis pyriformis, plate, 5X, bed 7.6.

C. Rhombiferan A (undescribed), plate, 10X, bed 10.9.

D. Macurdablastus uniplicatus, plate, 10X, bed 7.6.

E. Ulrichocystis eximia, plate, 10X, bed 31.

F. Holdfasts, 1X, hand specimen from bed 10.9.

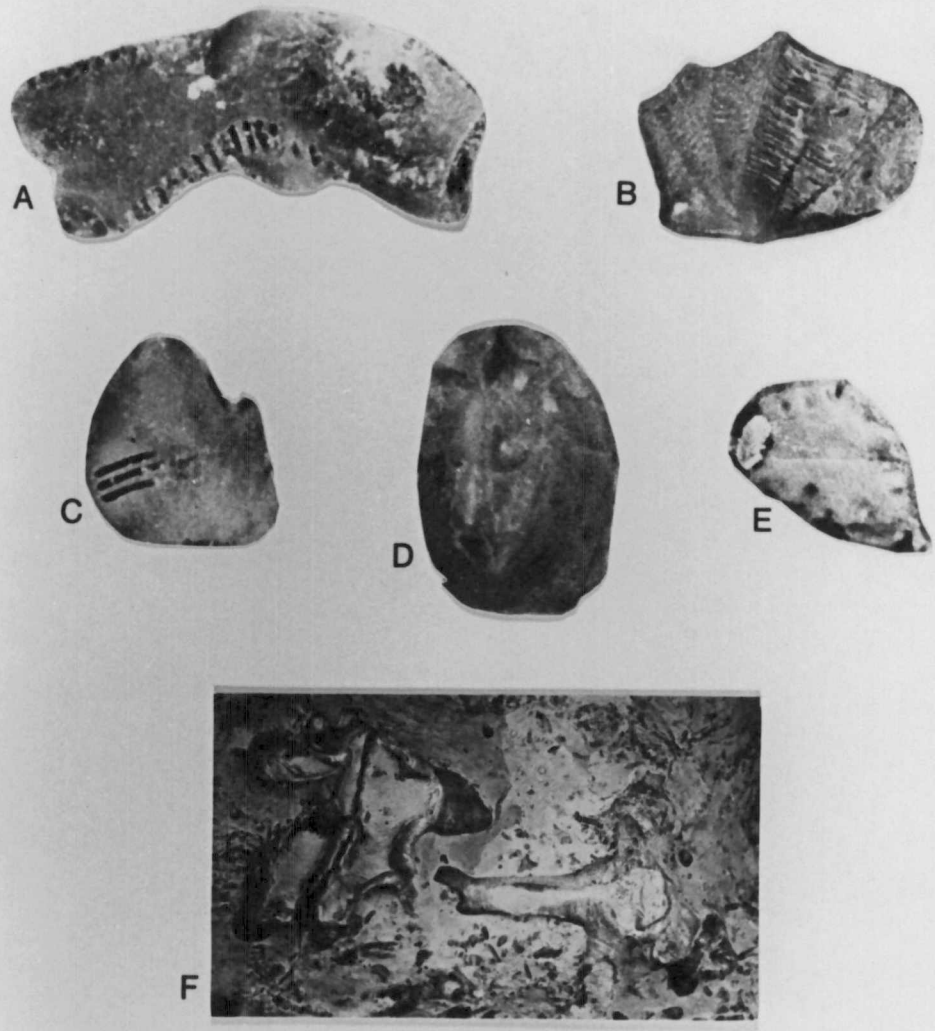


Plate E-4.

Plate E-5. Trilobita (A-C), Gastropoda (D-G), and Bryozoa (H-L).

A. Isotelus sp., dorsal view of cephalon, 3X, bed 7.6.

B. Illaneus sp., dorsal view of pygidium, 5X, bed 7.6.

C. Calyptaulax sp., dorsal view of cephalon, 5X, bed 7.6.

D. Gastropod A, 10X, bed 63.

E,F,G. Raphistoma staminea, apertural, umbilical, and spiral views, 4X, hand specimen from the Benbolt Formation.

H. Phyloporinnid bryozoan, 3X, bed 7.6.

I. Cylindrical bryozoan, 5X, bed 7.6.

J. Cuplike bryozoan, 5X, bed 7.6.

K. Encrusting bryozoan, 3X, bed 63.

L. Branching bryozoan, 3X, bed 7.6.

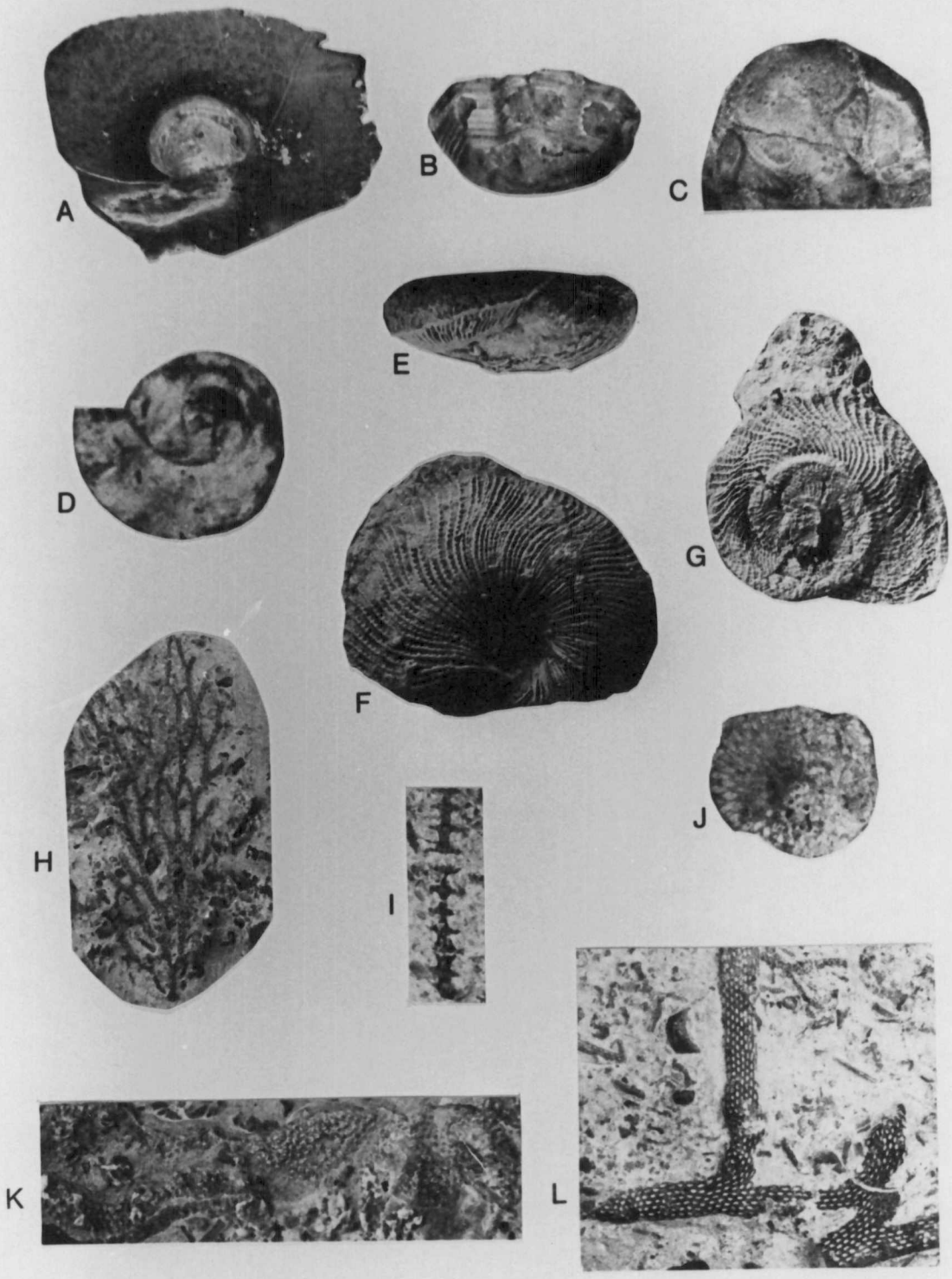


Plate E-5.

Plate E-6. Algae.

A. Girvanella sp., view of Girvanella oncolites, 10X, sample Bn-41.

B. Girvanella sp., loose tubules, 60X, sample R-2.

C. Solenopora (type P), transverse view, 7X, sample K-43.

D. Nuia sp., transverse view, 80X, sample E-11.

E. Spongiostroma sp., 12X, sample K-49.3.

F. Kazakhstanelia sp., longitudinal view, 10X, sample F-53.

G. Vermiporella sp., oblique view, 20X, sample Bn-66.

H. Contexta sp., transverse view, 20X, sample Bn-68.

I. Sphaerocodium sp., longitudinal view, 20X, sample R-LC.

J. Hedstroemia sp., transverse view of tubules, 12X, sample K-49.3.

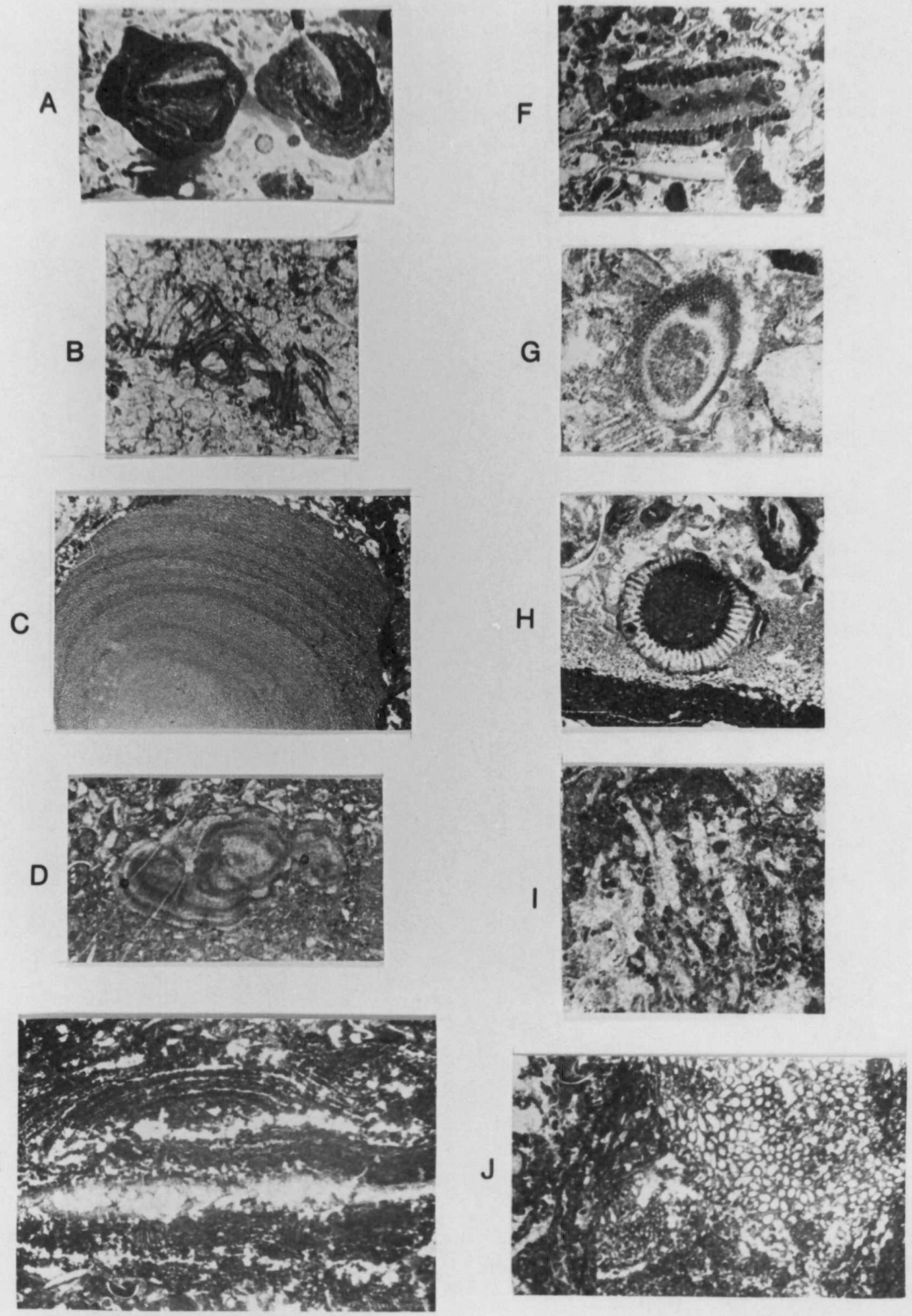


Plate E-6.

VITA

James Kenneth Ashworth was born in Chattanooga, Tennessee on December 14, 1955. He attended elementary, junior high, and senior high schools in Calhoun, Georgia, and graduated from high school in June 1974. He entered West Georgia College, Georgia, in September 1974, and graduated in June 1979 with a Bachelor of Arts degree in geology. In September 1979, he entered The University of Tennessee at Knoxville and graduated with a Master of Science degree in August 1982. He started work for Exxon U.S.A. Company, New Orleans, Louisiana, in August 1982.