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ENVIRONMENTAL SEDIMENTOLOGY OF THE LOWER MIDDLE ORDOVICIAN IN THE LAY SCHOOL SECTION HOGSKIN VALLEY, GRAINGER COUNTY, TENNESSEE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ernest L. Ewing, Jr.

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Mrs. Mary Lu Weaver Ewing, for her unbelievable patience and unceasing hope. Now that I've finally finished, perhaps she can focus on raising the price of oil so that I can repay her.

ABSTRACT

Approximately 450 meters of Middle Ordovician rocks are exposed at Lay School, Hogskin Valley, Tennessee. This sequence is composed of seven formations, in ascending order: Blackford Formation, Lincolnshire Formation (Elway Member, Hogskin Member, and Upper Member, respectively), Rockdell Formation, Benbolt Formation, Wardell Formation, Bowen Formation, and Witten Formation. The top of the Section is cut by the Copper Creek Fault which brings the Cambrian Rome Formantion onto Middle Ordovician Moccasin Formation (the latter not studied here). Detailed petrographic examination of 302 thin-sections of these rocks was made for environmentally relevant fossil and sediment features selected from taphonomic, paleontologic, and sedimentologic studies. Presence/absence information was collected on 51 such features or parameters and 255 samples were subjected to Q-mode multivariate cluster analysis to reveal groups of samples with similar environmental aspect. The cluster analysis determined seven sample groups of distinctive character here termed ecofacies. Eco-facies No. 1 is characterized by good sorting, fossil fragmentation and abrasion, and horizontal orientation of elongate particles. A sample group containing laminated, cross-laminated, and well-sorted lithologies (Ecofacies 2) also had common horizontal particles. The third ecofacies (Ecofacies 3) with a well-sorted aspect contains common bimodal samples with a larger size fraction of whole and incrusted fossils, a fragmented and abraded smaller fraction, shelter pores, and horizontal allochems. The largest sample group (Ecofacies 4) has frequent

bioturbation (which destroyed primary depositional features), as well as micritic features (adhered and infilled micrite, intraclasts, coated grains). Ecofacies 5 and 6 are also poorly-sorted and contain some bioturbation features but also exhibit primary depositional parameters (e.g., shelter phenomena) in addition to micritic features, oncolites (No. 5), and horizontal particles (No. 6). The last, Ecofacies 7, is characterized by pelmatozoan holdfasts, crustose sheets and boundstones, poorly-sorted and incrusted fossils, and occasional radiaxial cement.

A R-mode or parameter cluster analysis was performed to determine which features co-occurred most frequently in overall distribution. Poorly-sorted fossils, whole fossils or parts, unabraded fossils, and 1-layer incrustations are associated in one group. Coated grains, adhered and infilled micrite, intraclasts, and blackened particles comprised the second group. A third cluster includes well-sorted fossils, pelloids, and fragmented and abraded fossils. Mud-filled burrows, swirled or concentric particles, and spar-filled burrows are features of a fourth group. Shelter phenomena, such as shelter pores, sheltered mud, and perched sediment are associated in the fifth group with unattached crustose bryozoan sheets, articulated bivalved fossils, and fecal pellets. Cement-filled moldic pores occur with 2- and 3-layer incrustations, matrix channel and vug pores (cement-filled), crystal silt, and pelmatozoan holdfasts (sixth group). A large cluster of rare features includes the smaller subgroups of the more common parameters ooids and hemispheroidal oncolites, and convex-up shells clustered with graded bedding. Borings in fossils are

associated with particles with 2- and 3-layers of incrustation, and also with bimodal size distributions and oncolites. Planar lamination or layering occurs with horizontal or oriented fossils.

The distribution of ecofacies and feature groups within the Lay School section was used along with Petrographic Fossil Diversity information to reconstruct environments of deposition. The Blackford Formation contains Ecofacies 1, 2, 3, and represents subtidal to supratidal subenvironments present in a coastal tidal flat setting. Ancient sediments consisted of well-sorted sands (Ecofacies 1), laminated muds and silts (Ecofacies 2), fenestral mudstones (Ecofacies 2), and bimodal sands (Ecofacies 3). The Elway Member contains shallowing-upward cycles which represent repeated tidal flat progradation or coastal accretion through the formation of barrier islands and subsequent leeward sedimentation. The progresson of ecofacies in such cycles is from sands of Ecofacies 1 and 3 near the base, to muddy sands of Ecofacies 4 and 5 at the middle, to laminated lithologies and fenestral dismicrites (Ecofacies 2) at the top. The Hogskin Member contains biostromes (stromatoporoid, Ecofacies 7), pelmatozoan sands (Ecofacies 1 and 3), bryozoan boundstones (Ecofacies 7), and other diverse lithologies which reflect deposition in shallowest subtidal offshore environments adjacent to tidal flats. These rocks are followed by an interval (Upper Member, Lincolnshire Formation) characterized by intense bioturbation of mud-supported lithologies (Ecofacies 4). The lower Rockdell Formation has small algal mud mounds (Ecofacies 7) flanked by variably micritic bryozoan/pelmatozoan sands (Ecofacies 5 and 6). The mounds formed through

the interaction of algal binding, bryozoan/pelmatozoan incrustation, early cementation, and sediment baffling. Deposition in an euphotic, above wave-base outer shelf margin is represented by the upper Rockdell Formation which contains diverse ecofacies. The Benbolt Formation was deposited in a normally quiet water, below wave base setting characterized by a scarcity of algae due to water depth or other factors. This interval has frequent fossil layers of Ecofacies 6, as well as containing Ecofacies 4 and 5. The lower Wardell Formation formed in a nearshore setting of shallow, standing water (Ecofacies 4) adjacent to ephemeral subtidal oncolite channels and shoals of Ecofacies 2 and 5. Shoreward, the tidal flat complexes represented by the upper Wardell, Bowen, and Witten Formations contain mainly Ecofacies 1, 2, and 3.

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CHAPTER 1

INTRODUCTION

Purpose

The primary goal of this study is to deduce the environments of deposition of the carbonate and associated siliciclastic rocks of the Chickamauga Group exposed near Lay School locality in Hogskin Valley, Grainger County, Tennessee. This area has been examined for two important regional Ordovician biostratigraphic studies (Cooper, 1956; Bergstrom and Carnes, 1976) and occupies a position on the ancient Middle Ordovician marine platform near (20-40 km) the boundary of major brachiopod and conodont biostratigraphic provinces (McLaughlin, 1973; Jaanusson et al., 1980). Reconstruction of environments of deposition is attempted by deriving environmental information from a carbonate deposit by viewing its mass of skeletal particles as a fossil assemblage. The characteristics of carbonate skeletal sediment particles may allow the reconstruction of fossil grain histories which could reflect taphonomic or depositional processes. Accordingly, attributes of fossil assemblages which suggest particular environmental conditions or processes were selected from many paleontological, paleoecological, and sedimentological studies and used as parameters to describe the carbonate microfacies present at the Lay School section. The section was then examined using multivariate cluster analysis for zones containing fossil particles of similar ecologic

aspect or condition. These zones were then related to possible marine carbonate environments. Finally, by discovering which assemblage features occur together over the entire section through cluster analysis, this study endeavors to outline changes in marine processes operating at this locality through time.

Location

Hogskin Valley is a northeastward continuation of Raccoon Valley and lies in the Valley and Ridge physiographic province of the Southern Appalachians. The valleys and ridges of this province are surficial expressions of northeast-striking belts of strata that dip to the southeast and are bounded by southeast-dipping thrust faults. The Lay School section occupies a small portion of the upper part of the Hunter Valley Allochthon (or St. Paul strike belt of Prouty, 1946), which is bounded by the Hunter Valley Fault to the northwest and the Copper Creek Fault to the southeast (Fig. 1-1).

The Middle Ordovician portion of the Hunter Valley strike belt chosen for this study begins at the post-Knox unconformity and extends to the reddish brown Moccasin Formation just below the Copper Creek Fault (Fig. 1-2). The Lay School section is a composite of five outcrops (A through E), which occur in the road cut and on hills by Hogskin Creek and to the north of it. The component outcrops are those utilized for the biostratigraphic study by Carnes (1975) with the exception of the lowermost outcrop A. The basal outcrops in A were chosen in the present study for their apparent

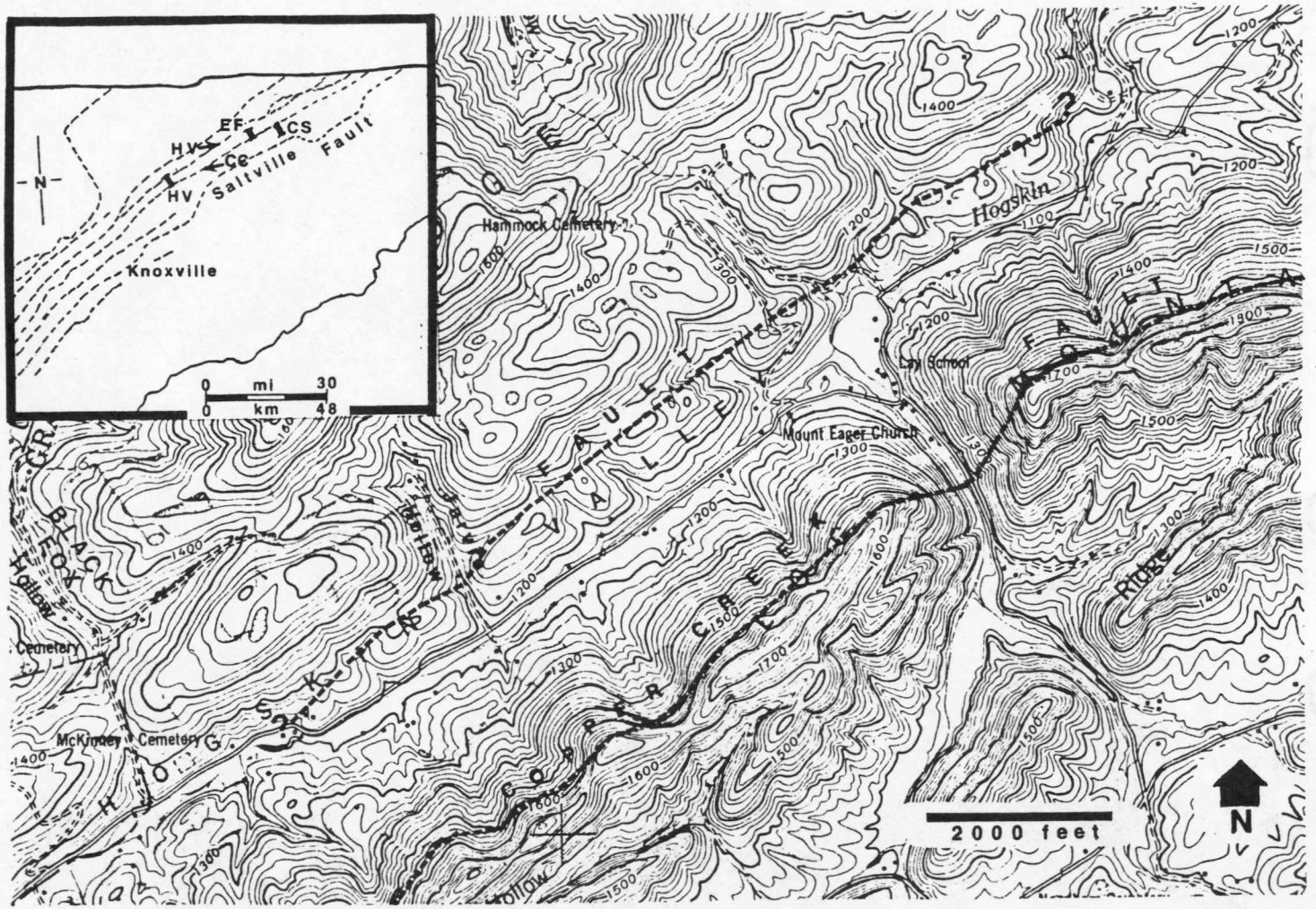


Figure 1-1. Hogskin Valley and vicinity. Inset shows position of valley in east Tennessee and relation to Saltville, Copper Creek faults.

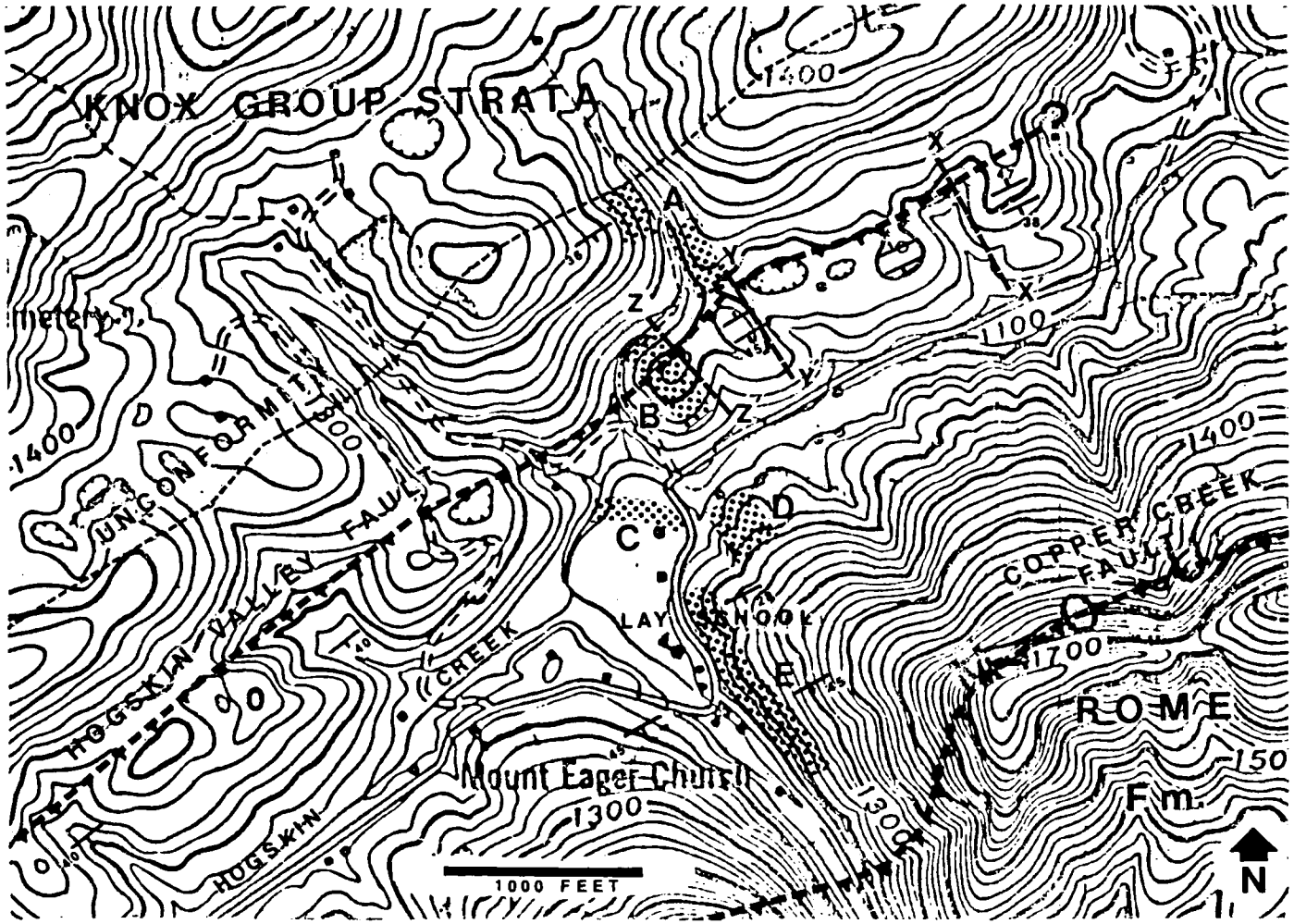


Figure 1-2. Lay School Section. Constituent parts of section indicated by stipled pattern and labeled A, B, C, D, and E. X-X', Y-Y', Z-Z' indicate locations of cross-sections depicted in a later figure.

continuity with B. Approximately 450 m of section are exposed at this locality, but an unknown thickness of strata is repeated due to thrust faulting. Exposures have strikes that range generally from N60°E to N70°E and dips that range from 20°-45°SE.

Part A begins on the northeast-facing hillside beside a small farm road and creek that trends northwest (Fig. 1-2), and includes the lowermost exposures above the post-Knox unconformity, which is not exposed at this locality. The location of the unconformity was estimated by the presence of abundant blocky chert in residuum of the hillside and outcrops of Knox Group rocks on the opposite hillside (southwest-facing). These thickly-bedded dolomitic rocks occur just below the covered interval where the unconformity lies. This agrees with the position of the unconformity as shown by Finlayson et al. (1965).

The lowermost portion of A (Samples A1-A12) has outcrops that are stratigraphically lower than any on the southwest-facing hillside. However, the southwest-facing hillside has the major exposure of A (A14-A60) and consists of two outcrop series, A14-18 and A19-60, separated by a covered interval. The hillside with A19-60 outcrops is wooded and becomes a saddle connecting with a small hill to the southeast. Beds strike to the northeast and dip southeast 35°-45° in A, but dip in the opposite direction (northwest) near the top of the hill. This is due to the presence of a fold whose apex or axial plane trace is exposed at the hilltop and strikes northeast-southwest.

Part B is almost identical to Leg II of Carnes's (1975) study which apparently begins on the southeast-facing hillside north of the

creek which divided lower Part A from upper Part A (A19-A60). The northernmost and higher of the two ridges is formed mainly by the Knox Group, whereas the smaller ridge, or series of hills, is composed of Chickamauga Group rocks. Part B includes strata on the smaller ridge, which begins about 2000 feet northeast of the intersection of Black Fox Hollow Road and Hogskin Valley Road, along Hogskin Valley Road. It continues up Hogskin Valley and ends about 2000 feet northeast of the Lay School section. Part B is about 100 m thick and dips uniformly to the southeast.

The stratigraphically highest outcrops in B can be followed along strike to the southwest to the basal exposures of Part C on the south side of Hogskin Valley Creek. Part C is Leg III of Carnes's study and is 90 m thick. It is exposed at the steeply sloping northern and northeastern margin of a small hill which was eroded by Hogskin Creek. Beds dip uniformly to the southeast.

Part D crops out on the lower slope of Log Mountain, which forms the southern border of Hogskin Valley. The outcrops begin on the eastern side of Hogskin Valley Road from the uppermost beds of C. Dips range from 5-10°SW in the lower beds to 35° in the upper ones. This part of the section is estimated to be 24 m thick. The upper beds are traceable along strike to the lower cobbly weathering beds of Part E.

Part E forms the longest and best exposed part of the Lay School section. The outcrops are in the road cut beside Hogskin Valley Road and the southeast-trending road to Potato Valley (Fig. 1-1). In this

part, 150 m of upper Chickamauga Group rocks are exposed, striking N65-70°E and dipping 28-45° southeast. The upper boundary of the stratigraphic section is the poorly exposed interval of reddish brown soil which underlies the reddish brown shale and mudstone of the Moccasin Formation.

Previous Investigations

Hogskin Valley is located in the Hunter Valley Allochthon, or St. Paul strike belt of Prouty (1946). The lithostratigraphy of units in this strike belt and their relation to units in adjacent belts was discussed by Rodgers in his study of the geology of eastern Tennessee (1953). For mapping purposes, the middle Ordovician strata in the strike belts immediately northwest of the Saltville Fault were subdivided into three heterogenous units. The lowermost unit (Chickamauga 1) consisted of a basal group of light-colored fine-grained limestones and upper, dark "crystalline" nodular limestone with lenses of coarser, fossiliferous "marble." This unit was thought to be roughly equivalent to the Lenoir and Holston formations in the strike belt between the Saltville and Knoxville thrust faults, which was used by Rodgers as a standard belt for comparison to other strike belts. The middle unit (Chickamauga 2) recognized in the northwest strike belts (Clinch Valley and Hunter Valley belts) included several types of shaly and nodular limestone and limy shale which interbedded with purer limestones. This unit corresponds stratigraphically to the Ottossee Formation in the "standard" belt. The upper, and most

easily recognized lithologic unit was termed the Moccasin Formation, retaining the name used by Campbell in 1894 for exposures at Moccasin Creek, Scott County, Virginia, in the Clinch Valley belt. This formation primarily consists of maroon calcareous shale, siltstone, and silty limestone which interbed with blue-weathering limestone. The blue limestone and a yellow, silty limestone displace the maroon lithologies in belts northwest of the Hunter Valley Fault.

In 1956, Hogskin Valley became the type locality for the Ashby Stage of G. A. Cooper's biostratigraphic subdivision of the Ordovician System (Cooper, 1956). On the basis of brachiopod faunas, Cooper established six stages in the Middle Ordovician, the Whiterock, Marmor, Ashby, Porterfield, Wilderness, and Trenton stages. The Ashby stage was named for a road intersection with Hogskin Creek, 3.3 miles southeast of Lay School in Hogskin Valley and the stratigraphic term "Hogskin Formation" or member of the Lincolnshire Formation was named for exposures in Hogskin Valley. Jarvis Hollow, a Cooper collecting locality, lies on the northern side of Hogskin Creek and Valley is shown in Fig. 1-1. The Hogskin member of the Lincolnshire Formation was described as a "yellow-weathering shale and limestone" of the "Ottossee type" which lies between the Eidson member of the Lincolnshire and the Ward Cove or Rockdell formations. The Hogskin Member is also defined by its brachiopod fauna, as listed by Cooper (1956).

McLaughlin (1973) reviewed the results of biostratigraphic studies (especially brachiopods) in east Tennessee and their relation to the

stratigraphy of the thrust fault belts. His study showed that 90% of the articulate brachiopod genera listed in Cooper's study (1956) are found almost exclusively on one side or the other of the Saltville Fault. Accordingly, McLaughlin suggested that lower middle Ordovician strata in eastern Tennessee be divided into two biostratigraphic provinces whose common boundary is the Saltville Fault. The province northwest of the fault was termed the Chickamaugan Province, whereas that to the southeast was termed the Blountian Province.

As McLaughlin (1973) pointed out, studies of post-Knox paleotopography indicate that features related to subaerial exposure (e.g., paleokarst features) on the Knox unconformity surface are best developed west and north of the Saltville Fault. Since this emergent paleokarst surface in the northwest is overlain by marine carbonates and clastics of increasingly deeper water aspect, it is generally understood that this post-Knox surface was transgressed by the sea from the southeast to the northwest (Rodgers, 1953; McLaughlin, 1973). It thus logically follows that the first marine deposits on the submerged erosional Knox surface in the northwest belts are younger than the lower post-Knox marine deposits in the Blountian Province to the southeast.

Carnes (1975) and Bergstrom and Carnes (1976) dated the post-Knox marine strata, including those at Lay School, in order to determine the age of the post-Knox unconformity. Biostratigraphic dating utilized conodonts in order to avoid facies-related distribution problems that made brachiopod-based studies unreliable (McLaughlin, 1973),

even though the conodont assemblages reflect a similar change in composition across the Saltville Fault provincial boundary (Sweet and Bergstrom, 1974). Because Cooper gave no single location in Hogskin Valley for the type section of the Hogskin Member or the Ashby Stage, a composite section at Lay School consisting of five parts or legs was formed by Carnes and Bergstrom. As previously mentioned, these correspond to Parts A-E in this study, with the exception of Part A or Leg I. Another locality sampled in the Hunter Valley Allochthon was the Evans Ferry section, which has since been studied petrographically and paleontologically by Sickfoose (1979).

The results of the regional conodont biostratigraphic study (Carnes, 1975; Bergstrom and Carnes, 1976) confirm the hypothesis that basal post-Knox marine deposits become younger to the northwest, in the direction of the lower middle Ordovician transgression of the post-Knox emergent shore. Apparently, the basal post-Knox marine strata in the Blountian Province lack equivalents in the northwestern belts of the Chickamaugan Province. As much as 500 feet of lower and middle Lenoir Formation of the Friendsville and Lenoir City belts lack correlatives in the belts northwest of the Saltville Fault (Bergstrom and Carnes, 1976). Basal Lenoir Formation in Blountian Province belts (termed Blountain Confacies Belt in Jaanusson and Bergstrom, 1980) began in the lower Pygodus serra conodont chronozone whereas the basal post-Knox Chickamauga strata in the northwest belts may have begun in the upper Pygodus anserinus conodont or Nemagraptus gracilis graptolite chronozones (Bergstrom and Carnes, 1976;

Jaanusson and Bergstrom, 1980). Thus, the Knox unconformity is overlain by progressively younger strata on an onlap basis from southeast to northwest, as suggested by Rodgers (1953) and McLaughlin (1973).

Study of the conodont faunas in sections in the Hunter Valley Allochthon reveals that this belt occupies an intermediate position (20-40 km) between two major conodont provinces--the Mid-Continent and the North Atlantic Provinces (Carnes, 1975; Bergstrom and Carnes, 1976). The boundary between the two conodont provinces is the same as that between brachiopod provinces, the Saltville Fault (Bergstrom, 1971; 1973). The belts between the Hunter Valley and Saltville Faults have been termed the Tazewell Confacies Belt in Jaanusson and Bergstrom (1980) because of their similar conodont and shelly faunas which contain elements of the two brachiopod and conodont provinces. Thus, the Lay School section in Hogskin Valley is transitional in terms of both brachiopod and conodont faunas with respect to sections northwest of the Hunter Valley Fault (the Lee Confacies Belt) and southeast of the Saltville Fault (Blount Confacies Belt of Jaanusson and Bergstrom, 1980).

Studies which are specifically paleoenvironmental in nature have been conducted on Ordovician strata in all the major strike belts in eastern Tennessee by workers at the Department of Geology at The University of Tennessee, Knoxville, since about 1970, mostly under the direction of Kenneth R. Walker. In general, these studies have concentrated on carbonate microfacies analysis aided by field mapping and paleoecological research. Additionally, there have been many

paleontological studies (before and after 1970) which have by necessity dealt with paleoenvironmental problems and provide significant information about the past environments of deposition of the Chickamauga Group and other Middle Ordovician units. Many of these localities are shown in Walker et al. (1980) and include sections in strike belts both north and south of the Saltville Fault. There are several localities north of the Saltville Fault, in or near the Hunter Valley belt, which are near the Lay School section and have been studied recently. Environments of deposition and patterns of community paleoecology were studied by Sickafoose (1979) at the section at Evans Ferry, 19 km northeast of Lay School in the Hunter Valley allochthon. The Chickamauga Group portion of the Evans Ferry section is 470 m thick from the top of the Knox to the top of the Witten Formation (as shown in Walker et al., 1980). This is thicker than the 455 m of equivalent section measured at Lay School and may provide a possible standard by which the amount of faulting at Lay School may be judged. While the upper halves of the two sections are similar, the lower half of the Lay School section contains extensive development of subtidal to supratidal facies cycles above the reddish laminated Blackford Formation which are absent from the Evans Ferry section. The Blackford (or Tumbez Fm.) at Lay School is also thicker than the equivalent strata at Evans Ferry (approximately 55 m at Lay School, 20-25 m at Evans Ferry). See Fig. 1-3 for the Lay School stratigraphic column. Additionally, the Evans Ferry section lacks a horizon of stromatoporoid biostrome in its post-Blackford, pre-Rockdell interval equivalent to that found at Lay School at the top of the Elway Formation cycles.

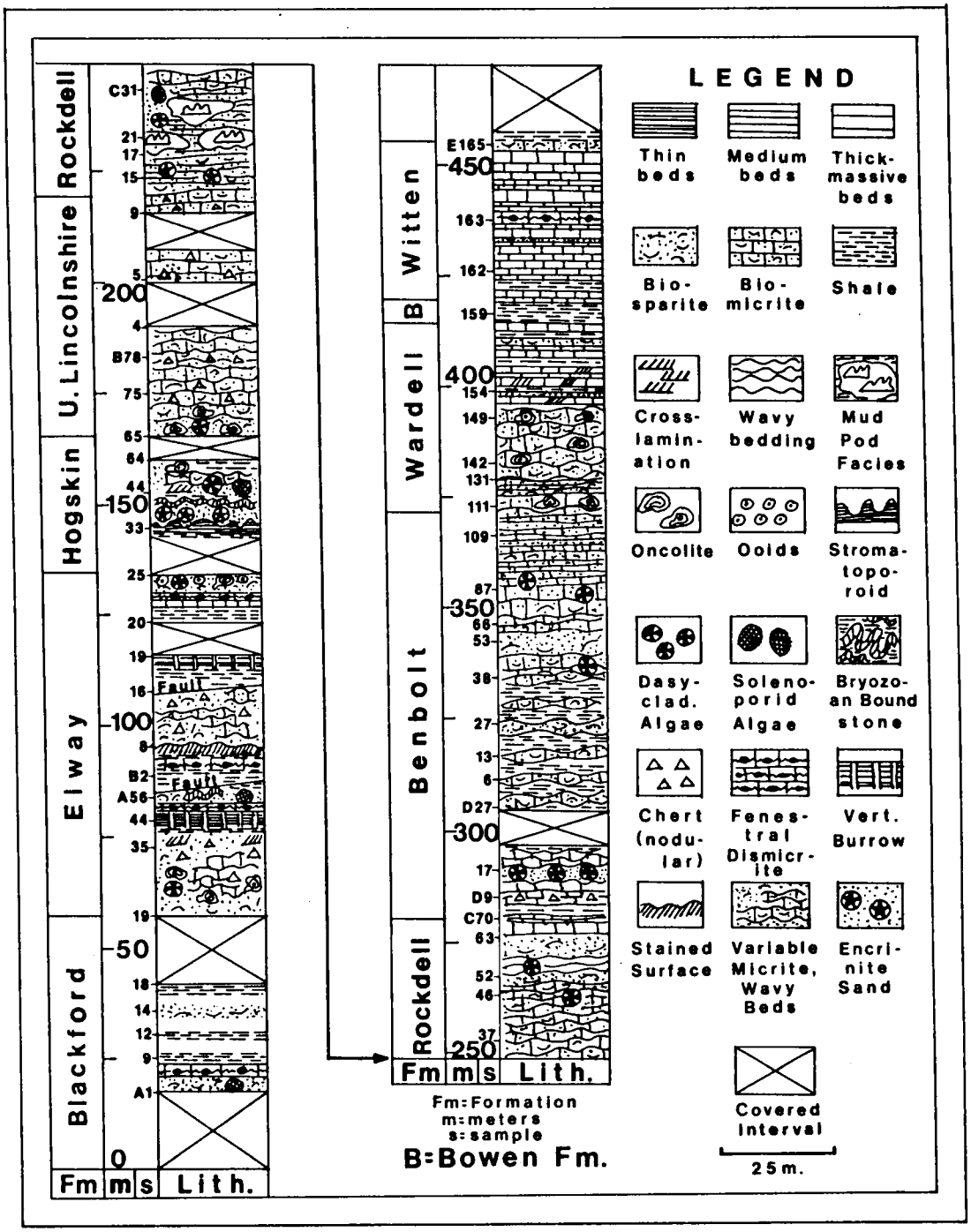


Figure 1-3. Stratigraphic column of the Lay School section. Left column represent the lower half of the section and the right column represents the upper half of the section. Location of selected samples are shown on the left side of column.

Finally, the Evans Ferry section lacks a zone of carbonate mud pods which contain abundant cement-filled stromatactoid and other cavities in algal biolithite which occurs in the lower part of the Rockdell Formation at Lay School.

The Stanley Farm section (425 m thick) (Ashworth, 1982), 17.5 miles or 28.2 km southwest of Lay School in the same strike belt has gray muddy and grainy lithologies in its lowermost units above the Knox Unconformity rather than red and pink lithologies present at Lay School. Red or maroon strata appear higher in the section at Stanley Farm, in the Fleanor Member of the Lincolnshire Formation. Oncolitic and algae-rich lithologies occur in the Lincolnshire Formation as a whole like they do at Lay School, and some intervals also have bryozoan boundstone. However, Stanley Farm lacks a stromatoporoid biostromal horizon present in the Lincolnshire at Lay School (in the Hogskin Formation). An intensely bioturbated interval of muddy lithologies is also absent from the upper Lincolnshire Formation at Stanley Farm. Finally, a zone of cavity-rich algal mud-pods flanked by grainy bryozoan/pelmatozoan beds does not occur at Stanley Farm.

The Cedar Springs section is in the next strike belt southeast of the Hunter Valley belt and was studied by Ruppel (1979) and Ruppel and Walker (1984). In some ways, it more closely resembles the Lay School section than does the Evans Ferry section in the Hunter Valley belt. The Cedar Springs section, for instance, has a stromatoporoid horizon in its first subtidal unit (Lincolnshire) above the predominantly peritidal strata (Five Oaks) overlying the Knox unconformity. This horizon, originally identified as algal stromatolites, occurs about

33 m from the base of the section. The stromatoporoid zone at Lay School is about 145 m from the Knox, a much higher level which may be partly due to repetition from faulting and partly from greater development of a nearshore island zone (Elway Formation cycles) at Lay School. Another point of similarity is the frequent reddish zones of various lithologies in the lower half of the Cedar Springs section and which also occur in the lower third of the Lay School section, the Stanley Farm section, and at other localities in Hogskin Valley. In total thickness, the Cedar Springs and Stanley Farm sections are closer to that of the Lay School than Evans Ferry (424 m at Cedar Springs, 470 m at Evans Ferry, 455 m at Lay School, 425 m at Stanley Farm).

Structural Setting

Exposures consist of northeast-striking parallel ledges and ridges which are topographic expressions of southeast-dipping strata and typify Valley and Ridge structure in Tennessee. In Hogskin Valley stratigraphy is complicated by thrust faulting within shaly or thin-bedded rocks of the lower Chickamauga (Elway Fm) on the north side of the valley. This fault is marked by a ridge of low hills on the north side of the valley between the higher hills containing the Knox Group rocks (ridge immediately southeast of Hinds Ridge) and Hogskin Creek. Because this line of hills only partly extends down the valley to the southwest, the magnitude of faulting may decrease in that direction. The strata on both sides of the fault dip to the southeast in this part of Hogskin Valley.

Northeast of the Lay School section, rocks on the southeastern side of the fault are folded rather than simply dipping to the southeast (Figs. 1-2, p. 4, and 1-4). The line of hills north of the creek marks the crest of the fold as the line is followed along strike to the northeast from the Part B hill. A good exposure of the structure within the upper plate is in the gulley about 500 m up the valley to the northeast of the Part B hill (Figs. 1-4a, 1-5a). The fold consists of northwest and southeast-dipping limbs whose axial-plane trace runs across the hill top southwest of the gulley at X-X'. The northwest-dipping limbs of the fold abut against the southeast-dipping thrust fault which underlies the fold. The crest or apex of the fold and the underlying thrust fault can be seen again at the hilltop immediately southeast of Part A, at Y-Y' in Fig. 1-2 and Fig. 1-4b. The apex occurs near the hilltop, where the northwest and southeast-dipping beds meet (Fig. 1-5b). The underlying thrust fault can be seen by walking down the northwest-dipping wooded hillside toward Part A. The fault occurs where the dips of the beds change from the northwest to the southeast, approximately 50 m from the apex of the fold or hilltop. The fault plane lies in shales and laminated lithologies.

The structural situation changes on the next hill down strike to the southwest, Part B hill. There, the fault trace is not so evident and strata on both sides of the fault dip to the southeast (Z-Z', Fig. 1-2; Fig. 1-4c). Evidence for faulting on the Part B hill includes small scale multiple folds in thin-medium bedded rocks at the B24-25 horizon (Fig. 1-5c). These are the first thicker beds above a shaly or laminated interval between B15-16 and B24-25. If the faulted zone

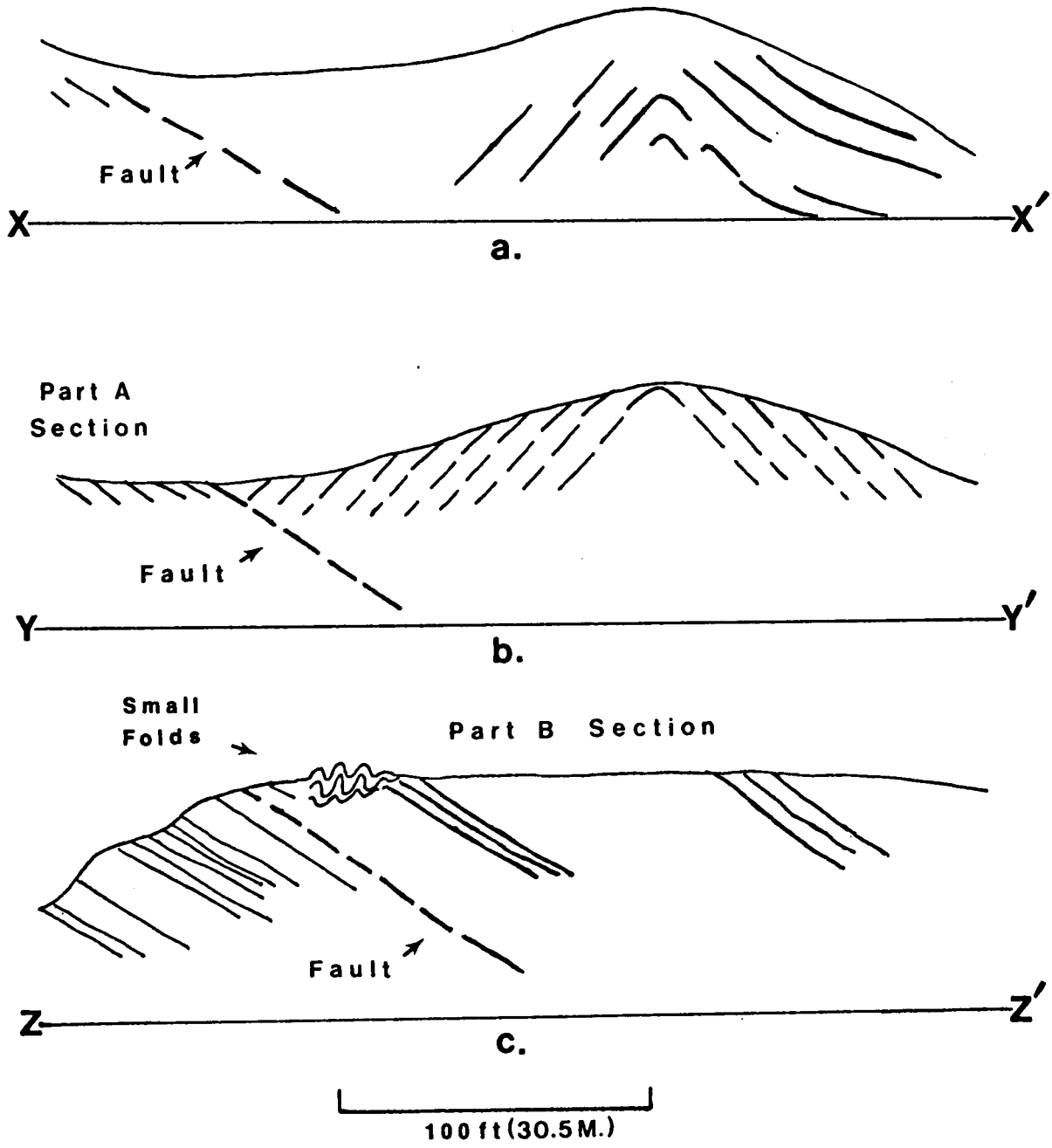


Figure 1-4. Field sketches of structural relations at cross-sections X-X', Y-Y', and Z-Z' in Fig. 1-2, p. 4, Hogskin Valley. All views looking northeast.

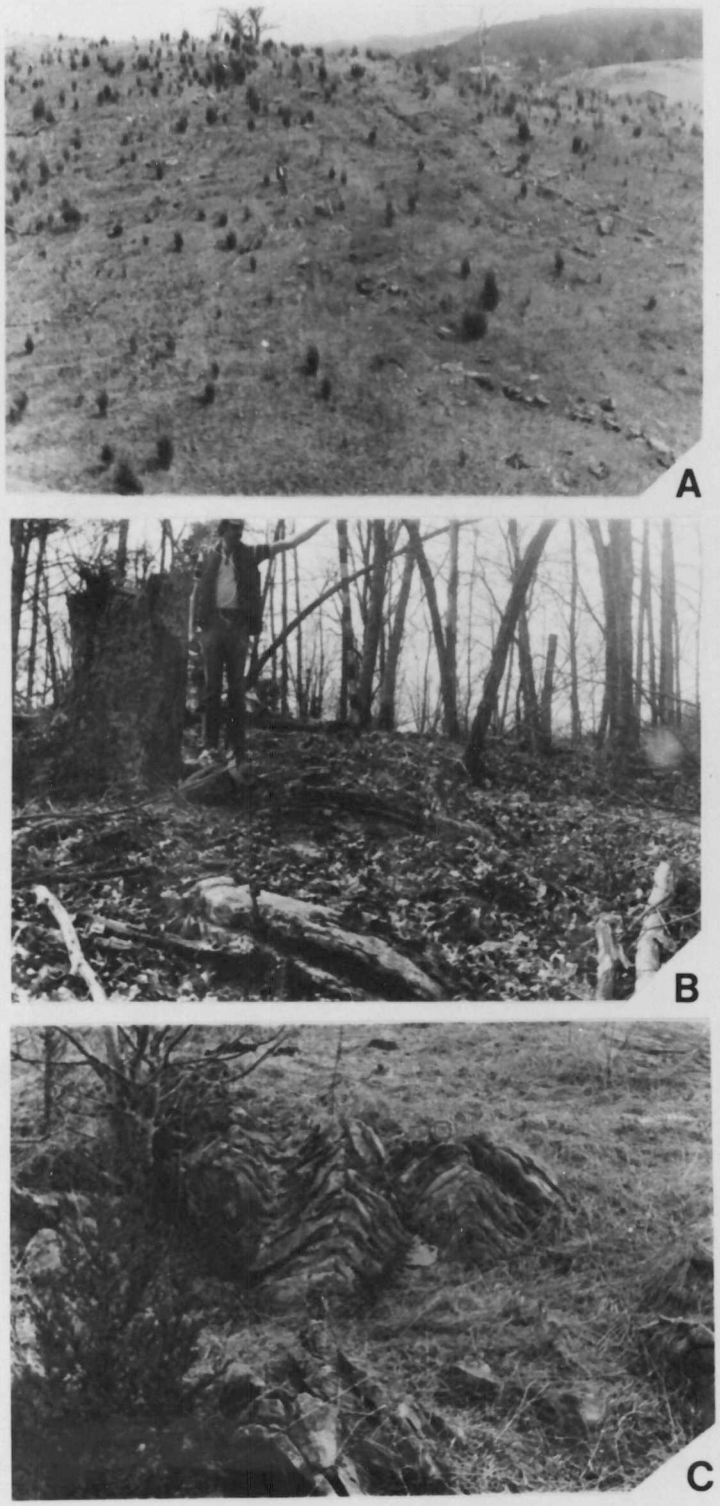


Figure 1-5. Photos of faults and folds in the study section.

A. Fold depicted in Fig. 1-4a.

B. Apex of fold depicted in Fig. 1-4b.

C. Small folds shown in Fig. 1-4c.

is confined to shaly or laminated units as in Hill A, the faulting probably occurs in that zone between B16 and B24. The fold whose axial trace was on the hill southeast of Part A is missing from Part B hill.

Other evidence of faulting in the lower Chickamauga formations occurs down strike from Part B hill to the southwest in Hogskin Valley. Immediately adjacent to the southwest-facing side of Part B hill is a small flood plain created by Hogskin Creek (Fig. 1-2, p. 4). On the north side of this field (floodplain) are exposures of lower Chickamauga units, including reddish shales. These beds dip to the southeast much more steeply than those in Part B. Carnes called this a "deformed" area and suggested that a "minor fault" cut through the beds (Carnes, 1975, Fig. 20). This author also believes the fault zone occurs in this area. The small private farm road which borders the flood plain on its north side (aforementioned "deformed beds") and east side (Part B Hill) turns north beyond the deformed zone and cuts across strike (Fig. 1-2). A short distance up the road after turns to the north (northwest), a low angle thrust fault with a small fold on the hanging wall is exposed in the road cut. This confirms the extension of the Hogskin Valley fault or fault zone thru the disturbed area southwest of Part B Hill and on down the valley in a southwest direction.

Additional evidence of faulting in the lower Chickamauga units southwest of the Lay School section in Hogskin Valley occurs in Jarvis Hollow, .75 miles (1.2 km) southwest of Mt. Eager Church (Fig. 1-1, p. 3). This was one of Cooper's (1956) brachiopod collecting localities. Faulting here occurs in shaly and thin-bedded rocks exposed on

the south side of the hollow. The zone of faulting is between the larger Knox Group ridge and the previously mentioned smaller row of hills immediately north of Hogskin Creek. Jarvis Hollow dissects this smaller row of hills approximately 2000 feet (610 m) from its southern terminus in the valley. The Hogskin Valley road makes a pronounced turn around the end of the row of hills. This is also where the Hogskin Valley fault either dies out or is covered by the Hogskin Creek floodplain.

The Hogskin Valley Fault causes an unknown amount of vertical displacement. In most places, the facies of rocks on either side of the fault is similar (i.e., usually shaly, laminated, or thin-bedded strata of peritidal or shallowest subtidal aspect). This fact and the low angle of the fault parallel to strata suggests that vertical displacement was small relative to horizontal displacement. The Lay School section is about 25 m thicker than the nearby Chickamauga section at Cedar Springs and Stanley Farm, which it resembles in several ways. It is, therefore, possible that some of that thickness is due to repetition by faulting. On the other hand, thrust faulting often results in the shortening of sections rather than their thickening (Billings, 1972). In this regard, it is interesting to note that Lay School is about 20-25 m thinner than the Evans Ferry section in the same strike belt. Furthermore, the composite nature of the Lay School section, the variations in dips in some parts of the section (e.g., 36°SE in lower A; steeply dipping poorly exposed parts of B16-B25; 28°SE in lower Part E; 45°SE in upper Part E), and the frequent covered intervals, especially in the lower half of the section, make some error unavoidable.

CHAPTER 2

ECOLOGIC FACIES DERIVED BY SAMPLE CLUSTER ANALYSIS

Results of Sample Clustering (Q-Mode) in Other Disciplines

The meaning of groups of data units with similar characteristics varies with the nature of the scientific discipline. In numerical taxonomy, the data units are specimens to be classified into species (Q-mode groups) on the basis of shared taxonomic characters (variables). Alternatively, the data units may be species which are classed into higher taxonomic groups with respect to a number of taxonomic characters (Sokal and Sneath, 1963). In sedimentologic studies, such as Imbrie and Purdy (1962), Purdy (1963), Ali et al. (1976), and Wigley (1977), the data units are sediment samples which are placed in groups of similar facies with respect to their constituent particles (variables). Maps of the resultant lithofacies groups of samples can then be constructed. In multivariate studies of ancient sediment, samples are commonly thin-sections which are examined with respect to constituent grain types and occasionally textures (Smosna and Warshauer, 1978, 1979; Ekdale et al., 1976). A quantitative ecologic study of a particular fauna, such as the study by Kaesler (1966) of the foraminifera and ostracoda in Todos Santos Bay (Mexico) or Gevirtz et al. (1971), involves the grouping of sample stations (data units) with respect to species present (variables). The results are

expressed as biotopes or biofacies. Biotopes are areas occupied by a particular fauna which is presumably adapted to environmental conditions existing there (Kaesler, 1966). Biofacies are the groups of organisms found together in a biotope. Finally, multivariate clustering techniques have been used in biostratigraphy to identify zones in borehole samples with similar microfossil composition (variables) (Millendorf et al., 1978; Brower et al., 1978), and in analyses of fossil communities (Fox, 1968; Valentine and Peddicord, 1967).

Sample Cluster Groups as Ecologic Facies (Ecofacies)

The sample cluster analysis of this study describes seven groups of samples with shared fossil particle and sediment characteristics (variables). The characteristics of features used to describe the Lay School rocks are listed below according to an environmental classification in Appendix B Part I. For a discussion of the classification and a glossary of features, see Appendix B.

Environmental Classification of Features Used in the Lay School Microfacies Analysis

A. Features Related to Water Turbulence (Functioning as Currents of Transport)

1. Presence of only spar in sediment matrix
2. Good sorting
3. Planar Layering or lamination
4. Horizontal or preferred particle orientation
5. Cross-lamination or bedding
6. Convex-up shells
7. Ooids
8. Graded bedding or laminae

9. Inverse or reverse grading
10. Fragmented fossils
11. Abraded fossils
12. Imbrication of fossils
13. Bimodal or polymodal particle size distribution
14. Oncolites

B. Features Related to Lack of Water Turbulence

1. Presence of only micrite in sediment matrix
2. Poor sorting
3. Whole fossils
4. Delicate Features on fossils preserved
5. Articulated bivalved fossils
6. Interstitial micrite increases upward in sediment
7. Micrite infilling of pores in fossils

C. Features Related to Water Turbulence (Functioning as Currents of Removal)

1. Presence of both micrite and spar in sediment matrix
2. Adhered micrite on fossil particles
3. Intraclasts
4. Pelloids
5. Sheltered micrite
6. Matrix channel pores
7. Interstitial spar increases upward in sediment

D. Features Related to Organo-Sedimentary Processes of Sediment Accumulation

1. Trapping and binding features
   a. Layered algal stromatolites, oncolites, and some coated grains
   b. Nonlayered algal boundstone or biolithite
   c. Lamellar bryozoan boundstone; bryozoan/algal multiple-layered particle incrustations
   d. Incrusting and binding pelmatozoan holdfast systems
2. Baffling features: bafflestone
3. Sheltering features: sheltered micrite in some poorly-washed biomicrites or packstones
4. Massive stony colonies: framestone

E. Features Related to Early Diagenetic Processes

1. Features related to biological diagenesis that occurs in epifaunal or infaunal situations
   a. Borings in skeletal particles
   b. Fragmentation of skeletal particles

2. Features related to biological diagenesis which are infaunal
   a. Mud-filled burrows, horizontal or random orientation
   b. Spar-filled burrows, horizontal or random orientation
   c. Concentrically arranged particles or churned particles
   d. Fecal pellets (oval, micritic particles)
   e. Pelleted mud
   f. Vertical burrows
3. Epifaunal biogenic diagenetic features
   a. Incrustations on particles
   b. Oncolites
   c. Coated grains
   d. Loose or unattached lamellar bryozoan sheets
4. Early chemical diagenetic features
   a. Pyritization or blackening of grains

F. Features Related to Early Lithification or Cementation

1. Radiaxial cement
2. Sediment surfaces incrusted by sessile, benthic marine plants or animals
3. Sediment surfaces which truncate underlying particles
4. Bored lithologies
5. Intraclasts
6. Pelloids
7. Moldic porosity
8. Fenestral porosity
9. Matrix vug porosity

G. Carbonate Pore Systems or Features (Cement-Filled)

1. Interparticle pores
2. Intraparticle pores
3. Moldic pores
4. Fenestral pores
5. Shelter pores
6. Matrix channel pores
7. Matrix vug pores

These sample groups can be viewed as fossil assemblages and sediments resulting from different combinations of processes in different environments. In that respect, these sample clusters are similar to the two models of fossil assemblages developed by Johnson (1960) to represent the results of two possible modes of formation. The two

models of Johnson (and the seven groups defined here) represent fossil assemblages with different particle histories. These particle histories are a result of particular combinations of water depth, turbulence, oxygenation, types of organisms, and all other environmental factors. Since the resulting particle assemblage has developed as a unique response to a combination of factors in a particular environment, the groups may be regarded as as environmental or ecologic facies (ecofacies). Use of this term connotes a broader meaning than that of depositional facies because some of the groups (clusters) are characterized by postdepositional bioturbation. The term or concept would also be broader than a taphonomic facies because some organo-sedimentary facies form prior to death and are preserved throughout the postmortem diagenetic period (e.g., boundstones). The word ecologic would also emphasize the importance of organo-sedimentary interactions in carbonate depositional regimes.

The term ecofacies somewhat resembles the concept of biofacies, the assemblage of organisms in a particular place, the biotope. The closest approximation to biotopes in this study are the ecozones in the Lay School stratigraphic column which are composed of particular ecofacies or groups of ecofacies. The division of the Lay School column into ecozones forms the basis of the chapter on the environments of deposition later in the thesis.

Feature Groups Used to Describe the Ecofacies

Although discussion of the significance of the cluster analysis of the taphonomic and environmental features (variable or R-mode) is

given in the the depositional environment chapter, a name for each group of positively associated features revealed by the R-mode clustering will aid the description of the ecofacies established by the Q-mode analysis. Each group is also listed by the number on the graphic summary of feature composition of each ecofacies.

Feature Group	Name
1	Poorly-sorted
2	Micritic
3	Well-sorted
4	Infaunal
5	Shelter
6	Porosity
7	Mixed
8	Bimodal
9	Horizontal

Dendrogram of Lay School Sample Cluster Analysis

The products of the sample cluster analysis on the 255 samples with respect to the 51 features or variables are a numerical summary of the clustering distances (Appendix C) and a cluster map showing which samples are in the clusters. The cluster map is 41 pages in length and therefore has not been included in this report. However, a large dendrogram was constructed from the cluster map, and is presented here as Fig. 2-1. Note that because of size constraints, only the samples forming the first and last member of each subcluster

Figure 2-1. Dendrogram depicting relations among sample groups formed by the sample cluster analysis (Q-mode) of 255 samples from the Lay School section. Only sample number of first and last samples in the subclusters are given because of size constraints. For a complete listing of the samples in each sample cluster, the reader is referred to Appendix D, Table D-2. Bottom scale is given in steps of computer program clustering process which begins with 255 groups and consolidates on the basis of similar features until all samples are in one group. Similarity between samples is calculated by means of the Euclidean distance, the greater the distance between samples means the less they have in common. The clusters of similar samples were calculated with respect to 51 features or variables. Each graphic summary adds the frequency of a variable's occurrence for each subcluster to obtain the displayed feature frequency for each cluster (ecofacies).

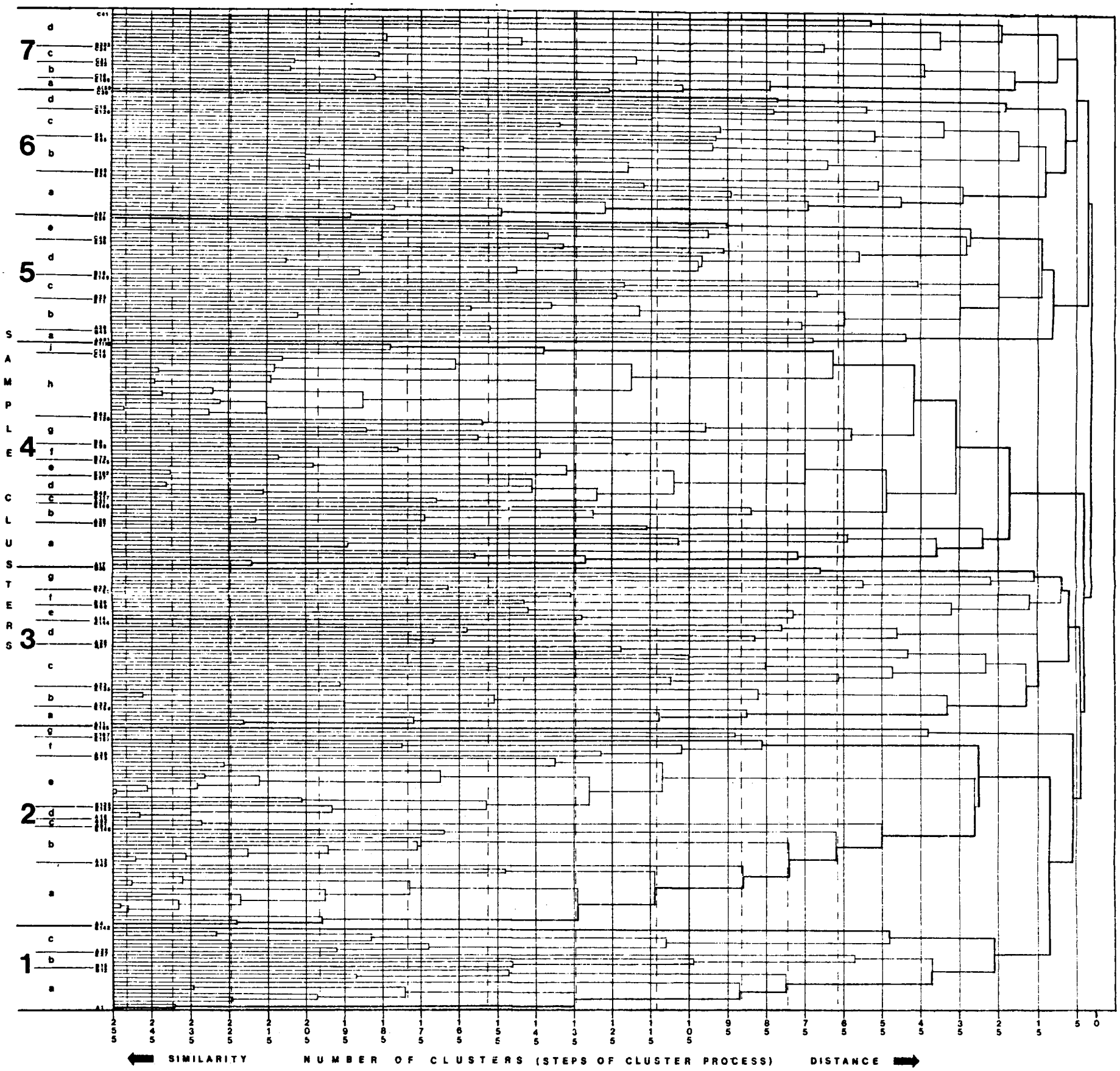


Figure 2-1.

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are listed in the figure. The order of samples listed on the vertical axis of a dendrogram is determined by the cluster analysis program. Refer to Appendix D, Table D-2 to find all the samples listed by subcluster. Appendix D, Table D-3 summarizes the effects found in each subcluster and was used to construct graphic summaries of the seven major sample clusters or ecofacies.

Lay School Ecofacies (or Sample Clusters)

Features Present in Ecofacies No. 1, Well-Sorted

The most frequently occurring group of features in this facies is the Well-sorted Group (No. 3 on Fig. 2-2), which includes: Well-sorted fossil fragments and nonfossil particles (WS); Pelloids (Pel) or well-sorted micritic, equant granules often less than .2 mm in diameter; Fragmented Fossils (FR); and Abraded Fossils (ABR). These are features probably related to grain transport and most of the samples in the ecofacies have them.

The next most frequent group of parameters is the Micritic Feature Group (No. 2 on Fig. 2-2). Among the features in this group are: Coated Grains or cortoids (CG), particles with micritic, presumably algal-derived coats or envelopes; Micrite Infillings (MI) of pores in fossils; Adhered Micrite (AM) on fossil particles; Intraclasts (INT) or micritic allochems of many sizes; and Blackened Grains (BG). Because most of the samples in this cluster are spar-rich, these micritic features suggest that nearby micrite-accumulating areas furnish considerable amounts of particles via reworking.

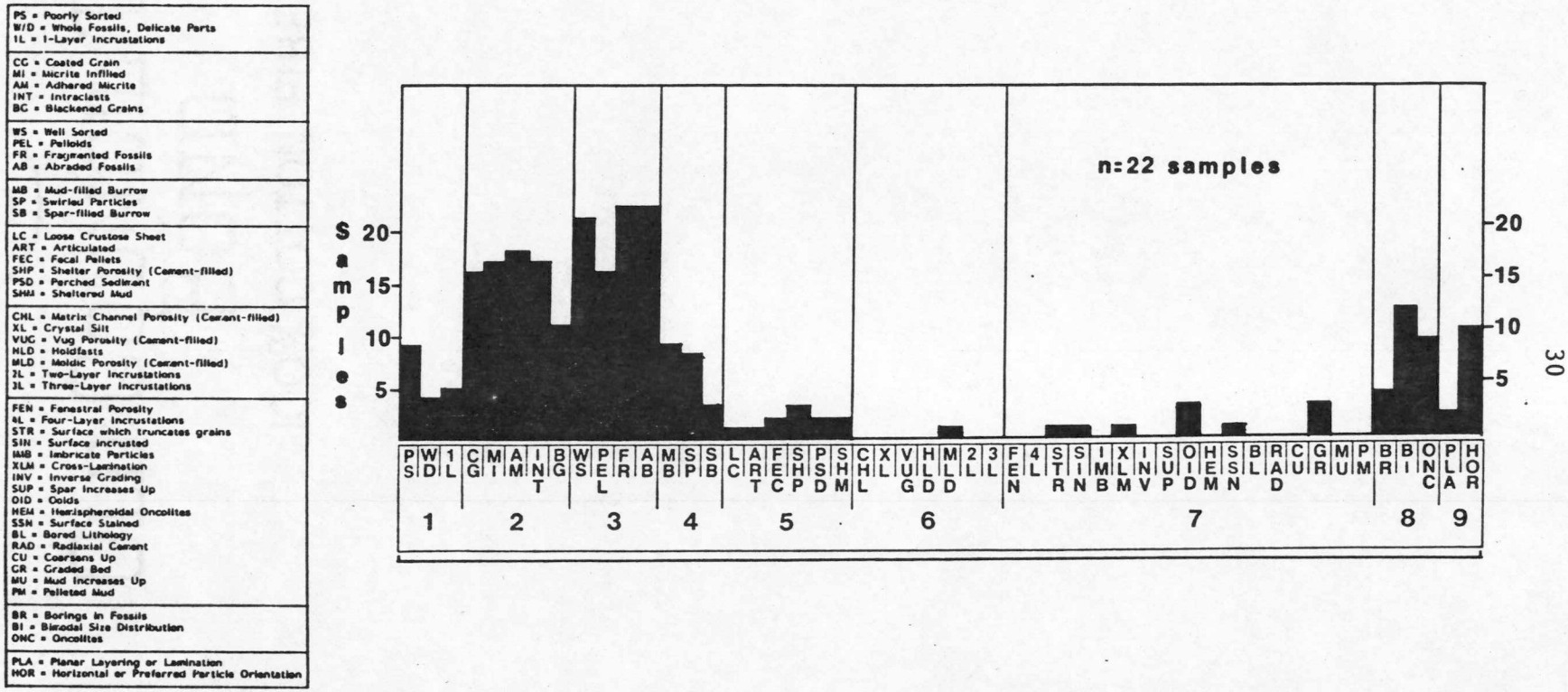


Figure 2-2. Graphic summary of features present in Ecofacies No. 1 (Sample or Q-mode Cluster 1). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at left. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Biomodal; No. 9 = Horizontal.

Features of the Bimodal Feature Group (No. 8 on Fig. 2-2) are next most common. These include Borings in fossils (BR), Bimodal Size Distribution (BI), and Oncolites (ONC). These occur mainly in subfacies (or subcluster) 1c, which lacks the Horizontal particle orientation (Horiz) found in some of the other subclusters and shown on the graphic summary. This subfacies also has a poorly-sorted fraction which commonly consists of trilobite or ostracode particles.

Other features are less frequently represented, such as the burrowing features in the Infaunal Feature Group (No. 4 in Fig. 2-2). Hydrodynamic structures such as lamination and cross-lamination are rare, as are most lithification features (except for intraclasts and pelloids).

Composite particle history. A minority of samples in these ecofacies or sample clusters display all of the features shown as characteristic of the ecofacies in the graphic summaries. Instead, subclusters or subfacies may share some features and lack others. The graphic summaries display a kind of ideal or "average" feature composition because subfacies are not distinguished. Nevertheless, a characteristic feature "signature" was distinguished by the computer clustering for this group of samples which is probably related to the combination of sedimentologic and ecologic factors existing at the site of deposition. Thus, it is relevant to an environmental study to construct an average or composite particle history of these ecofacies just as Johnson (1960) constructed such histories for his ideal or model fossil assemblages. Judgments regarding particle history using

paleoecologic criteria similar to that used here are routinely made in carbonate microfacies studies (e.g., Wilson, 1975). In the case of Ecofacies 1 (or Well-sorted Ecofacies), the samples display facies whose features are a result of extensive sorting and probably grain transport. Sediment particles in these samples were probably not produced in the area of deposition, with the possible exception of larger, less fragmented arthropods (trilobites, ostracodes). The majority of particles were transported by waves or currents as laterally accreting sand bodies rather than as tidal fluxes involving vertical accretion of fines resulting in lamination. Good sorting produced by transport resulted in few larger bioclasts suitable for incrustation. Sediment grains were exposed at the sediment-water interface at their site of formation long enough for algal coatings to form. Water turbulence was high and constant enough to prevent deposition of fines and organic detritus. Hence, postdepositional burrowing is mainly confined to habitat burrows rather than those formed by sediment eating activities. The source area of some particles was much less agitated, as evidenced by blackened grains as well as micritic features. Interparticle porosities were high in these samples and the lack of larger bioclasts resulted in low shelter porosities. Pore cementation after burial was by blocky cement; or where echinoderm grains are abundant, by syntaxial cement.

Features Present in Ecofacies No. 2, Layered or Laminated

The most frequent features in this facies are, once again, to be found in the Well-sorted Feature Group (No. 3 in Fig. 2-3). These

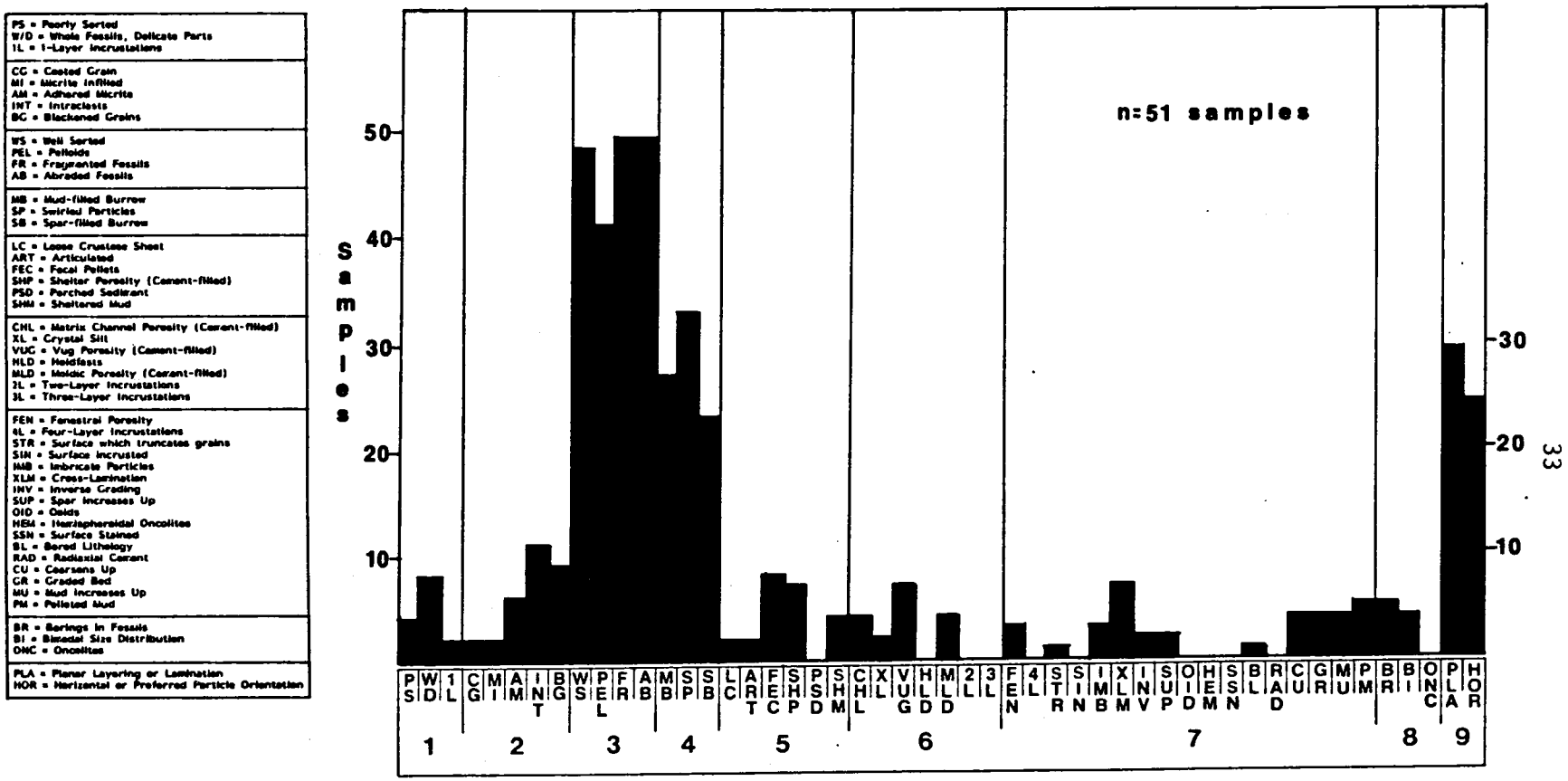


Figure 2-3. Graphic summary of features present in Ecofacies No. 2 (Sample or Q-mode Cluster 2). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at left. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

include Well-sorted particles, Pelloids, Fragmented fossils, and Abraded fossils. In this case, these effects are associated with other grain transport features such as Planar Layering (PLA) and Horizontal Particle Orientation (HOR) which constitute the Horizontal Feature Group (No. 9 in Fig. 2-3).

Also well represented are the bioturbation features in the Infaunal Feature Group, which includes Mud-filled Burrows (MB), Spar-filled Burrows (SB), and Swirled or concentrically arranged particles (SP). Burrows may be vertical (as in A44 and B19), horizontal, or U-shaped (as in A1 and A39).

Features clustered into the Micritic Group (No. 2) are far less frequent than they were in the previous facies. They include Coated Grains, Micritic pore infillings, and Intraclasts. Intraclasts are most abundant of these and are present in 11 of 51 slide of this facies.

The bulk of the features shown in the graphic summary from the Poorly-sorted Feature Group (No. 1) are from three samples which constitute subfacies 2g. This subcluster is associated with the other subclusters in this ecofacies at a very low level of similarity (Fig. 2-1, p. 27). All three of the samples contain a larger-sized fraction of convex-up brachiopod shells which cause the recording of Poorly-sorted features as well as the Shelter Group Features (No. 5).

The Porosity features (all cement-filled) shown in this facies are mainly due to the three dismicrites which begin subcluster 2a and those which constitute subcluster 2c. These features include Matrix channel pores (CHNL), Matrix vug pores, and Moldic porosity which

are associated with the dismicrite. These lithologies were grouped with the other samples in this facies due to their relatively good sorting and other effects in the Well-sorted Feature Group.

This laminated or layered ecofacies also contains cross-laminated lithologies, as in the subcluster or subfacies 2f. Subfacies 2g has samples with Imbricate and Convex-up fossils associated with Horizontal particles and Bimodal size distribution. These are transport-related features.

Composite particle history. Because this ecologic facies contains so many layered or laminated samples it is called the Layered Facies. Sediment particles consist of extensively transported skeletal particles and nonfossil allochems such as pelloids and intraclasts. Many of the particles were transported by frequent tidal currents characterized by a combination of traction and suspension transport resulting in common graded laminae with sharp bottoms. These and other primary depositional features are preserved due to lack of sediment bioturbation. Infauna were mainly suspension feeders residing in vertical or U-shaped burrows. Periodic subaerial exposure of some facies caused desiccation features, lack of algal-related coated grains, and a lack of larger incrusted fossil particles. The episodic nature of sedimentation in this facies caused deposition of fines which substantially reduced interparticle porosity or acted as impermeable layers. Fenestral pores are common in the subaerially exposed subfacies and are now filled with blocky calcite cements.

Features Present in Ecofacies No. 3, Biomodal

Ecofacies No. 3 is the third such facies to have frequent Well-sorted group features, i.e., well-sorted particles, pelloids, fragmented and abraded grains. Unlike the previous sample clusters, these features primarily describe matrix particles because there is a frequent Poorly-sorted (PS) fraction of the sediment which has Whole and Unabraded Fossils (W/D). One-layered incrustations (mainly bryozoan and worm tubes) are common among these larger fossil particles. The larger size fraction also accounts for the pronounced bimodality (BI) shown in the Bimodal Feature Group (No. 8 in Fig. 2-4).

The larger size fraction of fossils in this facies causes considerable shelter porosity as well as some of the other features the R-mode clustering shows to be associated with shelter pores, such as, Sheltered Micrite (SHM), Perched Sediment (PS), and Loose or unattached bryozoan crustose sheets (LC). Presumably the unattached bryozoan sheets were torn loose or otherwise separated from sites of attachment on the larger-sized fraction of fossils. A small portion of these samples have Fecal Pellets, which are commonly preserved under shelters as perched sediment is present above them.

Intraclasts (INT) and fossils with Adhered Micrite are present in over half of the samples in this ecologic facies. Along with Micrite Infilled fossil pores (MI) and Coated Grains (CG), these features suggest their production in nearby, quieter areas where micrite accumulation and algal activity were common.

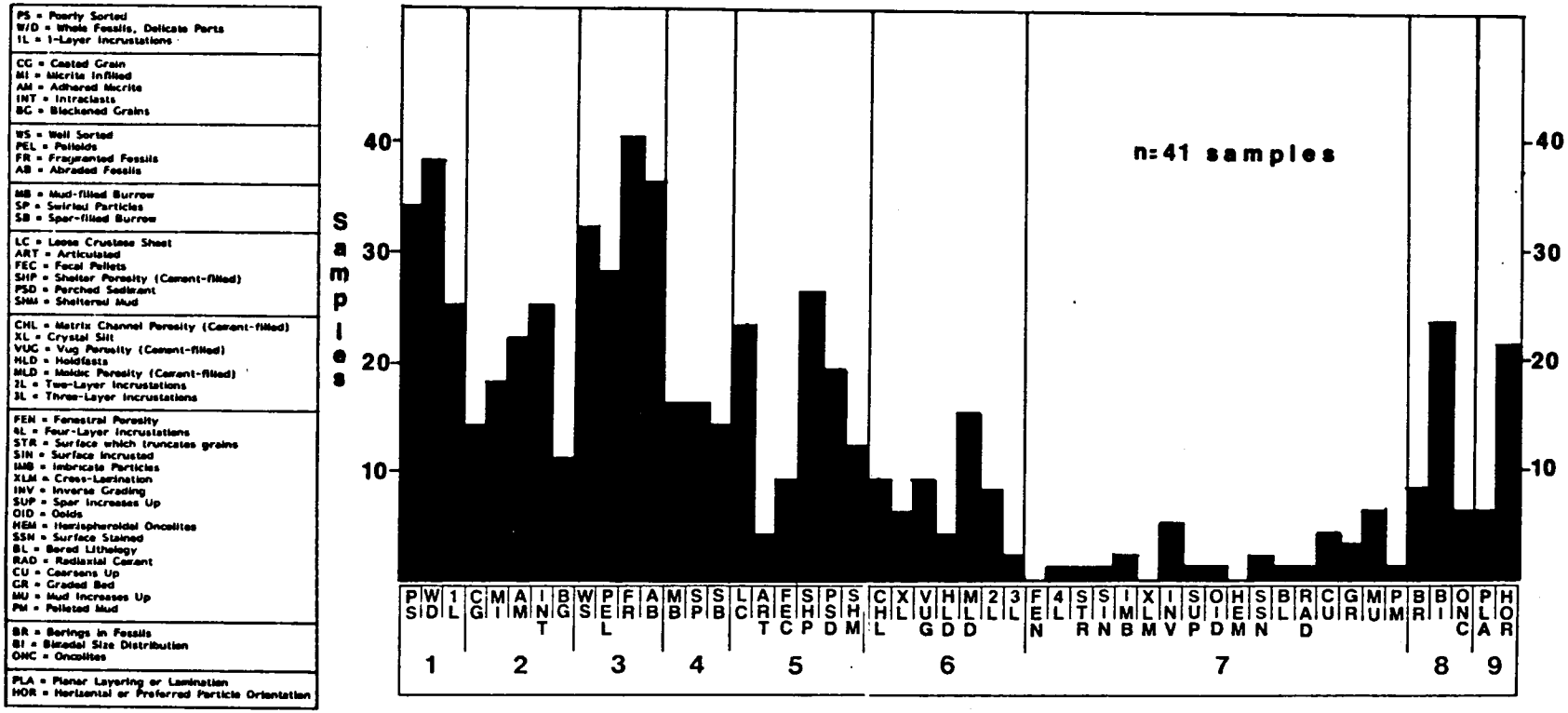


Figure 2-4. Graphic summary of features present in Ecofacies No. 3 (Sample or Q-mode Cluster 3). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at left. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

This is the first ecofacies containing samples with significant interstitial micrite (see Appendix D, Table D-4). As is often the case for Lay School samples, those with matrix micrite frequently have bioturbation features. This ecofacies, for instance, has features from the Infaunal Group (Mud Burrows, Swirled particles, Spar-filled burrows) in about a third of its slides.

The Porosity Feature Group (No. 6) shows a substantial increase in features compared to the previous facies. Cement-filled moldic porosity is the most frequent of these features and is followed by cement-filled matrix vug and channel porosity. These features mainly occur in the sample subclusters 3e-3g, which contain calcareous sandy lithologies in various stages of washing or winnowing. Particles in some of these lithologies were exposed at the sediment-water-interface long enough for two-layer incrustations to form.

A few of the samples in this ecologic facies have early lithification characteristics, such as the erosional surfaces in B33(1) which truncates underlying particles and is itself incrusted. There is also a scattering of hydrodynamic effects depicted in the Mixed Feature Group (No. 7), such as Graded Bedding (GR), Inverse or reverse Grading (INV), and Imbrication (IMB). Another possible hydrodynamic feature, Horizontal Particle Orientation (HOR), is a common feature of the sample in this facies.

Composite particle history. Many of the fossil particles in this facies have been transported. Both skeletal and nonskeletal grains are common. Presence of poorly-sorted and well-sorted sediment fractions

suggest that grains of this facies were less extensively transported than those of the previous facies and occupied an environment intermediate in position between continuously turbulent and quiet water settings. Some of the larger fossil particles served as sites for colonization by incrusting benthic organisms (e.g., bryozoans, algae) which occasionally formed multiple concentric layers around the center particle. Water turbulence was frequent enough to winnow out fines in some samples and yet inadequate to remove interstitial micrite in lithologies with burrowing and bioturbation features. The commonly reworked fossils and other sediment particles formed porous accumulations when redeposited and these contained shelter pores as well as winnowed pores (matrix channel pores), vuggy matrix pores, and interparticle pores. Postburial permeability lead to fluid transport which assisted in dissolving some skeletal grains, as shown by the moldic pores in some facies. Cement is primarily blocky calcite.

Features Present in Ecofacies No. 4, Bioturbated

This is the largest sample group or facies in the cluster study and its feature composition is different from the preceding three clusters. Whereas fragmented and apparently abraded fossil particles are as frequent as in the earlier groups, samples with a well-sorted fraction are far fewer. Like the earlier facies, however, this facies has a poorly-sorted aspect (Fig. 2-5). The poor sorting is a noticeably more frequent feature of the Poorly-sorted Feature Group than either 1-layer incrustations or whole fossils with delicate parts preserved.

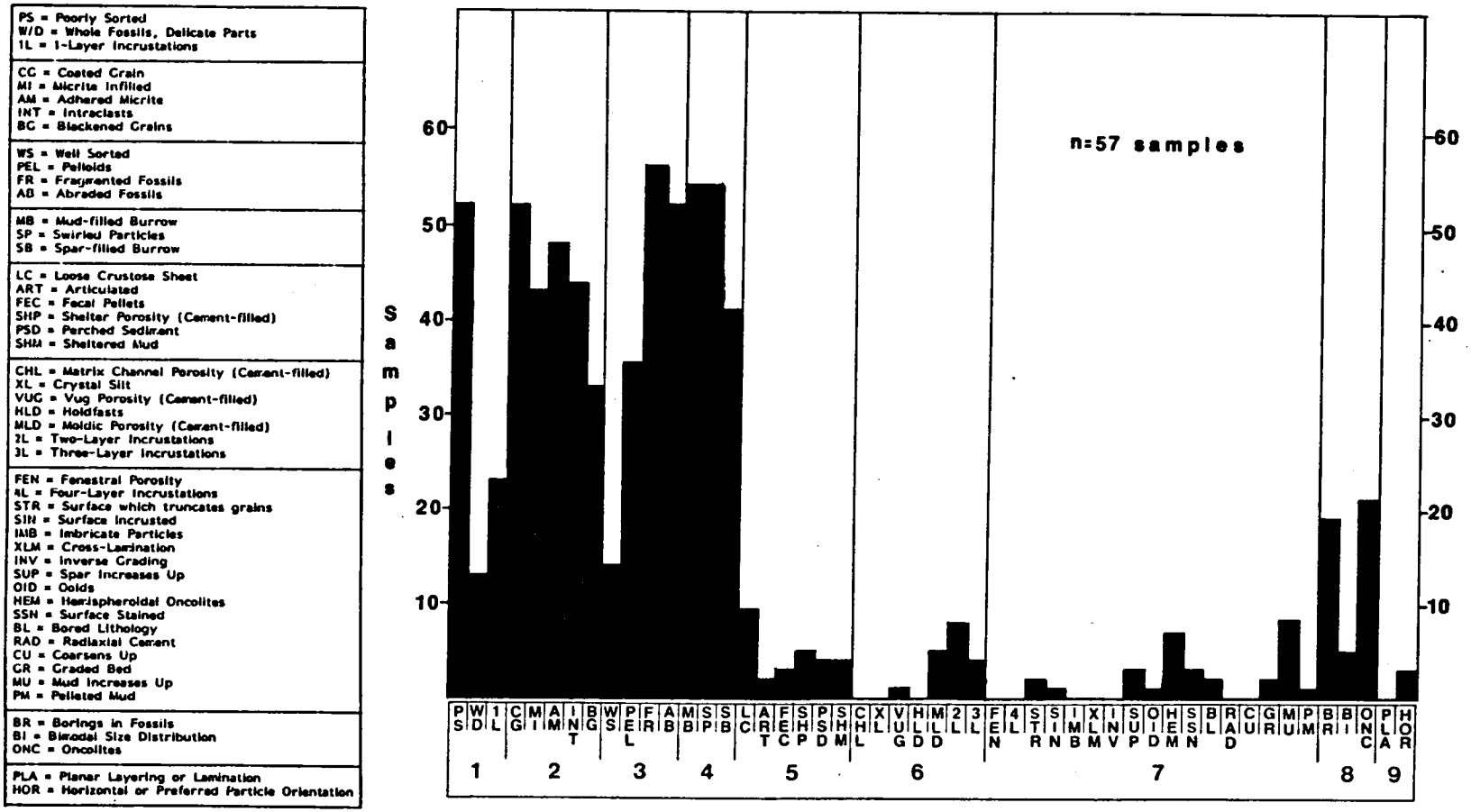


Figure 2-5. Graphic summary of features present in Ecofacies No. 4 (Sample or Q-mode Cluster 4). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at left. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

Most of the samples in this facies are rich in interstitial micrite and have frequent Infaunal Feature Group effects, such as mud and spar-filled burrows and churned particles. Not surprisingly, Micritic features are also common in this facies. Most of the thin-sections contain coated grains, micritic pore infillings, and intraclasts. Blackened or pyritized particles are also common, a plausible effect in an area with poor circulation or normally low water-turbulence. The co-occurrence of extensive bioturbation and mud-rich lithologies in this cluster confirms ecological relationships between deposit-feeding benthos and mud substrates observed by Rhoads (1970, 1973) and first detailed by Sanders (1958).

Bioturbation also explains the paucity of shelter effects seen in this facies as well as other primary depositional features such as layering or horizontally-oriented particles.

There are some features which are consistent with particle exposure in this facies. For example, more samples have Bored fossils (BR) (other than endolithic algal or fungal borings) than in any of the previous facies. Also oncolites, which require exposure at the sediment-water-interface in order to form, are present in this facies. Additionally, there are 2 and 3-layered incrustations on some particles (Porosity Feature Group or No. 6 in Fig. 2-5) which would require epifaunal exposure to form.

Cement-filled pores related to primary depositional processes are rare in this sample group. Matrix channel porosity is absent, matrix vugs are present in only one sample, and even moldic porosity is relatively rare.

Composite particle history. The extensive bioturbation exhibited in this facies suggests that it be called the Bioturbated Ecofacies. Its fossils may be partly indigenous and partly transported into the area by episodic events (e.g., storms) whose depositional record was destroyed by bioturbation. The abundance of fine-grained carbonate indicates that suspension settling was an important mode of sediment transport and deposition. The accumulation of organic detritus with fine carbonate resulted in extensive bioturbation by infaunal sediment feeders. Fossils commonly remained at the sediment-water-interface after death long enough for incrustations and algal degradation to occur. Other organisms possibly contributed to particle size reduction by boring (e.g., worms, sponges, bryozoans). As mentioned, algal (and fungal) activity was a possibly important part of this destructive biogenic diagenesis. Turbulence was normally low, but episodic enough to move particles to form oncolites, coated grains, and multiple incrustations. Alternatively, some of those feature could have formed in more turbulent adjacent environments and been washed in by occasional turbulent events. The generally low turbulence resulted in poor oxygenation, as shown by common blackened or pyritized particles.

Features Present in Ecofacies No. 5, Poorly-Sorted, Jumbled

Almost all the samples in this facies have all three features in the Poorly-sorted Feature Group (i.e., Poorly-sorted particles, Whole fossils with Delicate parts preserved, and 1-layer incrustations). The increase relative to the previous facies in large, whole fossils with

delicate parts gives this facies an in situ aspect lacking from Ecofacies No. 4. Yet, there are plenty of particles displaying fragmentation and apparent abrasion, as in the previous ecofacies. There is a much higher percentage of fossil particles with 1-layer incrustations than in the previous facies (Fig. 2-6).

Micritic Features are abundant and include Intraclasts, Adhered micrite on fossils, Infilled fossil pores, and Coated grains. Pelloids, another micritic particle type, are in at least half the samples. Blackened particles are not as common as the other Micritic Group features, but are still in two-thirds of the slides.

Matrix spar is more common in this ecofacies and a substantial part of the cement-filled matrix porosity is cement-filled shelter porosity. Sheltering is also responsible for the Sheltered Micrite, where micrite under a large skeletal particle was protected from postdepositional turbulence as inferred from sparry sediment above the particle. This is the only ecofacies where Sheltered micrite features are so common that they are more frequent than Shelter pores (cement-filled). Unattached crustose bryozoan sheets and fecal pellets are also associated features.

Bioturbation features are not as frequent as in the previous group of samples, although they are not rare. Over half the slides contain spar-filled burrows, for instance. Mud-filled burrows and swirled particles are present in less than half the samples. Significantly, those subclusters (5a, 5b, 5c) with the most burrowing features have the fewest shelter pores. Also, this ecofacies as a

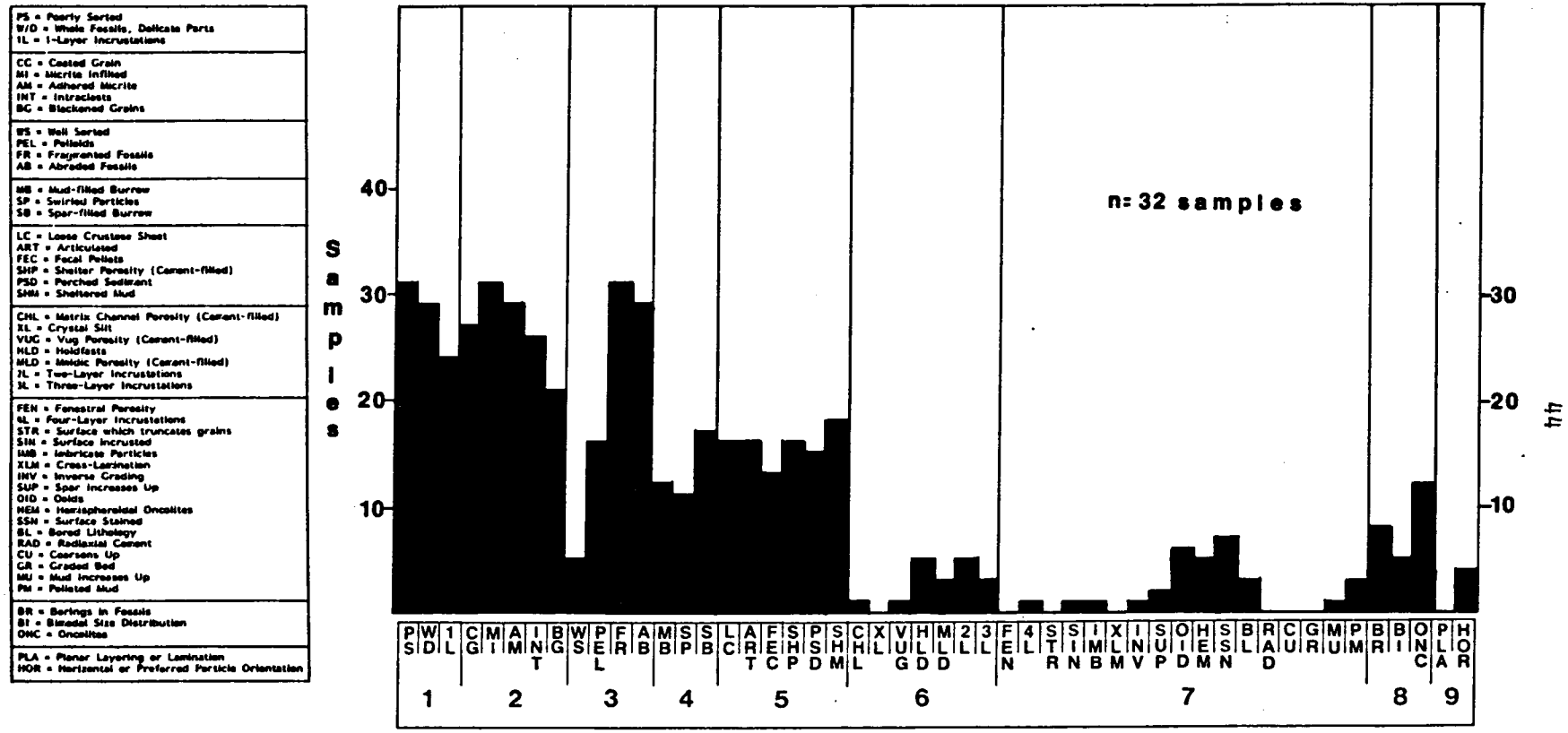


Figure 2-6. Graphic summary of features present in Ecofacies No. 5 (Sample or Q-mode Cluster 5). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at left. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

whole again displays the relationship between mud substrates and bioturbation observed by Sanders (1958) and Rhoads (1970, 1973) in modern environments, indicating the close association between mud substrates and infaunal sediment eating. In this case, there is less mud in the lithologies in this ecofacies and less bioturbation.

Other kinds of cement-filled pore systems are not as frequent as shelter pores. The Porosity Feature Group is barely represented (No. 6 in Fig. 2-6). This may be related to the fact that this ecofacies has a jumbled particle fabric and evidence of channel pores as well as hydrodynamic features such as Horizontally-oriented particles, convex-up shells, or grading are absent. The Horizontal Feature Group, for example, is barely represented and very few samples are bimodal.

Oncolites, the most frequent feature in the Bimodal Feature Group, are present in a little more than a third of the thin-sections in this facies. Yet their presence and the abundance of presumably algal-related coated grains suggests that algal activity was a feature of this environment.

Stained sediment surfaces occur in several samples in this ecofacies. Other features from the large, Mixed Feature Group which occur in this facies are ooids and hemispherioidal oncolites. The only sample in the Lay School section that contains enough ooids to be considered an oolite (B25) is in this facies (i.e., greater than 75%, after Folk, 1974). Several thin-sections (including B25) contain both ooids and oncolites. Their association in this ecofacies suggests the close proximity of ooid and oncolite-forming environments.

Composite particle history. Fossils are indigenous or nearly so. Upon death, the skeletal particle was modified by incrustations and algal degradation at the sediment-water-interface for some time before it was buried. The normally quiet water provided a setting for deposition of carbonate mud which buried the fossils. Migration into the area by a turbulent regime such as a near shore shoal zone or a channel resulted in exhumation of many fossil particles with adhered micrite, as well as intraclasts, pelloids, and other micritic features. The buried fossils sometimes shielded the underlying mud from reworking. The shelter pores from the reworking event or events are preserved, but turbulence did not last long enough to sort particles or cause other sedimentary structures, such as grading or cross-lamination. Those exhumed or slightly reworked fossil accumulations lying on mud substrates were bioturbated. Blocky cements filled in the porous areas.

Features Present in Ecofacies No. 6, Shelter, Horizontal

Ecofacies No. 6 is another poorly-sorted facies. Like the previous facies, all the Poorly-sorted Group features are abundant (No. 1 in Fig. 2-7). Most samples have whole fossils with delicate parts and 1-layer incrustations. Unlike the previous facies, there are fewer features from the Micritic Group. Whereas micritic infillings of fossil pores and adhered micrite on fossils are common, coated grains and blackened grains are not. Intraclasts are fewer as well.

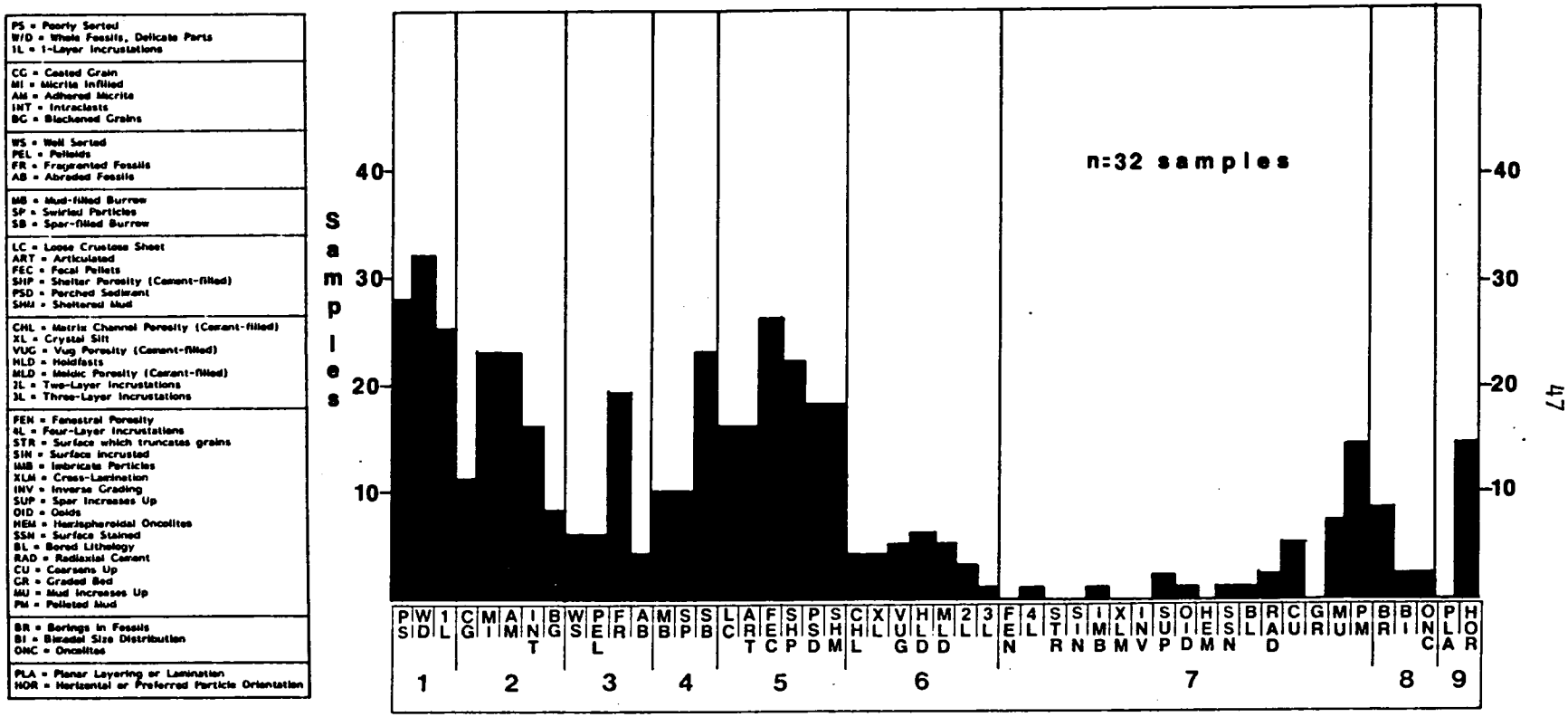


Figure 2-7. Graphic summary of features present in Ecofacies No. 6 (Sample or Q-mode Cluster 6). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at right. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

Fossil fragmentation is the only common feature from the Well-sorted Feature Group. Abrasion of fossils is rare, especially when compared to fragmentation. The lack of coated particles and oncolites in this facies when considered with the abnormally low amount of abrasion suggests that much apparent abrasion recorded in facies discussed earlier could have actually been caused by degradation of fossil particles by endolithic algae.

Shelter Group Features are prominent in this facies. Both shelter pores and sheltered micrite are common and fecal pellets are frequent. Articulated bivalved fossils and unattached crustose sheets often form shelters under which fecal pellets are preserved. Likewise, pelleted mud occurs more frequently than in any other sample group.

Another interesting aspect of bioturbation in this facies is the proportion of burrow types represented in the Infaunal Feature Group in Fig. 2-7. Over two-thirds of the thin-sections (i.e., 23) contain spar-filled burrows while mud-filled burrows and areas of swirled particles are present in only half that number. Thus, in some slides there is no evidence of burrowing other than spar-filled burrows. Yet the pelleted mud indicates that deposit-feeding activity was present. One possible explanation of these differences in bioturbation features may be related to the mineralogic composition of the mud in this facies, or at least in that part of the Lay School column where this facies is best developed--the lower third of Part E. Whereas other muddy areas in the Lay School section are dominated by fine-grained carbonates, samples in lower Part E have substantial clay minerals as well. This is

reflected in the shaly and crumbly nature of the outcrops in addition to the abundance of clay-rich stylocumulate. Thus, the preservation of spar-filled burrows, fecal pellets, and pelleted mud may be related to different lithification or coherency characteristics from the carbonate muds in other parts of the column.

Porosity features other than shelter pores are uncommon in this facies. Pelmatozoan holdfasts are the most frequent feature of the Porosity Group (No. 6 in Fig. 2-7) and are relatively rare.

Features possibly related to hydrodynamic processes are confined to subfacies in two parts of the column. Convex-up brachiopod and pelecypod shells occur along with horizontal fossil particles in Part E of the section. Other Horizontal particles in this facies are present in variably sparry bryozoan-rich beds which flank mud pods in the central Part C of the column. One of these samples (C22) contains another feature from the Mixed Feature Group, that is, spar increasing upward in sediment. An increase in interparticle spar upwards in a bed (or thin-section) could suggest winnowing activity. A more common feature, found in Part E mainly, is the increase in micrite upwards in a bed or thin-section. This describes the situation where a spar-rich layer is overlain with a diffuse or irregular boundary by a mud-rich layer.

Composite particle history. Features in this facies resulted from conditions in two settings. There are, therefore, two slightly different particle histories. First, fossil bryozoans and pelmatozoans grew in profusion around the micritic pods or mounds whose facies are

described in the next ecofacies. Upon death, these fossils accumulated in low areas, sometimes with micrite. Subsequent winnowing and movement by currents caused horizontal particle alignment, shelter pores, and other porosity features. These pore systems were later filled with syntaxial and blocky calcite cements.

The other depositional setting contains particles with different histories. A more diverse variety of organisms lived in a quiet, deep water setting characterized by normally low turbulence but open marine circulation (little pyrite). Upon death, skeletal elements remained at the sediment-water-interface long enough for single-layer bryozoan incrustations. Burial was by clay-rich fine-grained carbonate and infaunal activity disrupted most grain-supported accumulations, resulting in jumbled, mud-supported lithologies. Later, sediment movement caused by occasional turbulent events would exhume fossils and transport them. These bodies of transported sediment are often have poorly-washed or partly sparry matrices and may have horizontal particle fabrics developed at their base or periphery. Abundance of larger, whole fossils resulted in frequent shelter pores and sheltered micrite in grain-supported textures. Algal activity was noticeably rare. Cementation was again by blocky or syntaxial cements.

Features Present in Ecofacies No. 7, In Situ Facies

The most common features of this this last ecofacies (sample cluster) are those of the Poorly-sorted Group, which were important in the previous two facies as well.

Also frequent in this group of slides are the Infaunal Group features Mud- and Spar-filled burrows. Swirled or concentrically arranged particles are unusually rare in this facies. For some subfacies this may be due to early lithification. Radiaxial cement, thought by some (Bathurst, 1975) to derive from early fibrous aragonitic marine cements, occurs in the mud pods which interfinger with bryozoan/pelmatozoan sands in the central Part C of the Lay School section (see column Fig. 1-3, p. 13). The cement occurs in cavities and crusts of apparently algal origin. Cavities have digitate or irregular roofs and flat floors consisting of dark, clotted particles and sediment which grades upward into micrite. The radiaxial cement partially lines some of these cavities and is present in pores in some of the spongiostrome walls. The majority of the cements in the cavities are blocky cements, however, suggesting that early marine cementation was incomplete. Other features which suggest early lithification are possible borings in crusts (Bored Lithology or BL in Fig. 2-8), and incrusted surfaces (SIN). These effects, and the general rarity of swirled particles, all seem to imply early solidification.

Evidence of algal activity is in the form of spongiostrome or clotted crusts and occasional stromatolitic layering rather than abundant coated grains or oncolites. Rarely, tubules of Girvanella are present in the clotted crusts although usually are not. A more complete description of both cavities and algal textures is given in the succeeding environmental chapter.

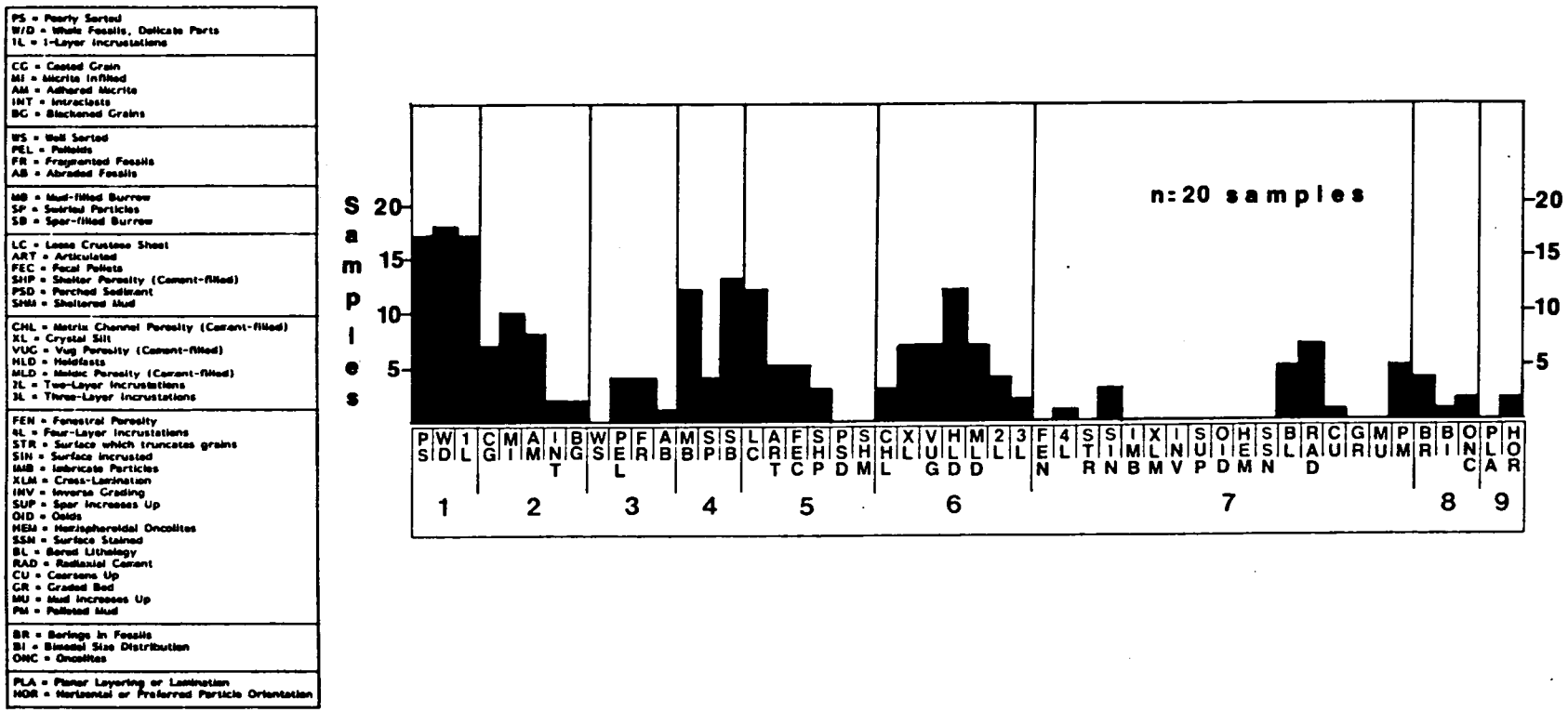


Figure 2-8. Graphic summary of features present in Ecofacies No. 7 (Sample or Q-mode Cluster 7). Features are arranged in groups of positively-associated features established by R-mode (or feature) cluster analysis presented in Appendix C, Fig. C-2. Abbreviation key is at right. Feature cluster names are: No. 1 = Poorly-sorted; No. 2 = Micritic; No. 3 = Well-sorted; No. 4 = Infaunal; No. 5 = Shelter; No. 6 = Porosity; No. 7 = Mixed; No. 8 = Bimodal; No. 9 = Horizontal.

There is a reduction in Micritic Group features in this facies, with micritic infillings and adhered micrite found in only half the slides. Intraclasts and blackened grains are rare.

Porosity Group features are a noticeable constituent feature group of this facies because of the cavities in the mud pod lithology. Pelmatozoan holdfast systems are the most frequent feature of the group. Vug, channel, and moldic cavities are types present in the mud pod lithology.

Hydrodynamic features are rare in this ecofacies. There are few present in the Mixed Feature Group, Well-sorted Feature Group, and the Horizontal Feature Group.

Composite particle history. There was common indigenous particle production in this setting, including micrite derived from algal disintegration. The bulk of skeletal particles came from in situ suspension feeding organisms, especially pelmatozoan echinoderms and bifoliate or rhomboporid bryozoans. In cross-section, the major facies consists of an irregular anastomosing framework of algal crusts with cavities containing variable amounts of winnowed sediment. Incrusting bryozoans and holdfasts of more erect suspension feeding organisms used the crusts as a firm substrate for colonization. Areas peripheral to algal-dominated mounds may have had greater numbers of stalked sessile suspension feeders which acted as baffles, causing algally-derived micrite particles to fall from suspension. Water turbulence was gentle to moderate. Primary depositional fabrics, for example

horizontally-oriented fossils, may be preserved in flanking accumulations. Infaunal burrowers were present in the absence of early lithification. Cavities and crusts commonly have brownish radiaxial cements that are isopachous or partially line cavities. Commonly, blocky cements fill most or the central portions of cavities, suggesting that marine cementation was arrested and replaced by freshwater cementation processes.

Summary of Table of Ecofacies

Table 2-1 summarizes the features of the seven ecologic facies obtained by Q-mode sample clustering. Categories of features correspond to the classification presented earlier in this chapter. The homogeneity of groups formed by Q-mode cluster analysis is strongly influenced by the nature of the variables measured in the samples. Both Q-mode factor and cluster analysis require uncorrelated or only slightly correlated variables to give the best results (Parks, 1968). Several highly-correlated variables can bias a Q-mode cluster analysis, and, consequently, in most multivariate Q-mode studies several R-mode analyses (factor or cluster) are performed first on the proposed variables to eliminate highly correlated ones. Because repeated access to a computer was not possible in the present study, the Q-mode clusters presented here are probably not as homogenous as possible. A review of the feature (variable) clusters produced by the R-mode analysis shows that several features are correlated. Whole fossils and Delicate parts on fossils are the most highly correlated. Consequently

Table 2-1. Summary of Ecofacies Characteristics Arranged According to the Environmental Classification Presented in Chapter 2 and Discussed in Appendix B, Part 1.

Ecologic Facies	Features Related to Water Turbulence			Features Related to Biogenic Accumulation				Features Related to Early Diagenesis					
								Biological			Chemical	Early Lithification or Cementation Features	Pore Systems (Cement-Filled)
	Currents of Transport	Currents of Removal	Lack of Currents	Trapping & Binding	Baffling	Sheltering	Other	Epifaunal & Infaunal	Infaunal Only	Epifaunal Only	Epifaunal & Infaunal		
1 (n=22)	Ooids*. Oncolites. Fragmented. Abraded. Well-sorted. Bimodal. Horiz. grns. Sparry litholo-gies(†). Graded laminae*.	Adhered micrite. Intraclasts.	Poorly-sorted fraction. Micritic infilling.	Oncolites. Algal coats.				Frag-mented.	Mud-filled burrows. Spar-filled burrows. Vertical burrows(†).	Oncolites. Algal coats.	Blackened grains.	Intraclasts. Pelloids.	Interparticle(†).
2 (n=51)	Fragmented. Abraded. Well-sorted. Planar laminae. X-laminae. Horiz. grns. Graded lamin.*. Convex-up*.	Pelloids.						Frag-mented.	Mud-filled burrows. Spar-filled burrows. Swirled particles. Vertical burrows(†).			Pelloids. Fenestral pores*. Matrix vug pores*. Moldic pores*.	Interparticle(†). Fenestral*. Matrix channel* pores. Matrix vug*. Moldic*.
3 (n=41)	Fragmented. Abraded. Well-sorted fraction. Bimodal. Horiz. grns. Inverse grading*. Convex-up*. Ooids*.	Micrite & spar in matrix(†). Adhered micrite. Intraclasts. Pelloids. Sheltered micrite. Channel Pore matrix*. Inverse grading*.	Poorly-sorted fraction. Whole & delicate fossils. Micritic infillings. Micrite increases up*.	Algal coats.		Sheltered micrite*.		Frag-mented. Borings*.	Mud-filled burrows. Spar-filled burrows. Swirled particles. Fecal pellets*.	1-layer incrusta-tion. 2-layer incrusts.*. Algal coats. Loose bryozoan crusts.	Blackened grains.	Intraclasts. Pelloids. Moldic pores*.	Interparticle(†). Intraparticle(†). Shelter. Moldic. Matrix channel*. Matrix vug*.
4 (n=57)	Fragmented. Abraded. Oncolites.	Adhered micrite. Intraclasts. Pelloids.	Micritic infilling. Poorly-sorted fraction. Micritic matrix(†). Micrite increases up*.	Algal coats. Oncolites.				Borings. Frag-mented.	Mud-filled burrows. Spar-filled burrows. Swirled particles.	1-layer incrusts. 2-layer incrusts.*. 3-layer incrusts.*. Algal coats. Loose bryozoan crusts*. Oncolites.	Blackened grains.	Intraclasts. Pelloids.	Intraparticle.

Table 2-1 (continued)

Ecologic Facies	Features Related to Water Turbulence			Features Related to Biogenic Accumulation				Features Related to Early Diagenesis					
								Biological			Chemical	Early Lithification or Cementation Features	Pore Systems (Cement-Filled)
	Currents of Transport	Currents of Removal	Lack of Currents	Trapping & Binding	Baffling	Sheltering	Other	Epifaunal & Infaunal	Infaunal Only	Epifaunal Only	Epifaunal & Infaunal		
5 (n=32)	Fragmented. Abraded. Oncolites. Ooids*.	Micrite & spar in matrix(†). Adhered micrite. Intraclasts. Pelloids. Sheltered micrite.	Poorly-sorted fraction. Articulated. Micritic infillings.	Algal coats. Oncolites. Pelmat holdfasts*.		Sheltered micrite.		Fragmented. Borings*.	Mud-filled burrows. Spar-filled burrows. Swirled particles. Fecal pellets.	1-layer incrusts. 2-layer incrusts.*. 3-layer incrusts.*. Loose bryozoan crusts.	Blackened grains.	Intraclasts. Pelloids. Stained sediment. Surface*.	Interparticle. Intraparticle. Shelter.
6 (n=32)	Fragmented. Horiz. grns. Convex-up*.	Micrite & spar in matrix(†). Adhered micrite. Intraclasts. Sheltered micrite. ChannelPore matrix*. Spar incr up*.	Poorly-sort. whole & delicate fossils. Articulated. Micritic infillings. Micrite increases up*.	Algal coats. Pelmat. holdfasts*.		Sheltered micrite.		Fragmented. Borings*.	Spar-filled burrows. Mud-filled burrows*. Swirled particles*. Fecal pellets. Pelleted mud.	1-layer incrusts. Loose bryozoan crusts. Algal coats.		Intraclasts. Moldic pores*.	Interparticle. Intraparticle. Shelter. Moldic*. Matrix channel*. Matrix vug*.
7 (n=20)	Crystal silt.	Adhered micrite. Matrix vug pores. Matrix channel pores*.	Micritic Matrix(†). Poorly-sort. Whole & delicate fossils. Articulated*. Micritic infillings.	Algal coats. Stromatolitic Layering(†). Spongiostrome algal Boundstone(†). Bryozoan boundstone(†). Pelmatozoan holdfasts.	Baffle-stone.		Stomatoporoid Framestone.	Algal coats.	Mud burrows. Spar-filled burrows. Fecal pellets*. Bored lithology*.	1-layer incrusts. 2-layer incrusts.*. Loose bryozoan crusts.		Radiaxial cement. Incrusted sediment surfaces*. Bored lithologies*. Matrix vug pores. Moldic pores. Crystal silt.	Intraparticle. Matrix vug. Moldic. Matrix channel*.

Note: Features presented are present in at least one third of the samples in an ecofacies, with two kinds of exceptions. Features followed by an asterisk (*) are present in fewer than a third of the samples of a given ecofacies, but are at a significantly high point in their distribution. Features followed by a (†) are environmentally relevant features excluded from the cluster analysis for various reasons.

these features were combined into a single feature, Whole/Delicate Fossils for the stratigraphic plot of features in the next chapter as well as in the graphic summaries in this chapter. Appendix D, Table D-2 which includes only 50 features reflects this consolidation.

Table 2-1 is a simplified summary of the ecofacies. Generally, if a feature was present in less than one-third of the samples in a cluster, it was omitted from the table. Important exceptions to this rule are features which occur in less than one-third of the samples but are at a significantly high point in their distribution among the sample clusters. For instance, Convex-up shells are never in as many samples as a third of a cluster, but are present with other possible turbulence indicators in three ecofacies (Nos. 2, 3, and 6). Environmentally significant features that were excluded from the cluster analysis were also included in the table, such as interparticle porosity, vertical burrows, or amount of spar in the matrix (i.e., completely sparry, micrite and spar, or completely micritic).

CHAPTER 3

LAY SCHOOL DEPOSITIONAL ENVIRONMENTS AND ECOFACIES

Types of Interpretive Information

Information relevant to environmental reconstruction which was obtained from the Lay School samples falls into two general categories: taphonomic and sedimentologic features (most of which were used to derive the ecologic facies described in the previous chapter), and paleontologic information, usually of a general or higher taxonomic nature.

Ecozones

The stratigraphic distribution of ecofacies (or sample clusters) in the Lay School section is depicted in Fig. 3-1. The vertical scale lists the samples in their correct stratigraphic positions while the horizontal scale serially lists the ecofacies and subfacies from left to right. When the samples are plotted and their points connected, the variations in ecofacies can be visually determined from the resulting graph.

The stratigraphic plot demonstrates that both individual ecofacies and suites of ecofacies are characteristic of zones in the Lay School section. There are seven zones or intervals of distinctive ecologic aspect in the section:

Zone I ranges from samples A1 to B60

Zone II ranges from samples B62 to C10

Zone III ranges from samples C12 to C37

Figure 3-1. Ecozone division of the stratigraphic section at Lay School. The stratigraphic distribution of ecofacies (or samples represented by their sample cluster number) in the Lay School section. The vertical scale lists the samples in their correct stratigraphic positions while the horizontal scale serially lists the ecofacies and subfacies (or sample cluster number and sample subcluster) from left to right. Seven zones of distinctive ecologic character (ecozones) are established. Some ecozones may be characterized by one ecofacies (or sample cluster) while others may contain several. The ecozones encompass the following stratigraphic intervals:

Zone I ranges from Samples A1 to Sample B60;

Zone II ranges from Sample B62 to Sample C10;

Zone III ranges from Sample C12 to Sample C37;

Zone IV ranges from Sample C41 to Sample D20;

Zone V ranges from Sample D27 to Sample E76;

Zone VI ranges from Sample E80 to Sample E149;

Zone VII ranges from Sample E152 to Sample E165.

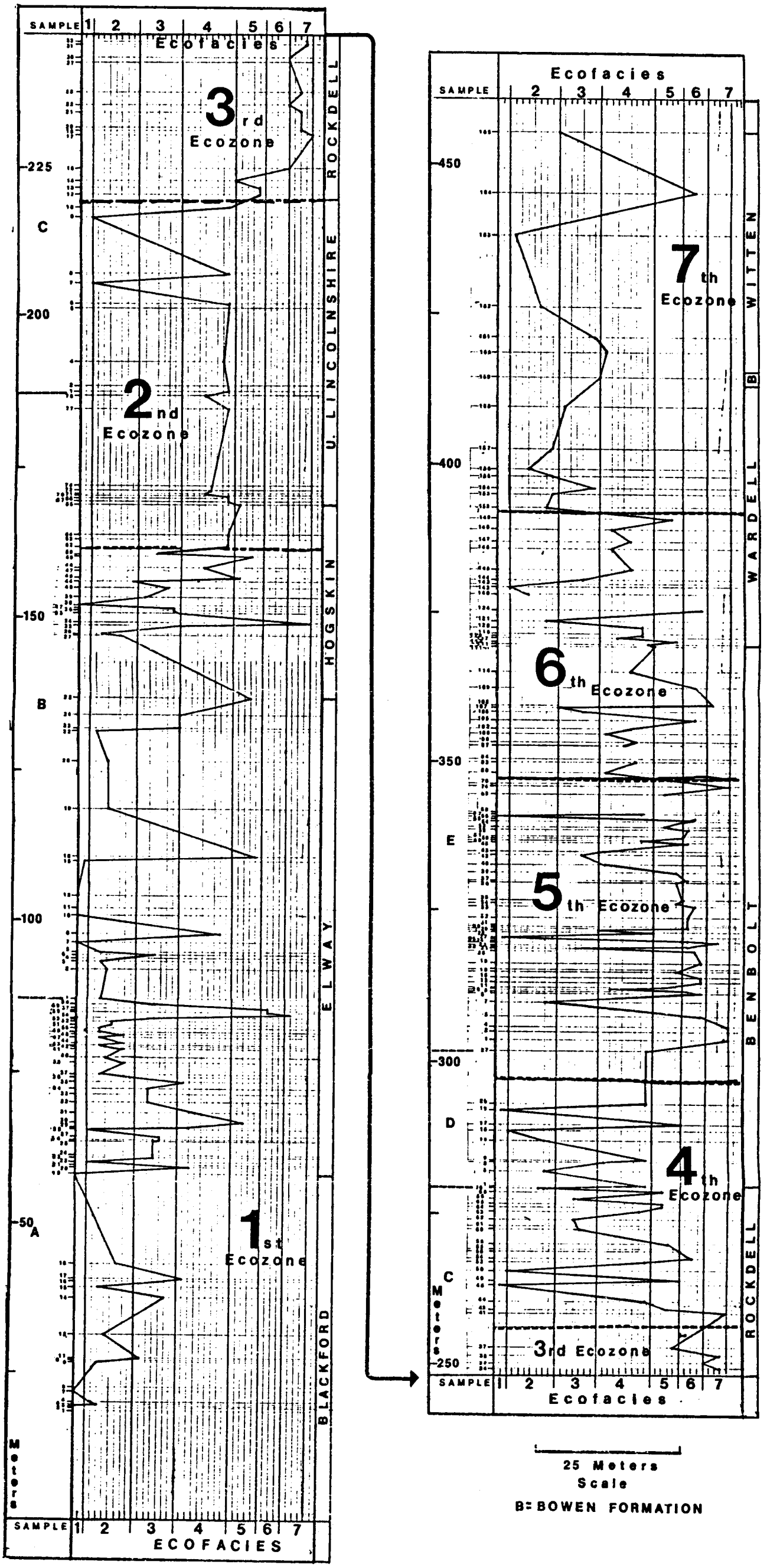


Figure 3-1.

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Zone IV ranges from samples C41 to D20

Zone V ranges from samples D27 to E76

Zone VI ranges from samples E80 to E149

Zone VII ranges from samples E152 to E165

Zone I is composed of Part A and Part B Sections and is dominated by transport-influenced Ecofacies 1-3. In certain parts of the zone, other ecofacies become important, such as Ecofacies 4 and 5 in the upper parts of A and B.

Zone II is characterized by the single ecofacies 4, which is dominated by bioturbation features. Lithologically, this interval contains fine-grained packstones and wackestones (biomicrites) with chert nodules.

Zone III contains a cement-filled cavity rich mud pod facies (Ecofacies 7) which is flanked and interfingered with bioclastic beds displaying horizontally-oriented fossils (Ecofacies 6).

Zone IV contains the most diverse suite of facies, both ecologic and lithologic. Beds of ecofacies 4 and 5 are most numerous.

Zone V also contains a number of ecofacies. Samples belonging to Ecofacies 5 and 6 are most common, although Ecofacies 4 and 7 are also well represented.

Zone VI's most frequently occurring ecofacies is the bioturbated facies, No. 4. As in the bottom part of the section, this interval is adjacent to one containing transport-influenced ecofacies. In this case, that zone is Zone VII and it occurs above the bioturbated ecozone. Ecofacies 2 and 3 are common in Ecozone VII. These seven

zones will form the basic framework for reconstructing the past environments represented at Lay School. Fig. 3-2 displays in another form the constituent ecofacies present in each ecozone and may be more useful in the following detailed environmental discussions.

Stratigraphy of Environmental Features

The discussion of past environments represented at Lay School will also refer to the distribution of individual features or groups of features. These are best displayed in feature groups which show maximum association, as determined by R-mode cluster analysis. This is shown in Fig. 3-3(a,b). Purdy (1963) found that similar groups of sediment particle types were related to specific environments in the modern Bahamas and termed the groups "Reaction Groups." Similarly, in ancient sediments, Smosna and Warshauer (1978) found that groups of sediment particle types and fossil types derived by R-mode cluster analysis of Silurian carbonate shelf samples corresponded to different paleoenvironments.

Stratigraphic Variations of Fossil Diversity

Most recent syntheses of carbonate petrology stress the interaction of physical and organic processes in the formation of carbonate rocks (e.g., Wilson, 1975). In order to be complete, therefore, environmental reconstructions in carbonate studies must consider organic or paleontologic aspects of sediment production and deposition. One such important aspect is the diversity of fossils which compose a

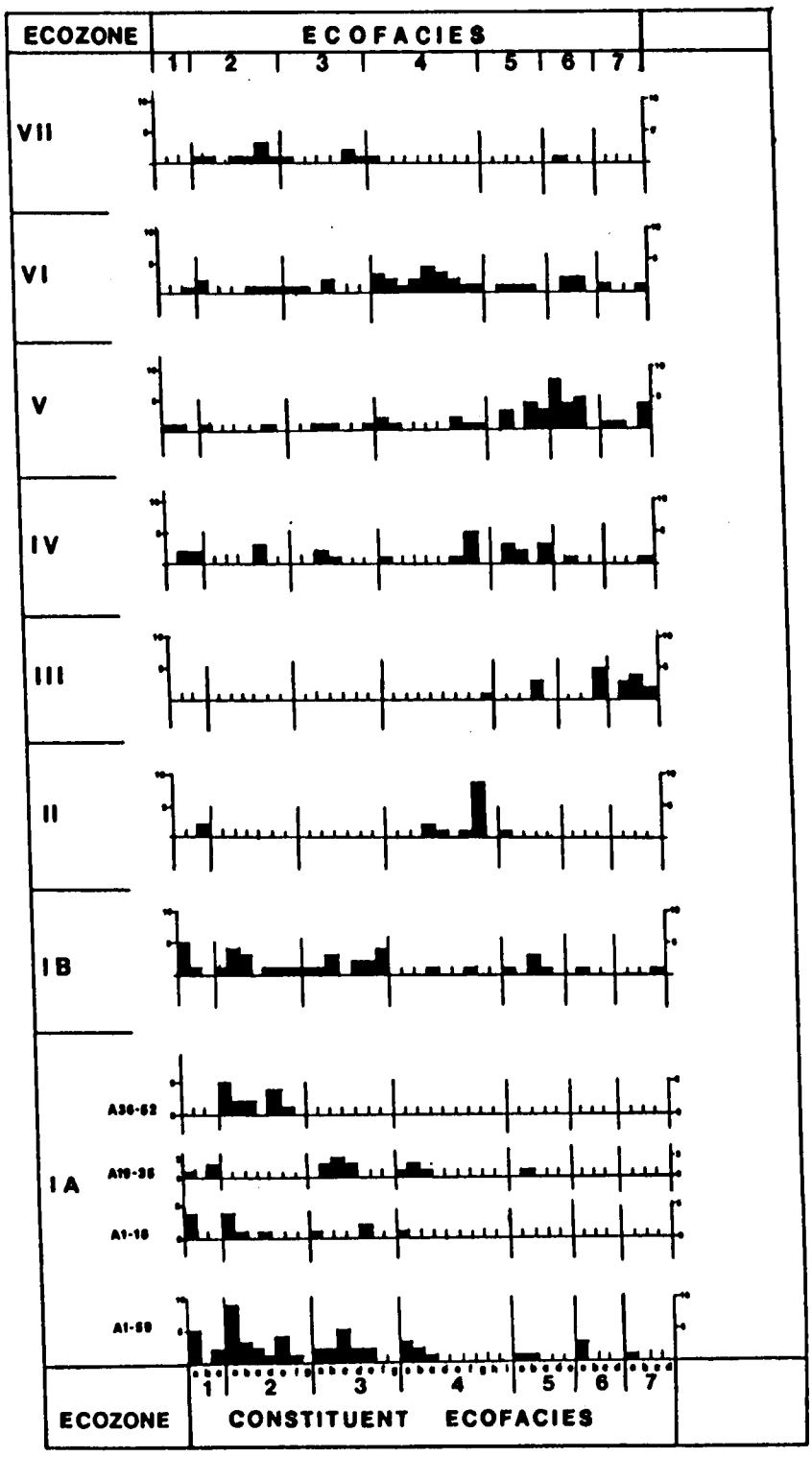


Figure 3-2. Constituent ecofacies of ecozones at Lay School. Figure displays the constituent ecofacies (numbers 1-7) and subfacies (letters a-h) on the horizontal scales. Vertical scale indicates number of samples of each ecofacies in the ecozone (numbered I-VII).

Figure 3-3. Stratigraphy of environmental features arranged by R-mode clustering into groups of maximum association. Figure lists samples in their correct stratigraphic position on the vertical scale. Environmental features used in cluster analysis are listed on horizontal scale, arranged by R-mode (feature or variable) clustering into groups of maximum association (or groups with shared patterns of association). Distribution of each feature in section is shown by single bars in each small column over the feature name. Stratigraphic variation of feature group as a whole is shown by the graph of the sum of the total features of each group found in each sample.

a.

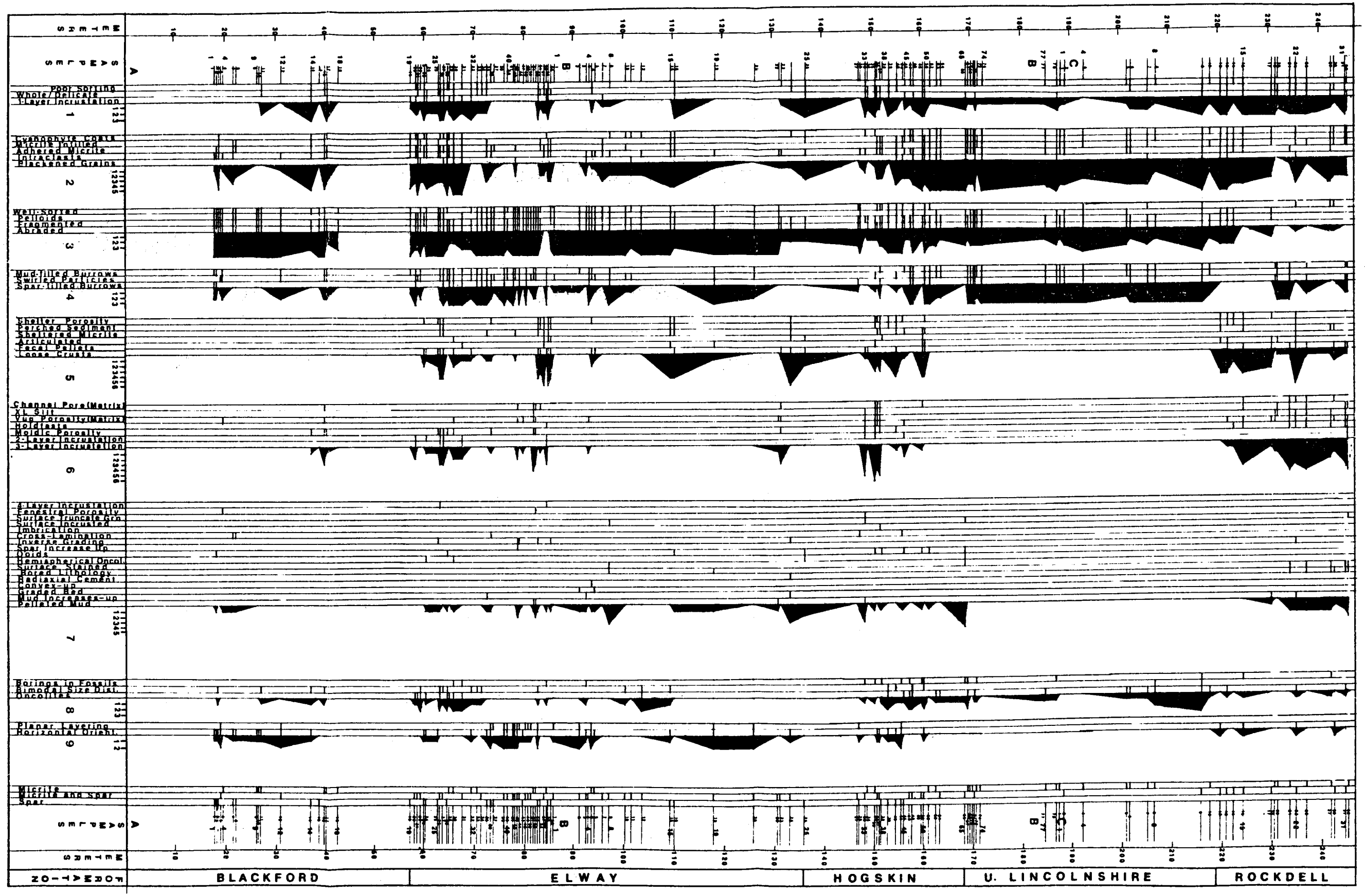


Figure 3-3.

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b.

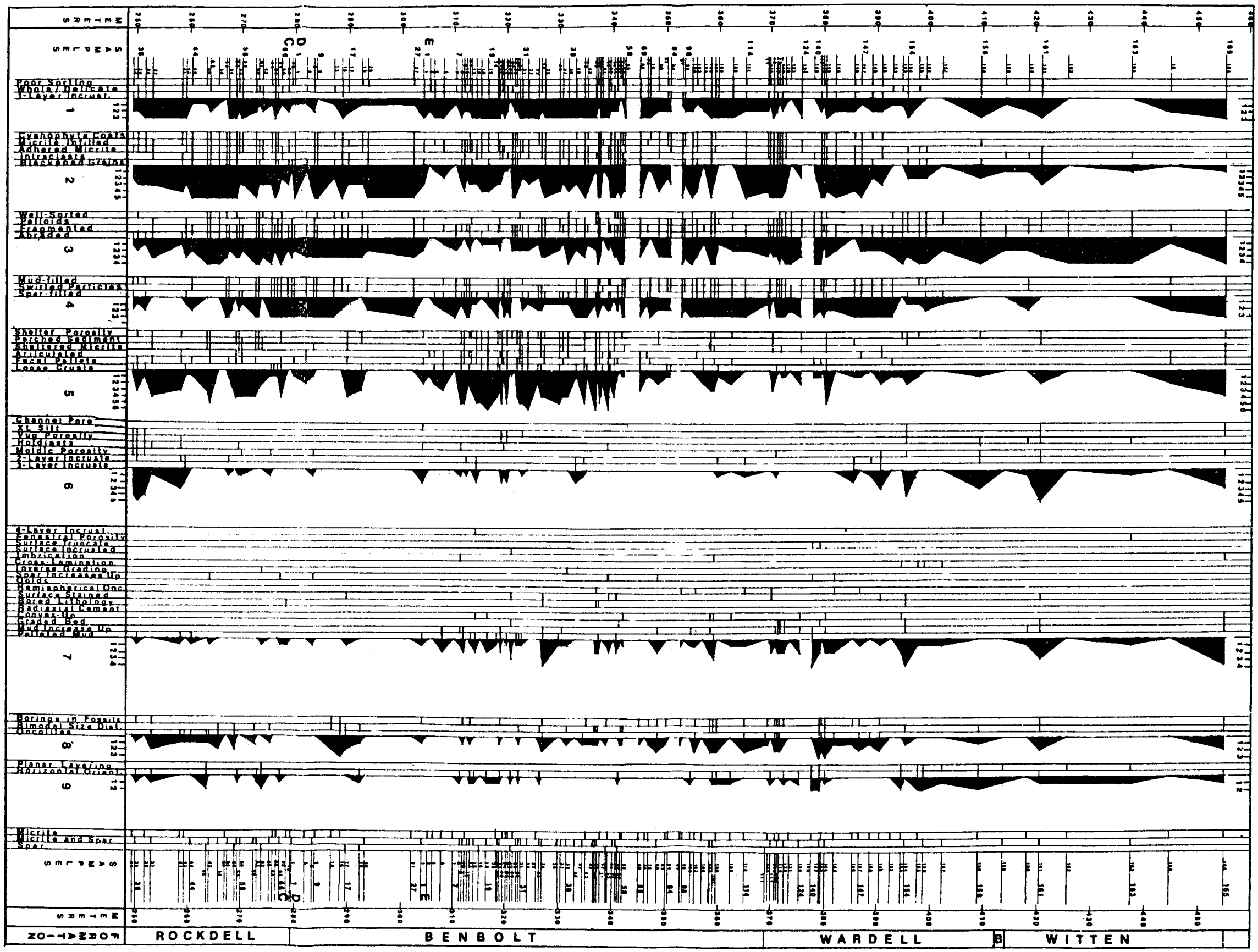


Figure 3-3 (continued).

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significant portion of a sediment. Diversity often reflects the physical stresses placed on organisms by their environments, as well as the variability or stability of environmental conditions (Walker and Laporte, 1970). Diversity information collected in this study is mainly in the form of the Petrographic Fossil Diversity (PFD) developed by Smosna and Warshauer (1978). In essence, this measure is the total number of dissimilar fossil types in a thin-section which are recognizable by a nonpaleontologist carbonate petrologist. While this figure is often less than one derived from bedding surface studies by a paleontologist, it can be shown that the overall fossil diversity (i.e., types recognized to many taxonomic levels) of a sediment is sufficient to withstand the information loss involved with nonspecialist identification by thin-section (Smosna and Warshauer, 1978). Furthermore, since this measure is based on recognition of fossil morphologies and microstructures only at the most generalized level, it should be a reliable and repeatable measure.

The paleontologic information obtained from each thin-section is presented in Appendix D, Table D-5. These data form the basis for the stratigraphic plot of diversity shown in Fig. 3-4. The first curve shown is the Petrographic Fossil Diversity (PFD) while the second curve is a 3 x 3 moving average of the PFD. Additional paleontologic information is provided in Fig. 3-5(a,b) which display the diversity of calcareous fossil algae and bryozoans.

Figure 3-4. Stratigraphic variation of Petrographic Fossil Diversity. Figure 3-4 displays the stratigraphic variation in Petrographic Fossil Diversity (PFD), or the total number of dissimilar fossil types recognizable in thin-section by a nonpaleontologist carbonate petrographer (Smosna and Warshauer, 1978). Recognition is based on identification of fossil morphologies and microstructures at a generalized level. PFD includes fossil calcareous algae as well as faunal skeletal allochems. Appendix D, Table D-5 is a list of the fossil particle types recognized in each thin-section. The vertical scale depicts Lay School samples in their correct stratigraphic positions. Horizontal scale displays the PFD for each sample and a 3 x 3 moving average of PFD.

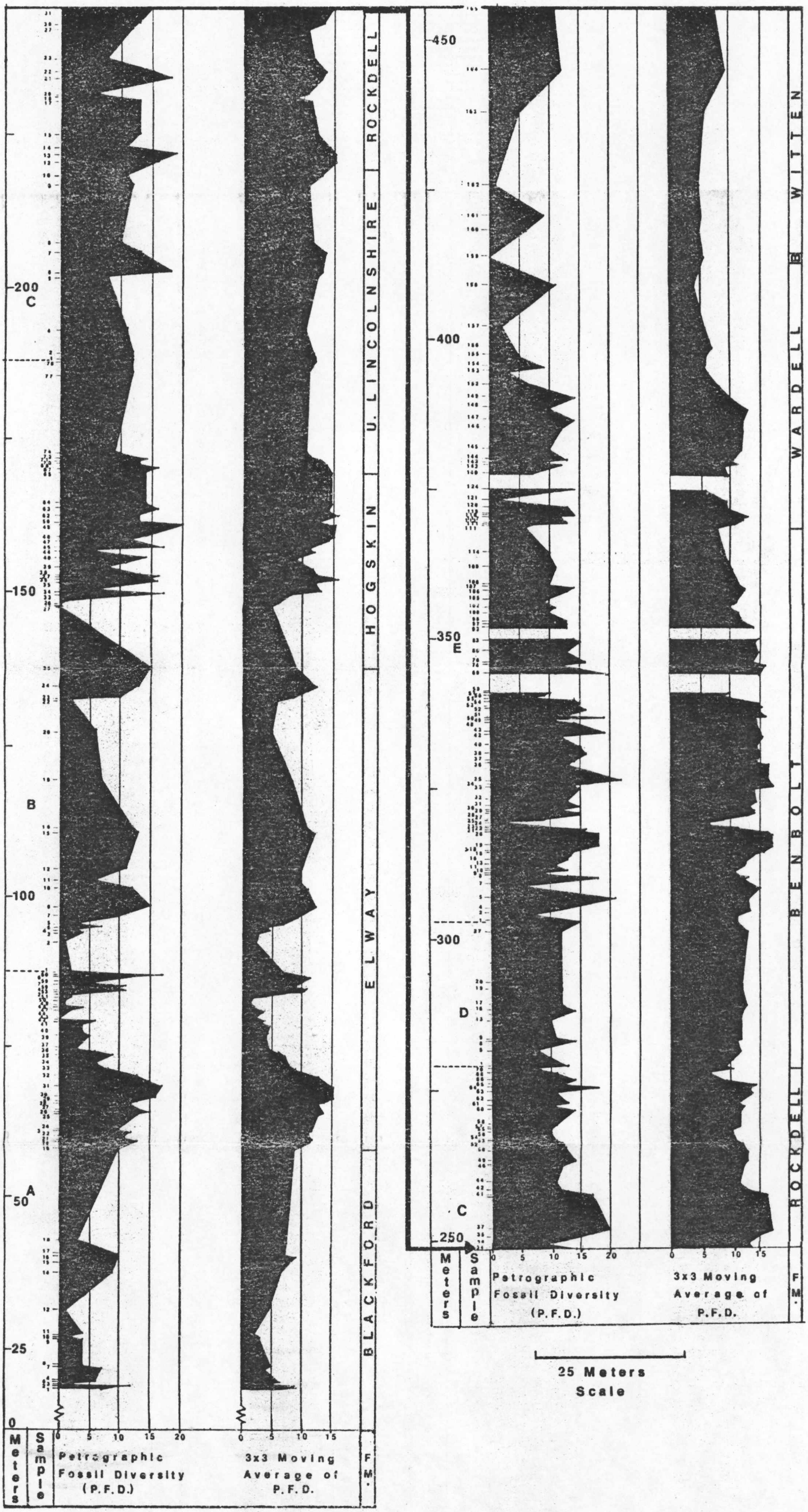


Figure 3-4.

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Figure 3-5. Stratigraphic variation in Petrographic Fossil Diversity of fossil calcareous algae and ectoproct bryozoans. Figure 3-5 depicts the stratigraphic variation in Petrographic Fossil Diversity of fossil calcareous algae and bryozoans. Categories of each type recognizable in sample thin-sections are listed in Appendix D, Table D-5.

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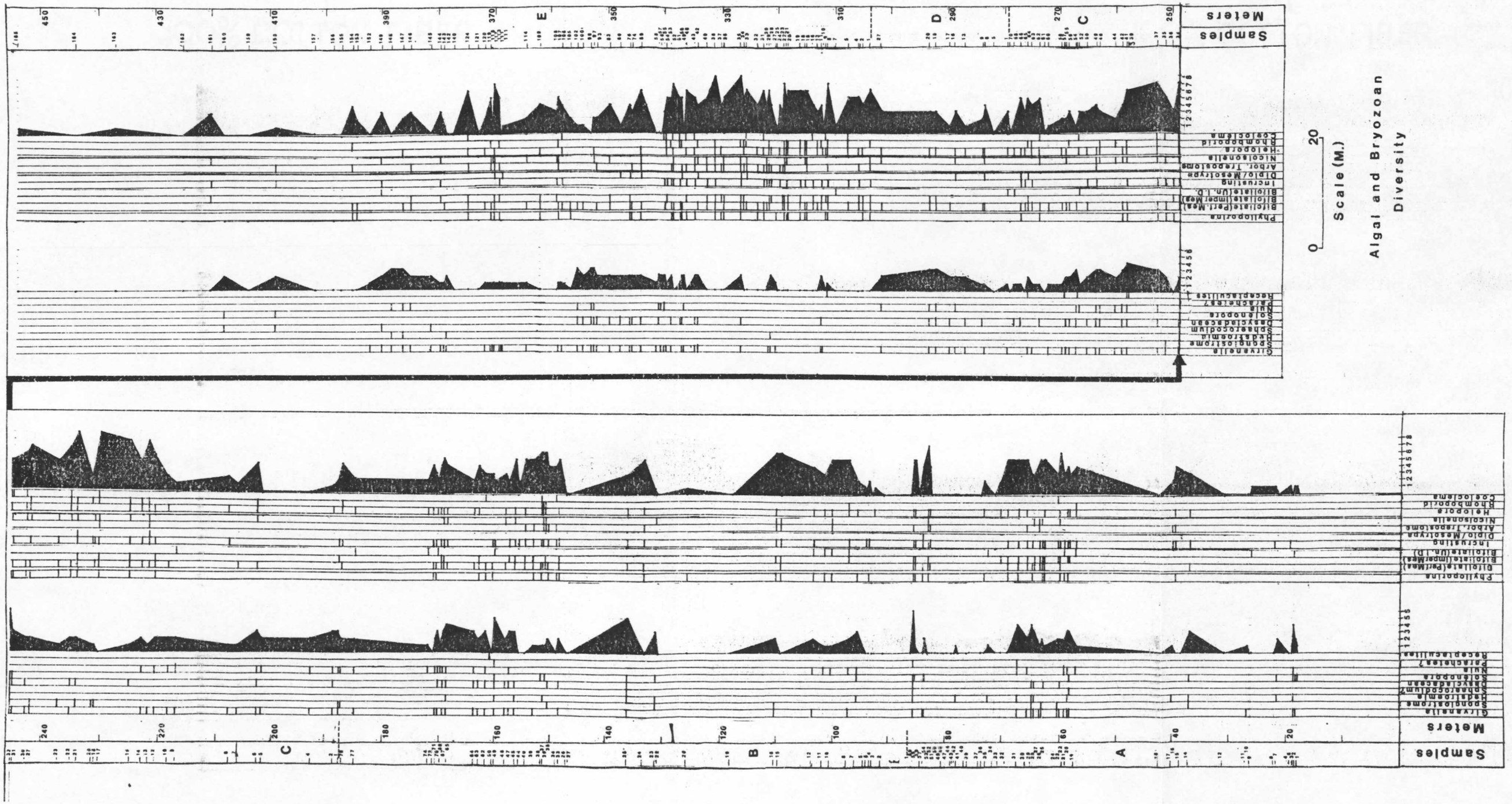


Figure 3-5.

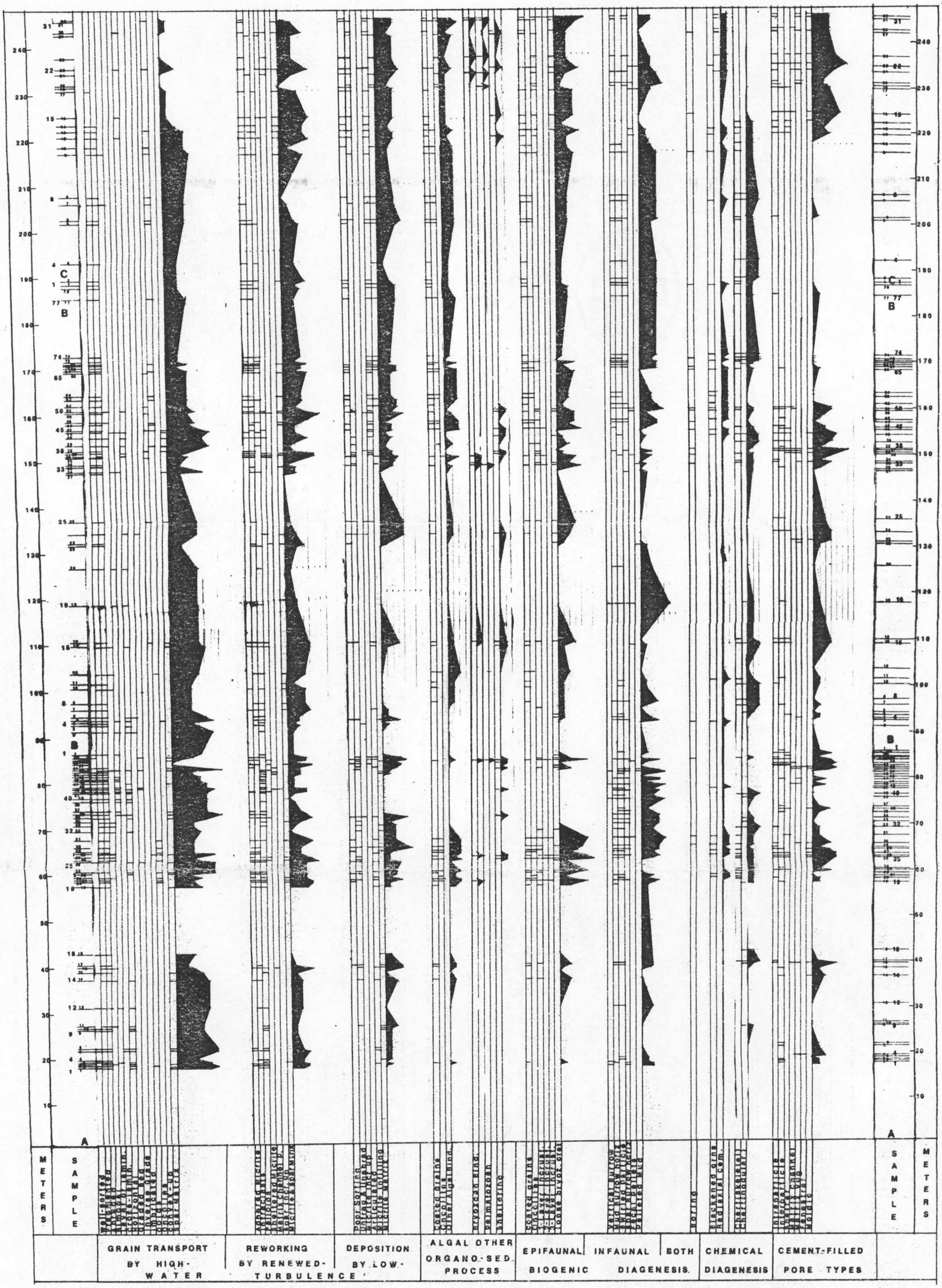
Stratigraphy of Environmental Components

Another way of displaying the Lay School particle history and sedimentological features which may be useful in environmental reconstruction is shown in Fig. 3-6a,b. In these figures, features are arranged into categories related to important factors or components of carbonate sedimentology and petrology. These figures contain the distribution of some features not included in the cluster analysis for various reasons (e.g., vertical burrows, intraparticle porosity). On the other hand, other features were included in the cluster analysis in order to determine their associations with other features and were difficult to place in environmental or sedimentological categories (e.g., hemispheroidal oncolites). These features were excluded from Fig. 3-6a,b.

Ecozone IA (A-Field Section)

Zone IA is readily divisable into four intervals, based on lithologic, ecologic, and paleontologic criteria. These are the subsections bounded by samples A1-28, A19-35, A36-52, and A53-60. Beginning with the lowermost interval, several samples contain features which have been shown to have environmental significance. Sample A4, (Fig. 3-7a), for instance, is a fenestral dismicrite. The presence of fenestrae or "birds-eyes" has been shown to be related to the formation of gas bubbles and shrinkage cracks accompanying desiccation (Shinn, 1968). Both of these features occur in supratidal or some intertidal sediments but not in subtidal ones (Shinn, 1968). Read

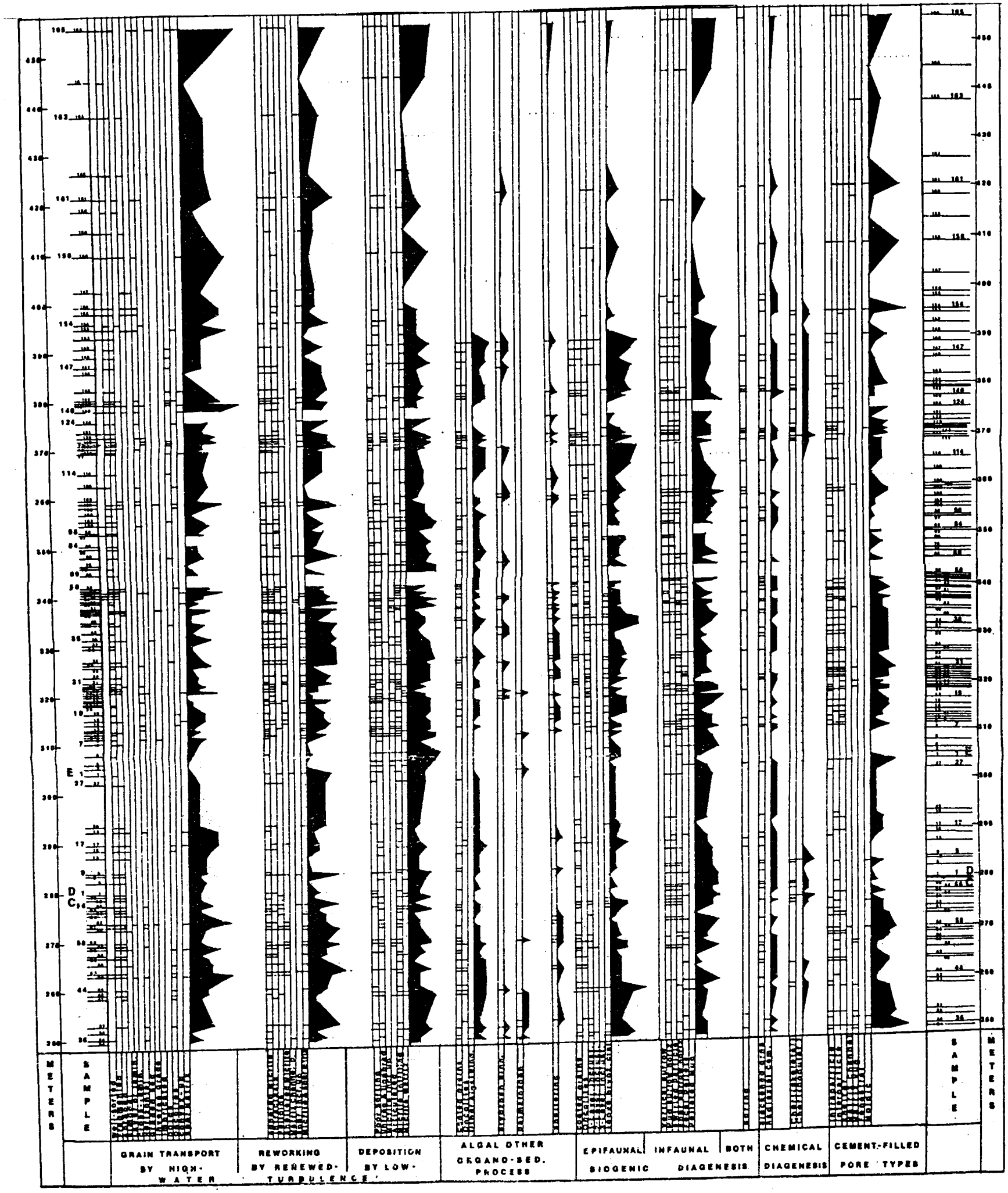
Figure 3-6. Stratigraphic variation in environmental and sedimentological features arranged into categories related to important factors or components of carbonate sedimentation and lithogenesis. The distribution of each feature is represented by a bar in the small column over the feature name. The stratigraphic variation of the group as a whole is shown by the graph of the sum of the group features present in a sample. 5.6a, lower 245 meters of Lay School section; 5.6b, upper 210 meters of L.S.S.



a.

Figure 3.6.

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b.

Figure 3-6 (continued).

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Figure 3-7. Photomicrographs and thin-section photographs of Zone I (Field Section A) rocks, including the Blackford and Elway Formations.

A. Photomicrograph of crinkled laminae, irregular fenestral pores (vugs), and laminoid fenestral pores of fenestral dismicrite A4 in the Blackford Formation. Bar is 1 mm long.

B. Thin-section of reddish laminated mudstone A12 of Blackford Formation. Ecofacies 2. Bar is 1 cm long.

C. Photomicrograph of U-shaped, mud-lined, spar-filled burrow in pink biopelsparite A1 of Blackford Formation. Bar is 1 mm long.

D. Thin-section of argillaceous biomicrite A16 of Blackford Formation. Ecofacies 3. Bar is 1 cm long.

E. Photomicrograph of multiple incrustations on trilobite fragment. Incrustations include incrusting bryozoans, micritic envelope (blue-green algal?), unidentified large tubule alga, and Solenopora. Sample A20, Elway Formation. Bar is 1 mm long.

F. Thin-section of biosparite A25. Ecofacies 3. Contains primary depositional features shelter porosity (cement-filled), horizontal fossils, and inverse grading. Elway Formation. Bar is 1 cm long.

G. Thin-section of biosparite/poorly-washed biomicrite A27, Ecofacies 3. Elway Formation. Bimodal particle size distribution. Bar is 1 cm long.

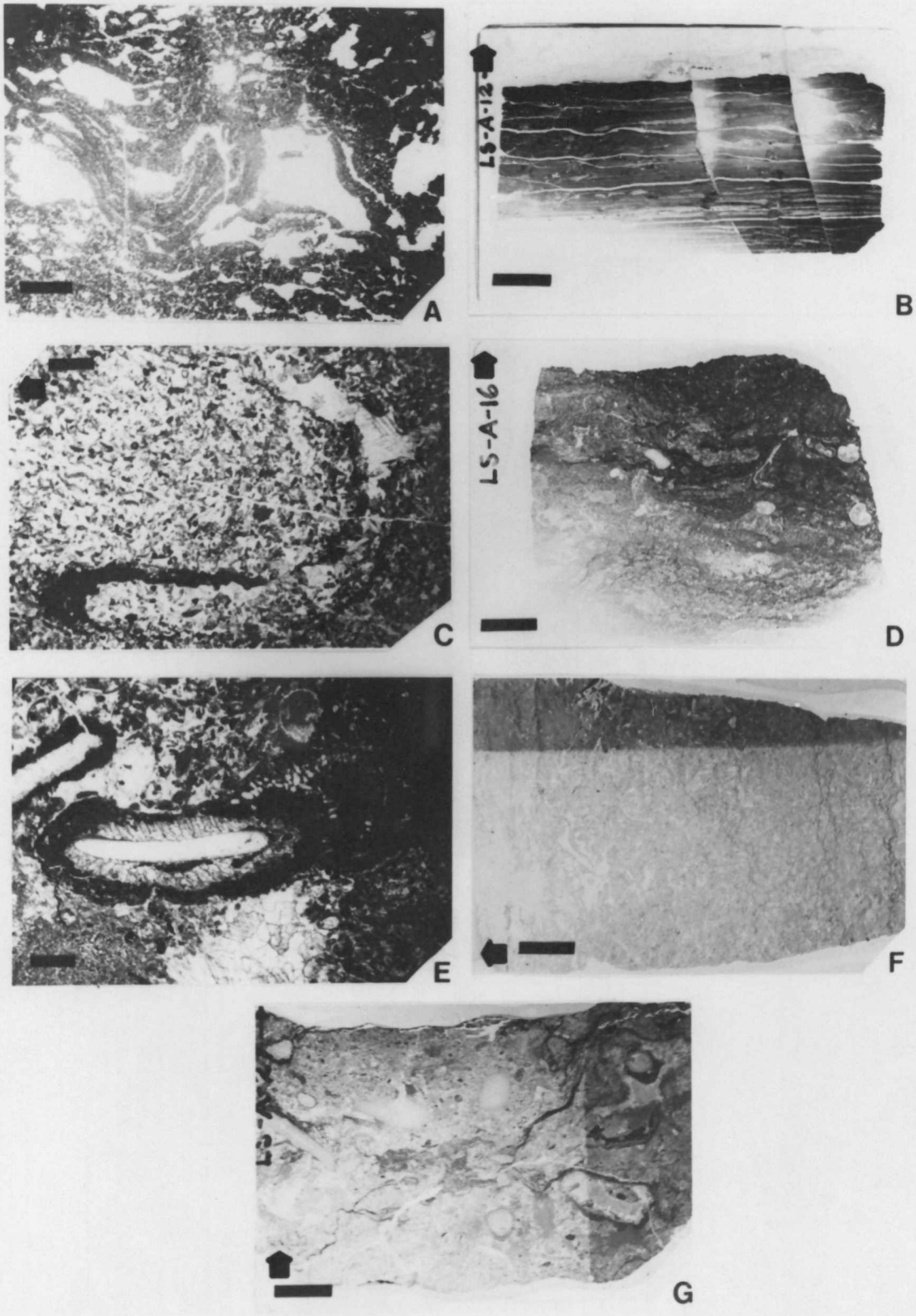


Figure 3-7.

(1973, 1978) has suggested a sequence of formation of three categories of cement-filled fenestral pore systems found in lowermost mid-Ordovician rocks in Virginia. These are tubular, irregular, and laminoid pores. Tubular fenestrae are vertical to subvertical cylindrical pores that occur in both grain and mud-supported rocks, display little variation in abundance, and are seldom the most abundant pore in a sample. Irregular fenestrae are equidimensional to irregular cement-filled pores that show little orientation with respect to bedding. These cavities have a wide range of shapes, are often larger than the other two types, and may coalesce with or be bounded by laminoid fenestrae. Laminoid types are usually subparallel to bedding, laterally discontinuous with much pinch and swell, and may also be concentrically arranged around tubular or irregular fenestrae. Tubular fenestrae seem to develop first, possibly caused by burrowing in the shallowest subtidal sediments. Irregular fenestrae form later, due to periodic wetting and desiccation in the intertidal zone. Since laminoid fenestral pores may develop around irregular ones, their formation must be contemporaneous with or after that of the irregular fenestrae. Thus, laminoid pore systems should be associated with sediments that are subaerially exposed for longer periods than the other two types (or would be found in sediments with high exposure indices, as defined in Hardie et al., 1977). The fenestral dismicrite sample A4 has abundant laminoid fenestrae as well as the irregular kind (Fig. 3-7a). It then could have resulted from subaerial exposure in a high intertidal to supratidal portion of a tidal-flat complex. This

sample's low fossil diversity (PFD = 6) is also consistent with a peritidal interpretation since diversity in tidal flat communities tends to be low (Sanders et al., 1962; Walker and Laporte, 1970).

The reddish laminated mud and calcareous silt (Sample A6), which underlies the light-colored dismicrite (A4) contains millimeter-sized laminae. So also does the laminite (A12) (Fig. 3-7b). Lamination of mud and skeletal or nonskeletal particles is a common feature in modern Bahamian carbonate tidal flats (Hardie et al., 1977). The small particle size of samples A6 and A12 would suggest a tidal channel levee crest or channel bar crest if the protected Bahamian tidal flat model is applicable to this sequence.

The pinkish skeletal sands (samples A1-3) beneath the reddish laminate A6 contain features which indicate that this lower part of A Section may not have been as protected an environment as the current day western Andros Island tidal flats. On the Andros Island flats, a high proportion of sediment grains are nonskeletal in origin, i.e., pelloids or pelletoids. The lowermost sands in this sequence, as well as most other samples in the zone are composed primarily of skeletal particles. The biosparites A1-3 (especially A3) also have a relatively high diversity (PFD of A3-12), including solenoporid algae, Hedstroemia, Nuia, and Girvanella. This high diversity suggests that relatively normal, open marine subtidal conditions prevailed nearby, since higher diversity communities are usually subtidal (Walker and Laporte, 1970). Modern red algae (Rhodophyceae) favor agitated bank-edge shoals, reefs, and rocky shores of normal salinity (34-36‰)

when they are found in shallow water setting (Ginsburg et al., 1972). Since solenoporids are usually considered to be an extinct type of red algae, it may also have had similar ecological requirements (Johnson, 1961; Ginsburg et al., 1972). Thus the solenoporids in these sands may suggest open or unrestricted circulation. The tidal flats of western Andros, Bahamas, on the other hand, develop in restricted conditions, contain abundant nonskeletal allochems, and are relatively low in biotic diversity (Hardie et al., 1977; Bathurst, 1975).

The lowermost grainstone samples A1-A3 are in the Ecofacies 1, which has features consistent with sediment transport (e.g., the Well-sorted feature group and only spar in the matrix). These grainstones also possess some features that could be related to peritidal or stressful conditions. Sample A1, for instance, contains a U-shaped, mud-lined, and spar-filled burrow (Fig. 3-7c). U-shaped burrows have been interpreted as an organism's response to the stresses of an intertidal existence (Walker and Laporte, 1970; Laporte, 1971, 1975). Similarly, the pink biosparite sample A3 has several subvertical, spar-filled burrows which could either be one of two tunnels in a U-shaped burrow or a simple, single tunnel vertical burrow. In either case, this could reflect an organism's life strategy to avoid the stresses of periodic subaerial exposure in an intertidal situation.

The other samples of Ecofacies 1 in this lower part of section A are the cream-colored biosparites (A7 and A8). These are faintly layered and cross-laminated, although recognition of individual laminae is difficult due to the particle color and small size range of particles in

and between laminae. Cross-laminated sediments occur in a variety of sedimentary subenvironments in or near a tidal flat complex. Among those are beaches and channel bars of subtidal channels which meander inland from nearshore subtidal areas (Hardie et al., 1977).

The last group of rocks in the lower interval of Part A (samples A1-A19) exhibit a sequence of facies or lithologies which is consistent with those resulting from the progradation of a tidal flat complex. The first sample (A14) in the sequence is a well-washed biosparite which contains enough larger, whole fossils to cause shelter pores (cement-filled). This bimodal particle size distribution, and well-sorted features (e.g., fragmented and abraded fossils) cause the sample to be classed in the Bimodal Ecofacies or Ecofacies 3. Sample A14 also has 1-layer bryozoan incrustations, coated grains (or those with micritic envelopes), and a moderately high fossil diversity (PFD = 9). Algal types include Hedstroemia and Solenopora while kinds of bryozoans present are bifoliates, incrusting forms (batostomids?), and Helopora. The high skeletal diversity, presence of incrusting organisms (bryozoans), and several types of calcareous algae are consistent with a subtidal setting of normal off-shore marine salinities and circulation (Walker and Laporte, 1970).

Sample A14 is the bottom of a fining-upward biosparite or sand which is topped by sample A15. Sample A15 is a very well sorted, fine-grained skeletal sand or silt with very few other features or recognizable biota. The bed A14-15, therefore, seems to lose aspects consistent with a relatively normal, open marine setting and gain

features associated with increasing protection (or decrease in turbulence) or restriction of circulation (i.e., a decrease in grain size and diversity of biota). The reduction in grain size continues in the overlying samples A16-18 which show an increase in brownish clay content.

The clay-rich samples A16 (Fig. 3-7d) and A17 resemble in color the brown argillaceous facies (A9-11) which overlie the sands (A7-8) in the lower part of this lowest interval of A Section. Samples A16-17 contain a considerably more abundant and diverse biota, however, which includes several bryozoan types (1-layer incrustations), coated grains, and Hedstroemia. Overall diversity is greater in samples A16-17 (PFD = 10) than in samples A9-11 (PFD = 3-4). There are also mud-filled horizontal burrows and swirled particles indicating bioturbation in Sample A17 which cause it to be clustered in Ecofacies 4. Small gastropods are common fossils in these samples, and bivalves (pelecypods) also occur. These aspects are consistent with a subtidal depositional setting. In addition to normal marine organisms (e.g., bryozoans, calcareous algae) and a moderate diversity, horizontal burrowing as found in A17 has been shown to be an indicator of subtidal shallow marine conditions. Rhoads (1976) has shown, for instance, that styles of burrowing change from intertidal to subtidal areas as the function of burrowing changes. Intertidal burrowers are frequently suspension-feeding organisms which require both protection from intertidal desiccation and access to the overlying water mass when the area is submerged. Consequently, intertidal infaunal organisms commonly make residential burrows that are vertically oriented. In

contrast, subtidal infaunal organisms are often sediment eaters that live on dispersed organic matter in the sediment. These burrowers move laterally in the sediment within a few centimeters of the sediment-water-interface, leaving horizontally oriented burrows behind them (Rhoads, 1967; Walker and Laporte, 1970).

The subtidal nature of these samples (A16-17) must be viewed in the context of a general decrease in grain size and increase in clays, from the bottom to the top of the sequence (A14-A19). Sample A18 immediately overlies samples A16-17 and is essentially a shale or mudstone with a very low diversity (PFD = 3). Immediately following sample A18 is a covered interval of soil which probably results from weathering of less resistant lithologies, such as shale or mudstone. Thus, this sequence of lithologies and facies conforms well to the ones which might be deposited at one spot by the seaward progradation of a near-shore sand bar belt and subsequent formation of increasingly protected leeward environments. The diverse skeletal sand (A14) could, then, represent a near-shore subtidal sand bar which became finer grained as fines were deposited in its lee as it prograded seaward. Further bar progradation would have increased protection from offshore currents and waves and would have caused deposition of more fines, including clays, in a shallow lagoon formed behind the shielding bar belt. Tidal passes between bars as well as episodic water movement over the bars maintained enough circulation for a lagoonal biota, in addition to occasionally bringing in more open marine organisms. Finally, the lagoon was filled in by the muds and silts of tidal flat deposits (A18 and covered interval).

Middle Interval

This middle interval between samples A19-35 begins the best exposed portion of Part A, forming massive to medium-bedded ledges with ill-defined bedding planes and a slightly cobbly appearance when weathered. The sequence begins with grainstones and packstones and becomes more muddy or micritic towards the center (samples A28-31). This interval is characterized by a poorly-sorted component of macrofossils, oncolites, and multiple incrustations (Fig. 3-7e, p. 76). These give many of the samples a bimodal character which accounts for the common occurrence of the Bimodal Ecofacies (No. 3) (e.g., A25, Fig. 3-7f; A27, Fig. 3-7g). Primary depositional features such as shelter porosity (cement-filled) and horizontal grain orientation also occur. In muddier lithologies, bioturbation occurs and these samples are usually clustered into Ecofacies No. 4. In addition to the Poorly-sorted feature group, the Micritic feature group is well represented, with coated particles, adhered and infilled micrite, intraclasts, and the first common occurrences of blackened or pyritized particles. Moldic fossil pores (cement-filled) are also present.

Floral and faunal diversity steadily increases up to the middle part between samples A28-31) of this interval and decreases thereafter (Fig. 3-4, p. 68). The Petrographic Fossil Diversity is always greater than ten up to samples A28-31, at which point it reaches 17. By sample 34, it has declined to six. The diversity values continue to decrease into the overlying laminated interval until they reach zero. This reduction in diversity above sample A31 corresponds with the

general decrease in grain size after that sample. Algal diversity follows the general trend of overall diversity (Fig. 3-5a, p. 70) and is at its highest in this part of A Section. It too declines to zero after sample A31 as calcareous algae disappear, save for one occurrence of Hedstroemia at sample A35. Girvanella (alga) is present in grain coatings, oncolites, and as loose clumps of tubules distributed in the matrix. Girvanella disappears after sample A31 until sample A<59 in the upper part of A Section. Spongiostrome crusts and clots are present in samples A19-31 and seem to be concentrated in the interval represented by samples A24-29. Hedstroemia, on the other hand, is widely scattered throughout A Section. Dasycladacean algae occur for the first time in this part of A Section and also disappear after sample A29. The problematic alga Nuia is present in the lowermost sands and the high diversity middle samples A30-31, while Solenopora sp. is restricted to the lowermost, better sorted samples.

Faunal diversity, as already mentioned, is at its highest here. Bryozoan diversity follows this trend and peaks in the middle part of this interval between samples A26-32. Common bryozoan types include Phylloporina, bifoliates, incrusting forms, and Helopora. Arborescent trepostomes are less common, as are nicholsonellids, rhomboporids, and Coeloclema. Sponge spicules are usually single rays or fragmental, especially in the less diverse zone between samples A31-35. Articulate, impunctate brachiopods are common up to sample A33, while there is only one example of a phosphatic inarticulate brachiopod, at sample A35. Other common invertebrate groups represented in this interval

include aragonitic and calcitic gastropods, such as Rhaphistoma. Rhaphistoma is recognized by its fluted or spiny shell composed of very small prismatic calcite crystals oriented perpendicular to the outer shell wall (Fig. 3-8a). This microstructure somewhat resembles that of the arthropods, for example trilobites or ostracodes. Unidentifiable mollusk fragments are common in this zone and could be degraded bivalve fragments. The only example of scaphopods in A Section occurs in this interval, in sample A32. Finally, echinoderm ossicles, trilobite plates, and ostracode valves are all liberally distributed throughout the interval.

The lower half of this interval between samples A19-31 has features consistent with a shallow, near shore subtidal depositional setting. There are no fenestral fabrics or other indicators of peritidal conditions. The lower half contains an abundant and diverse macrofauna, including normally marine benthic organisms such as several bryozoan types, articulate brachiopods, etc. Calcareous algae are diverse and include oncolites. These are commonly formed in continuously agitated, shallow subtidal environments (Logan et al., 1964). Dasycladacean algae, occurring for the first time in this section, have been shown to occur in shallow subtidal setting in many eras (Jamieson, 1970; Devonian; Conrad, M. A., 1977, Cretaceous; Flugel, 1977, Permian; Wray, 1972, early Cenozoic; Wray, 1970, overview of all eras). Finally, bedding in this part of the interval is massive or thick in nature, with ill-defined bedding planes and a cobbly appearance. Poorly-defined, homogeneous bedding is characteristic of

Figure 3-8. Photomicrographs and thin-section photographs of Zone I (Field Section A) rocks, Elway Formation.

A. Photomicrograph of calcitic gastropod Rhaphistoma, displaying characteristic shell ornamentation and microstructure. Shell wall composed of finely prismatic crystals oriented perpendicular to wall. C60. Bar is 1 mm long.

B. Thin-section photograph of oncolites in biosparite/poorly-washed biomicrite A31 of Elway Formation. Bar is 1 cm long.

C. Thin-section photograph of burrowed cross-lamination in biosparite A36, Elway Formation. Erosive ripple cross-lamination with bundle-wise arrangement of forset laminae developed over planar laminae. Bar is 1 cm long.

D. Thin-section photograph of vertical and horizontal burrows in laminated mudstone A44, Elway Formation. Bar is 1 cm long.

E. Photomicrograph of possible U-shaped burrow in laminated mudstone A39, Elway Formation. Bar is 1 mm long.

F. Thin-section photograph of laminated mudstone A50, displaying both broken and deformed layers. Elway Formation. Bar is 1 cm long.

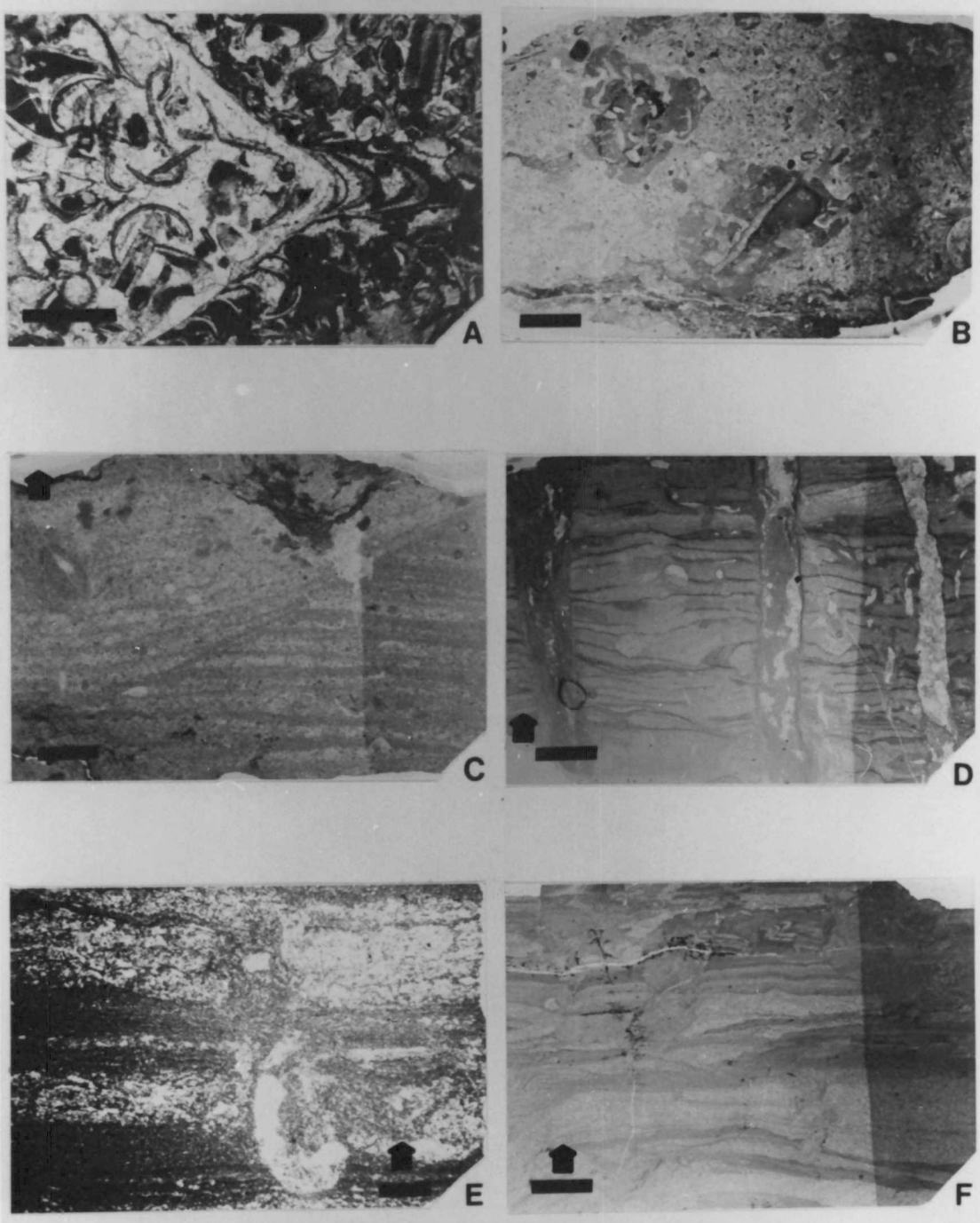


Figure 3-8.

offshore, subtidal facies adjacent to the western Andros tidal flats (Hardie et al., 1977).

There are two types of facies in this lower half of the middle interval of A Section. There are spar-rich grainstones and packstones, especially samples A19-27, and there are micrite-rich packstones and occasional wackestones (samples A29-35). This suggests two, slightly different subtidal settings. The lesser amounts of interparticle micrite in the lower sparry facies implies sufficient water movement to prevent deposition of fines or nearly complete winnowing of fines (Dunham, 1962). Some sparry facies (those of Ecofacies 1 and 3) have retained such primary depositional features as shelter phenomena and horizontally-oriented fossils. The retention of primary features in skeletal sands is likely to result from continuous turbulence or water movement (Anderson, 1974). This is because the lack of fines in such facies prevents attraction of deposit-feeding benthos which destroy primary depositional features. These sparry facies containing primary features may represent sand bodies, such as bars or shoals, which are the result of transport by waves and longshore currents in a shallow shelf setting. Since these bodies are mainly in the lower part of this interval, just above a shaly or laminated zone, they could have been formed just offshore from the tidal flats whose deposits are represented in samples A1-19 (lowermost A Section).

The other group of facies in the lower half of A section contains more interparticle micrite. Also present are oncolites and multiple incrustations on particles. These two features suggest that there was

some continuity of water movement which is also indicated by those samples with some interparticle spar. However, the increased amounts of matrix micrite and some other features imply weaker water movement. Very poor sorting due to abundant fossils, large oncolites, and coated particles (sample A31, Fig. 3-8b) is consistent with gentler water turbulence, as is the presence of blackened or pyritized particles. The association of these with other Micritic group features, such as adhered and infilled micrite, intraclasts, and interparticle micrite could reflect a similar association of sulfides in modern muddy inner shelf sediments in the Florida keys (Ginsburg, 1957). These sulfides are associated with fine sediments deposited in restricted or stagnant conditions (see p. 130). Bioturbation, which accompanies the increase in micrite in this interval, probably accounts for the lack of shelter pores or other primary features. All of these features suggest that these sediments were deposited in a less turbulent setting than the previous beds.

The samples A32-35 experience a decrease in grain size and diversity (e.g., A35). It seems to be a transitional zone between the poorly sorted, oncolitic interval just discussed and the overlying laminated sediment. Lithofacies exposed are biopelmicrites and biopelsparites. Chert increases in abundance, occurring more as nodules and irregular masses than as fossil replacements. As sorting improves, blackened grains become less common. Improved sorting suggests sustained currents than in the previous part of this interval, although the decrease in grain size indicates that the currents of

transport may have been weak in magnitude. Since diversity also decreases rapidly, the sequence of facies discussed so far in this middle interval (samples A19-35) also seems compatible with a shallowing upward model of environments. This seems especially the case since the overlying laminated interval contains such peritidal indicators as vertical burrows and fenestral dismicrites.

Upper Interval

The upper interval ranges from sample A36 through sample A52. It contains samples that were all clustered into the Laminated or Layered Ecofacies No. 2, which displays Well-sorted Group features in addition to lamination or layering. Beginning with sample A36, layering is in the form of small, festoon cross-lamination (Fig. 3-8c) of medium and fine biopelsparite. Grain size decreases rapidly and most samples above A36 have laminated silt and mud. Some laminated samples have vertical burrows (A44, A48; Fig. 3-8d) and U-shaped burrows (A39, Fig. 3-8e). In sample A44, these burrows average 1 cm in diameter and extend from the bottom to the top of a 10 cm thick bed. These are larger burrows than is normally the case in the Lay School section. Various kinds of laminated and fine grained lithologies extend from samples A36 to A51 (e.g., A50, Fig. 3-8f).

This laminated part of upper A Section contains features and facies characteristic of tidal flat complexes. Millimeter lamination frequently occurs in several subenvironments in the modern day Bahamian tidal flats, such as crests of natural levees bordering subtidal channels, intertidal channel bar crests, beach terraces, and

washover crests (Hardie et al., 1977). Cross-lamination occurs in subtidal channel floors and channel bars, as well as beach ridge hummocks, although the latter are too large and coarse-grained to resemble the cross-lamination in this series of laminated rocks A36-52 (Hardie et al., 1977). As mentioned in the discussion of the environmental setting of lowermost A Section, vertical burrows are an indicator of peritidal or intertidal settings (Rhoads, 1967; Walker and Laporte, 1970).

These laminated lithologies are capped by two fenestral dismicrite beds (samples A51 and A52, Fig. 3-9a). These contain tubular, irregular, and laminoid cement-filled fenestral pores according to the classification of Read (1973) and Grover and Read (1978). The dismicrites are unlaminated, and laminoid fenestrae surround irregular pores (vugs) rather than paralleling lamination as in sample A4. Fenestral porosity occurs in supratidal and intertidal sediment (Shinn, 1968). Read has suggested that laminoid fenestral pores are the last to form in sediment containing all three pore types and therefore, may be the result of more subaerial exposure than the others (Read, 1973). Hence, these dismicrite beds suggests a supratidal environment. The environmental significance of this sequence of facies (samples A19 to A52) will be more fully examined following a description of lithologies which overlie the laminated interval.

Uppermost A Section

Directly above the fenestral dismicrite which caps the laminated interval are biosparite/grainstones of Ecofacies 3 samples A53

Figure 3-9. Photomicrographs and thin-section photographs of the Elway Formation (Field Section A).

A. Thin-section of dismicrite A52, Elway Formation. Bar is 1 cm long.

B. Thin-section of biosparite A53, showing layer with inverse grading. Elway Formation. Bar is 1 cm long. Arrow marks up direction.

C. Thin-section of bryozoan/pelmatozoan boundstone A<59, Elway Formation. Bar is 1 cm long.

D. Thin-section of large, multigeneric oncolites in biomicrite A60-1, Elway Formation. Bar is 1 cm long.

E. Photomicrograph of two algal types in oncolites in A60-1. Solenopora (S) Type-R (Moore, 1978) and unidentified alga with long, sinuous tubules and incrusting habit. Elway Formation. Bar is 1 mm long.

F. Photomicrograph of borings in algal/bryozoan layers in oncolites of A60-1, Elway Formation. Bar in 1 mm long.

G. Photomicrograph of multiple incrustation sequence in boundstone A<59, Elway Formation. Bryozoan colonies incrusted by micritic layer (blue-green algae?), Solenopora, and incrusting bryozoan sheets. Bar is 1 mm long.

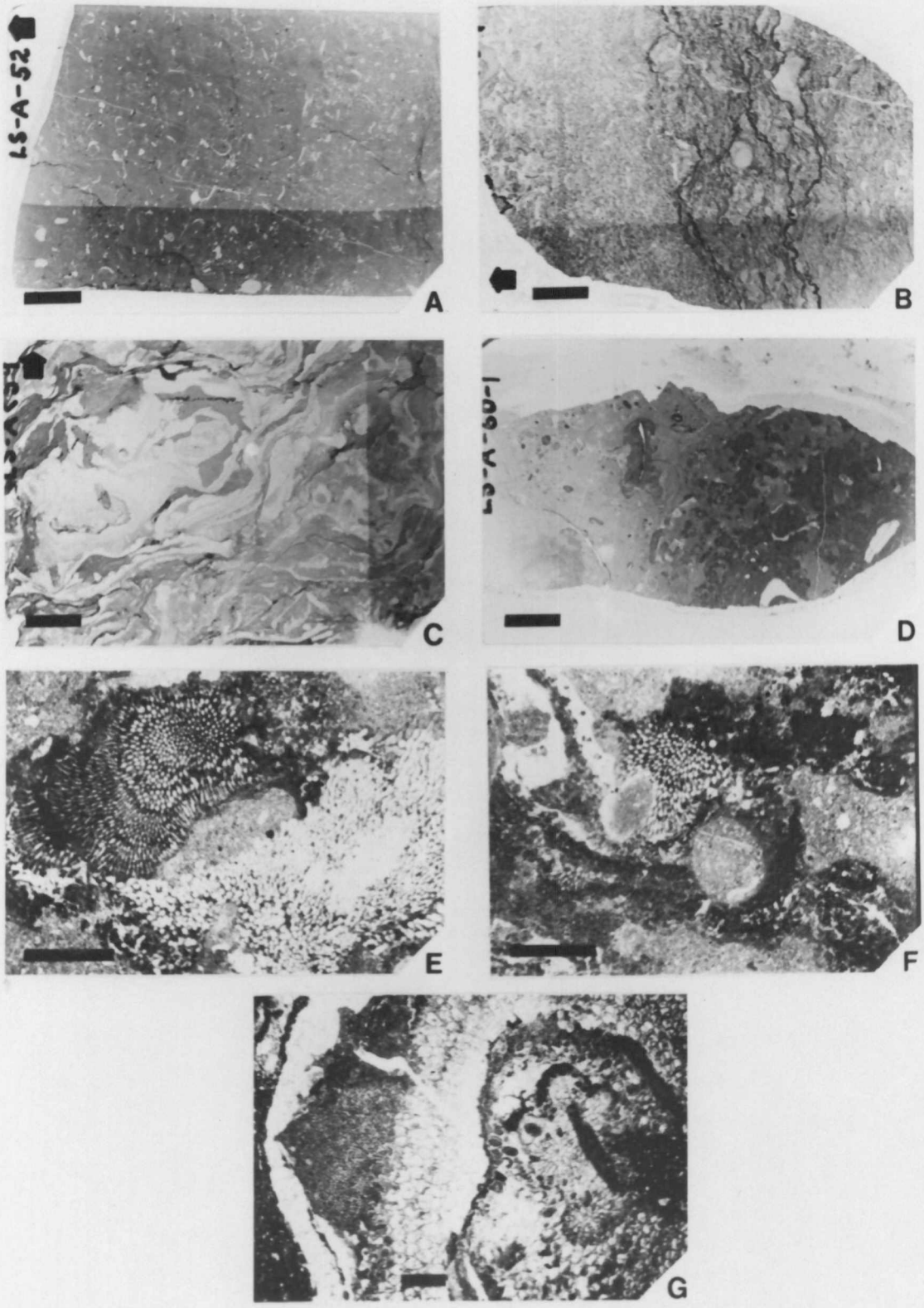


Figure 3-9.

(Fig. 3-9b), A54, A56, partly muddy packstones (sample A57) of Ecofacies 6, and bryozoan boundstone sample A<59 (Fig. 3-9c) of Ecofacies 7. The biosparite/grainstones retain primary depositional features such as horizontal particle orientation (sample A53), inverse grading (sample A53), and shelter pores (samples A53, 54, 57, 56, 59) and sheltered micrite (samples A53, A57, A59). Additionally, they have Poorly-sorted Group features, such as poor sorting, whole fossils, and 1-layer incrustations. Some have adhered and infilled micrite as well as intraclasts. Fragmented and abraded fossil particles also occur, and one (sample A53) has a bimodal particle size distribution. These sands are also faunally diverse, with Petrographic Fossil Diversities usually above 10. Girvanella and Solenopora occur but calcareous algae in general are not abundant, unless float specimens above sample A56 (i.e., A60, A60-1) are considered to be near true stratigraphic position. This is somewhat unclear since sample A60 and A60-1 resemble specimens washed down from the fold on the hill southeast of sample zone A19-56. Sample A60, A60-1 is a biomicrite with large oncolites of Girvanella, micritic laminae, and an unknown incrusting algal type (Fig. 3-9d,e). Arborescent trepostome bryozoans, bifoliates, incrusting forms, heloporids, and Phylloporina fenestrate bryozoans all occur in the biosparites. Articulate impunctate and rhynchonellid brachiopods also are present.

The example of bryozoan boundstone in this postlaminated interval is sample A<59, which contains incrusting batostomid bryozoans. These lamellar, sheet-like colonies incrust pelmatozoan holdfasts which

in turn incrust other fossil allochems. Calcareous and quartzose silt was trapped by bryozoan sheets. The bryozoan sheets themselves are incrusted in places by girvanellid and solenoporid algae (Fig. 3-9g).

The reappearance of skeletal sands containing algae and a diverse, normal marine fauna suggests a return to subtidal conditions. Additionally, the coarser fraction of occasional whole fossils implies a nearby source for these sediments. The retention of primary depositional fabrics such as shelter pores or horizontally-oriented grains in the sediment indicates transport and deposition by hydrodynamic processes. Anderson (1974) concluded that preservation of primary depositional structures in sand suggests constant current activity. Thus, these sands were possibly deposited in a nearshore subtidal environment that was continuously agitated by currents or waves. Like the similar sand at sample A14, these may have formed sand bars or shoals. Since the upper Interval A sands directly overlie laminated, peritidal sediments, a stratigraphic reconstruction would suggest that they may have formed on the windward or seaward side of an island. Studies of islands in the modern Bahamas show that coarse skeletal sands are usually deposited on the windward margins of islands, while finer-grained, pelloid-rich sediments characterize leeward sediments (Beach and Ginsburg, 1981). The same study also confirms that reefal boundstones and framestones often characterize modern windward island margins. Thus the presence of bryozoan boundstones with these coarse skeletal sands is entirely consistent with a windward island margin environmental setting. These bryozoan

boundstones would, in that case, occupy a similar ecological niche to that of some of the modern incrusting organisms which live on windward margins.

Possible organo-sedimentary mechanisms explaining windward margin skeletal sand accumulation and colonization can be derived from studies of modern carbonate environments. Even though modern marine benthic organisms are different from those in the Ordovician, careful environmental studies have demonstrated that in many cases similar niches or ecologic roles have been filled by different organisms in different eras (Walker and Laporte, 1970). One possible example or analog from a modern carbonate setting of windward margin accumulation of skeletal sands and incrusting colonization is that of the shoal-fringe community of the Florida Keys (Swanson and Turmel, 1976; Enos and Perkins, 1977). Finger-sized corals (Porites), a red incrusting alga (Goniolithon), and a segmented green alga (Halimeda) form successive zones on banks and islands of the inner shelf margin. Sediment on the banks fines progressively from gravel and sand size on the windward margin to mud in the bank interior. Some banks may form by initial incrustation of a hard substrate by the red alga, colonization of red algal sediment by the finger coral, and subsequent growth of green and red algae in the lee of the coarse-grained coral lip (Enos and Perkins, 1977).

The sediments above the peritidal-laminated interval in A Section contain several morphologically analogous organisms to members of the Florida shoal-fringe community. Arborescent trepostome bryozoans,

such as Amplexopora, Anaphragma, or Eridotrypa sometimes grow to centimeters in length and have a similar growth habit to Porites (but are smaller) or Goniolithon. These and the smaller cryptosome bifoliate bryozoans form a major part of the skeletal sands in A and B Sections. Other major sediment producers are pelmatozoan echinoderms, whose incrusting basal holdfasts are present in the boundstone sample A<59. In addition to producing numerous segments upon death which are of similar size, like Halimeda algae, these animals also had an erect growth form. Incrusting forms include both plant and animal types, with batostomid and Constellaria bryozoans forming the bulk of most boundstones in this part of the section. Solenoporid red alga, while usually occurring as roughly equant grains the size of a pea or greater, is also found incrusting bryozoans and other organisms. Other, unidentified incrusting algae also occur (A60, Fig. 3-9e).

There are several possible combinations or associations of these animals and plants which could result in sediment production and stabilization. An observed association is that of pelmatozoan holdfasts and incrusting bryozoans seen in sample A<59 (Fig. 3-9c). In this case, pelmatozoans filled a dual role as incrusting sediment stabilizers and sediment producers (upon death and disintegration). Direct colonization of a skeletal sand by bryozoan boundstone (observed only once in the field) could therefore be initiated by pelmatozoan holdfast systems which not only would stabilize loose sediment but also provide sites for bryozoan incrustation. Another association, observed in B Section sample (B34), is bryozoan boundstone which contains incrusted

arborescent trepostome bryozoans as well as the lamellar incrusting forms. Finally, the abundant and varied calcareous algal flora is found in a variety of associations which have the potential for sediment binding and consequent bank formation or leeward sediment accumulation. Sample B35, for instance, contains multiple incrustations of spongiostrome algae, incrusting bryozoans, and Phylloporina fronds.

Stratigraphic Synthesis

The sequence of facies in middle and upper A Section is a progression of successively shallower environments. Shallowing-up sequences are fairly common in carbonate deposits because high rates of carbonate sediment production in shallow shelf environments often outstrip the rate of subsidence of the shelf (James, 1979). Hence, the shallow shelf carbonates frequently build up to sea level and above. James describes two main types of shallowing-up progressions, a muddy and a grainy kind. The Lay School sequences most resemble his muddy model, which is characterized by a basal, intraclastic layer followed by a lime mud or muddy sand that contains a diverse fauna and bioturbation. This main subtidal unit grades into laminated deposits which have laminar fenestral porosity in their lower parts and pustular or irregular vuggy porosity in the upper portions (Opposite that found by Read, 1973; Grover and Read, 1978). The uppermost, supratidal parts of the sequence have mudcracks or desiccation polygons, flat-pebble breccias, and very even lamination. The units, which may be repeated numerous times, can be formed by progradation

of wide, continental tidal flats or by shallowing of offshore barriers as they develop (James, 1979).

Read proposed a similar environmental setting for cyclic, shallowing-up units of the Blackford-Elway Formations in northwestern and western Virginia (Read, 1980). The Elway Formation occupies a similar stratigraphic position over the red mudrock and dolomites of the Blackford Formation that the middle and upper parts of A section occupy with respect to the reddish sands and laminated sediments in the lower part of section A. The Blackford Formation is present in the more western of the thrust blocks of the Valley and Ridge Province in Virginia, including those west of the Copper Creek thrust fault. The cyclic Elway Formation passes into noncyclic beds to the northwest and merges with the skeletal limestones of the Lenoir/ Lincolnshire to the southeast (Read, 1980). A typical cycle begins with skeletal grainstones, packstones, and wackestones which may have a diverse assemblage including calcareous algae, bryozoans, and brachiopods. Some such subtidal units may have a restricted assemblage of calcareous algae, mollusks, and ostracodes. These pass into cherty, fine-grained pelmatozoan pellet grainstones and lenses of coarser, skeletal intraclast grainstone. Ripple cross-lamination is common and is often succeeded by planar-laminated pellet grainstone. At the top, the cycle has fenestral limestones (locally, red mudrock and dolomite) with very rare mudcracks, cryptalgal lamination, and palisade structures. The resemblance of this Virginia sequence to that of middle and upper A Section at Lay School is striking, save for the

mudcracks and dolomite at the top of the Virginia sequence. Read attributes a depositional setting of periodic marine transgressions across tidal flat deposits and subsequent progradation of these deposits under a stable sea level period (Read, 1980). The cross-laminated pellet-grainstones and skeletal lags of the middle part of each cycle suggested to Read deposition as spits, sand flats and beaches which formed protective barriers between open-marine and tidal flat settings. The lower parts of a cycle (grainstone to wackestone) were deposited in subtidal, often open marine conditions, while the cycle tops resulted from inter-supratidal deposition (Read, 1980).

The Lay School shallowing-up sequences (here termed Elway Formation cycles) are similar in many ways to the two examples described above. Two mechanisms were proposed for the formation of such cycles: progradation of wide tidal flat belts and the building up of offshore barrier complexes to sealevel with concomitant leeward sedimentation. Of the two, the latter would seem more common since sedimentation rates of open offshore marine setting are usually viewed as being greater than those for tidal flats (see, for example, Wilson, 1975). The presence of boundstones in the facies above laminated units in the Lay School A Section (and B Section as well) suggests the influence of organo-sedimentary processes in the formation of shallowing-up cycles through their possible role in sediment stabilization. The Lay School example may indicate that a process of barrier island development through sediment stabilization and subsequent

leeward sedimentation is a common process of tidal flat progradation itself. Important steps in this process can be reconstructed from the already described Lay School facies:

1. Formation of skeletal sand bars offshore by longshore currents.
2. Stabilization of the skeletal sand bodies by incrusting pelmatozoan holdfast systems, incrusting bryozoans, and calcareous algae.
3. Further colonization of sand bodies by more pelmatozoans and arborescent bryozoans. These not only give increased height to the sand bodies (increasing leeward sedimentation), but also produce particles upon death.
4. Deposition of sediment to the leeward of the now-colonized sand body. Formation of oncolites in the low, protected areas in the lee.
5. Development of colonized sand body into a shoal by continued windward boundstone accretion and leeward deposition of sediment. Increasing restriction landward of shoals marked by disappearance of oncolites, appearance of pelloids, decrease in faunal diversity, and an increase in small-scale sedimentary structures.
6. Shoal builds to water surface and above, becoming a barrier island, with fenestral fabrics and mudcracks in fine sediments.

7. Leeward lagoon is filled-in by increasingly peritidal sediments as tidal flat complex is established. Progradation of tidal flats now complete, as earlier shoreline flats now extend to islands.
8. If sea level rises, tidal flats are drowned and the process begins again.

Zone I (B Section)

The B part of Zone I is the same as "Leg II" of the regional biostratigraphic study of Carnes (1975). Thrust faulting occurs in this section, apparently in the shaly or laminated lower sequences above sample B16. Therefore, the great similarity in shallowing-up intervals in the lower half of Part B to those in Part A may be the result of repetition of beds by faulting. The beds in lower Part B could be slightly more seaward facies of those in Part A, because most thrust faulting in east Tennessee brings allochthons of eastern sediments to the west. The shallow Ordovician shelf had a depositional strike that was roughly northeast to southwest (Walker and Alberstadt, 1973), so that thrust faulting would bring rocks representing more seaward facies westward into contact with those from shoreward facies. Since lithologies exposed in lower Part B are similar to those in Part A, they will not be discussed in as great a detail, with a few exceptions.

A summary of ecofacies in B Section of Zone I is shown in Fig. 3-2 (p. 63). B Section (Zone I) divides easily into three parts samples B1-19, samples B19-33, and samples B33-62. The first or

lower part of Zone I (B Section) begins with a sequence of laminites and dismicrites, samples B1-4 (Fig. 3-10a). Immediately above the laminites-dismicrites there occurs a dark brown, cherty argillaceous facies (B5,6) (Fig. 3-10b) very similar to that described near peritidal facies in A Section (A9-11, A16-17). After a well-sorted muddy sand with an occasional oncolite (sample B7), an example of a stained sediment surface occurs at sample B8. This sample consists of a dark, relatively unfossiliferous spicular micrite, stained dark brown on its upper surface, with diffuse-walled burrows containing the overlying lithology (Fig. 3-10c). The overlying lithology is a muddy packstone with abundant fragments of the Nuia. The surface of the stained micrite is incrusted in one small area by a micritic coating similar to that which coats particles. The rest of the lower part of B Section consists of skeletal grainstones and variably sparry packstones containing a diverse biota (PFD from samples B8-16 ranges from 6-15). Their general good sorting places them in Ecofacies 1 and they seem to lack such primary depositional features as horizontal grains or shelter pores. If the shallowing-up facies sequence continued in B Section as it did in A Section, this type of sand (Ecofacies 1 or 3) would be followed by increasingly muddy and bioturbated facies (Ecofacies 4) and more poorly sorted, oncolitic lithologies (Ecofacies 5). But here the low angle thrust-faulting apparently brings another laminated sequence opposite these skeletal sands and provides a place to separate units of different character.

Figure 3-10. Photomicrographs and thin-section photographs of the Elway Formation (Field Section B).

A. Thin-section of laminated mudstone B1. Ecofacies 2. Bar is 1 cm long.

B. Thin-section of argillaceous, cherty biomicrite B6. Bar is 1 cm long.

C. Thin-section of stained surface in sample B8. Stained lithology is micrite. Overlying lithology is packed biomicrite containing the problematic alga Nuia. Micrite has burrows containing biomicrite with Nuia. Bar is 1 cm long.

D. Thin-section of laminated calcareous siltstone with vertical and horizontal burrows. Vertical burrows truncate horizontal burrows. B19. Bar is 1 cm long.

E. Photomicrograph of Tetradium in biointramicrite B23. Bar is 1 mm long.

F. Thin-section of oolite B25, showing Solenopora (S) grains. Bar is 1 cm long.

G. Photomicrograph of B25, showing ooids, superficial ooids, and skeletal allochems with micritic coats. Rhynchonellid brachiopod and intraclast with oolitic coats (OC). Pelmatozoan ossicle with micritic coat (M). Ooids (O). Bar is 1 mm long.

H. Photomicrograph of club-shaped thalli of Solenopora, Type P (Moore, 1978). B25. Bar is 1 mm long.

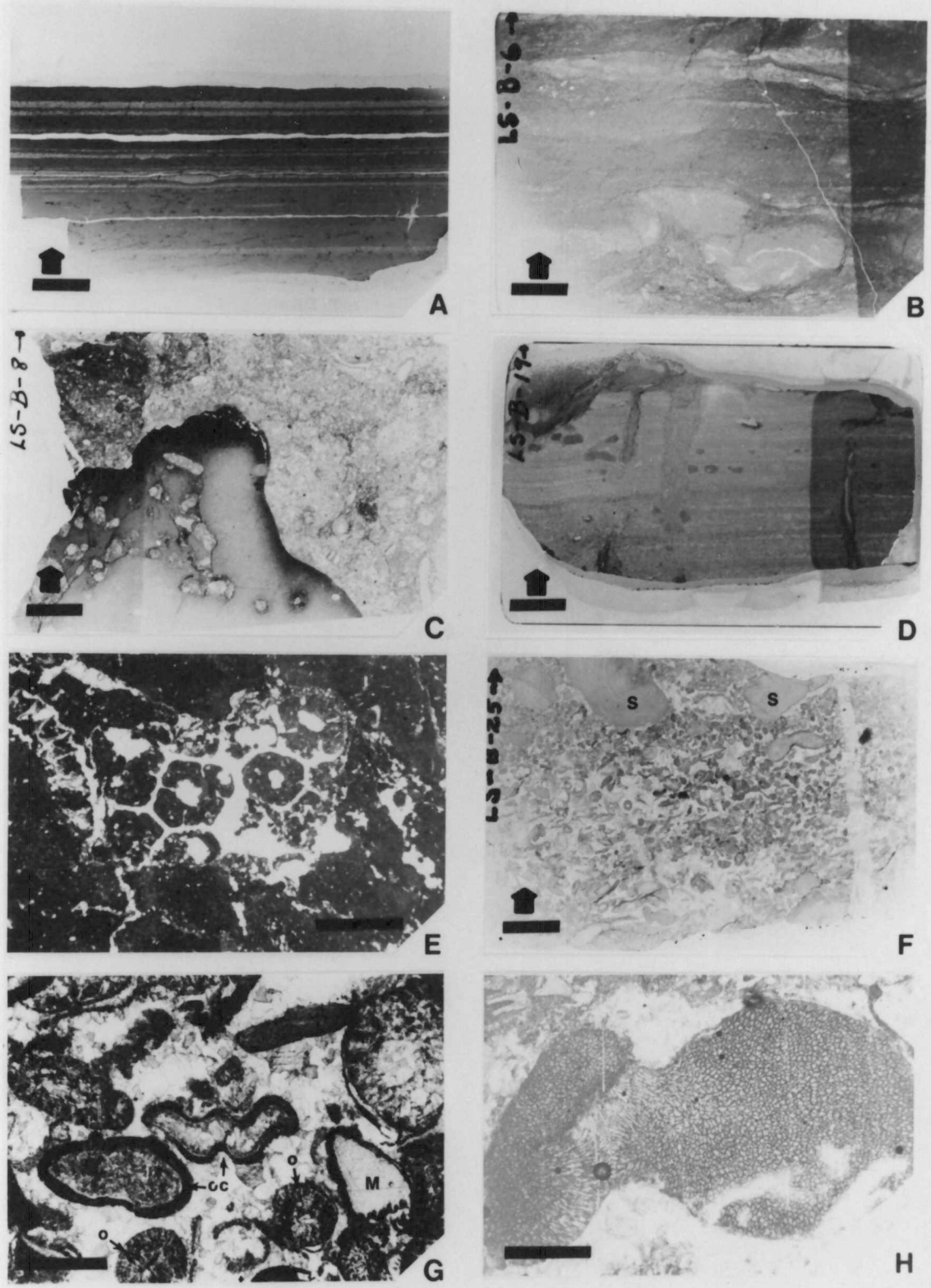


Figure 3-10.

The middle part of B Section begins with laminated facies which are exposed above a covered interval between samples B16 and B19 in which the above-mentioned faulting may take place. Sample B19 is a good example of these laminated facies and contains vertical burrows (Fig. 3-10d). Some of these vertical burrows truncate earlier, mud-filled horizontal burrows. Following sample B19 is a light-colored dismicrite (sample B22) and an intradismicrite (sample B23) which has the calcareous alga Hedstroemia and fragments of the tabulate "coral" Tetradium (Fig. 3-10e). In between these lithologies and another poorly-exposed interval of shaly or laminated rocks (samples B25-26), there are thin to medium beds of a diverse skeletal sand (sample B24) and an oolite (sample B25). Both of these facies display primary depositional features (e.g., shelter pores or horizontal grain orientation). The poorly-sorted oolite sample B25 (Fig. 3-10f) contains worn, laminated lithoclasts and mainly superficial ooids, with centers consisting of both fossil and nonfossil allochems. Among those fossil allochems are articulated ostracodes, articulated rhynchonellid brachiopods, pelmatozoan columnals, arborescent trepostome bryozoans, bifoliate cryptosome bryozoans, and articulated bivalves (pelecypods). There are intraclasts of oomicrite, frequent micrite envelopes or coatings, and common micrite-infilled and articulated rhynchonellid brachiopods (Fig. 3-10g). Algae include Hedstroemia, Solenopora, dasycladacean algae, and an unknown, large tubule incrusting variety. A Solenopora "head" or biscuit is shown in Fig. 3-10h.

A 10 m thick covered interval with occasional thin float slabs and chips of yellow-brown laminite immediately overlies the oolite of sample

B25. In place samples from the top of the interval are yellowish, silt-rich, poorly-layered mudstone (sample B27) and dolomitic siltstone (sample B26) with gently curved laminae. Both lithologies are almost devoid of fossils and underlie a biostromal stromatoporoid layer of variable thickness (sample B33). This type sample (B33) and the underlying oolite B25 are unrepresented in the A Section of Zone I. The biostrome is recognized in the field by its irregular surface topography which consists of layered pinnacles and debris-filled cavities. The cavities contain large, broken chunks of stromatoporoid as well as endocerid cephalopods in various states of disintegration. In places, only the cigar-sized siphuncles remain and these fill pockets which are usually biomicritic. Unlike other mid-Ordovician stromatoporoid build-ups (Kapp, 1975; Harlan, 1981) the smooth-walled cavities here are filled with several generations of biomicrite instead of sparry calcite (Fig. 3-11a). The poorly-sorted bioclasts may be bored and are often incrusted by pelmatozoan holdfasts (Fig. 3-11b), incrusting bryozoans, and felt-like masses of sponge spicules (Fig. 3-11c). Multiple episodes of cavity-filling by large bioclasts, incrustation by the above-mentioned organisms, and interstitial micrite infiltration and lithification are suggested by multiple sediment surfaces in the cavity-fill which truncate underlying fossils (Fig. 3-11d) and are themselves incrusted by pelmatozoan holdfasts.

The stromatoporoid forming the build-up layer has been severely recrystallized and partially replaced by chert, making identification difficult. Some general characteristics are a sheet-like and lamellar

Figure 3-11. Photomicrographs and thin-section photographs of the Hogskin Formation (or member of the Lincolnshire Formation).

A. Thin-section photograph of bioclastic sediment filling cavity on stromatoporoid biostrome. Thin-section is horizontal view of cavity, with two vertical walls at lower right--vertical sediment surface in earlier fill (S) and vertical wall cut in stromatoporoid (St). Bioclasts include endocerid cephalopod siphuncles (C) and incrusting pelmatozoan holdfasts (P). B33(1). Bar is 1 cm long.

B. Photomicrograph of incrusting pelmatozoan holdfast systems (P). Holdfasts incrust cephalopod siphuncle (C). B33(1). Bar is 1 mm long.

C. Photomicrograph of felty mass of sponge spicules (S) which fill interstices of holdfast system (H) and form wall of cement-filled cavity (C). B33(1). Bar is 1 mm long.

D. Photomicrograph of erosion surface (S) in earlier cavity fill which truncates bioclasts (B). B33(1). Bar is 1 mm long.

E. Thin-section photograph of stromatoporoid showing mamelons (M) and denticles (small dark spots in lighter wavy laminae of mamelons). B33(2). 16.25 X.

F. Photomicrograph of recrystallized stromatoporoid displaying cysts (C) and pillars (P). B33(2). Bar is 1 mm long.

G. Photomicrograph of stromatoporoid displaying cysts (C). B33(2). Bar is 1 mm long.

H. Thin-section photograph of pelmatozoan biosparite showing faint inclined lamination (L) of parallel surfaces of micrite sediment floors in interparticle pores in poorly-washed areas. B37. Bar is 1 cm long.

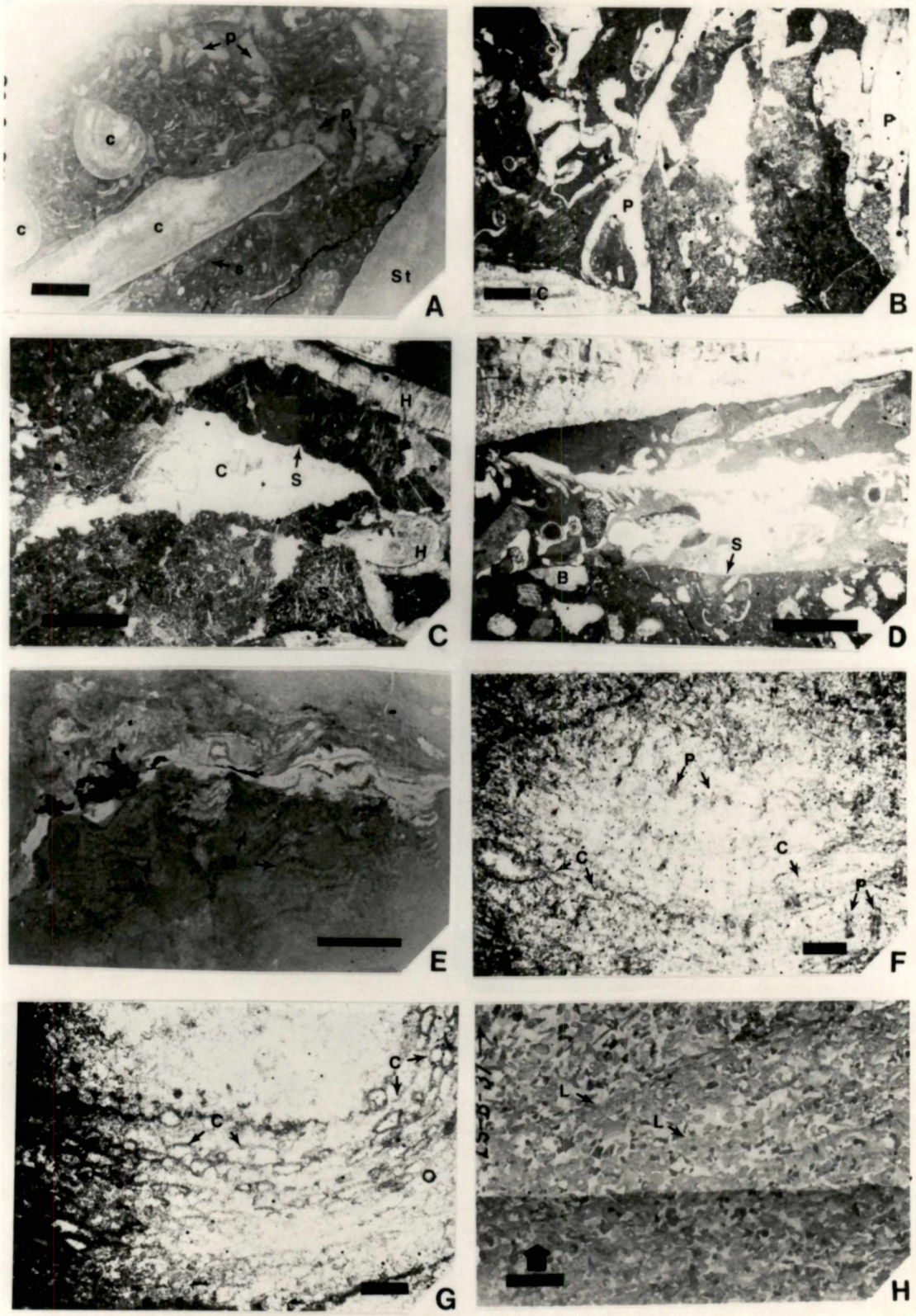


Figure 3-11.

coenostea with prominent, steep-sided mamelons (Fig. 3-11e) and cysts (Fig. 3-11g), while pillars are dark, diffuse structures in different parts of the coenostea (Fig. 3-11f). Sections cut tangential to mamelons reveal denticles, which are circular, tooth-like bumps or projections of the laminae (Fig. 3-11e). Kapp and Stearn (1975) recognized two Chazyan genera with sheet-like coenostea, mamelons, cysts, and laminae, namely Labechia and Pachystylostroma. Of the species illustrated in Kapp and Stearn (1975), the limited number of Lay School thin-sections most resemble Pachystylostroma goodsellense and Labechia eatoni. Similar appearing samples have been found approximately 30 m from the base of the Chickamauga section at Cedar Springs and were previously identified as stromatolites (see Ruppel, in Walker et al., 1980).

In some places, this biostrome is overlain by bryozoan boundstones (sample B34) similar to those found with skeletal sands in uppermost A Section (e.g., sample A<59). The boundstone contains quartzose silt, arborescent trepostome bryozoans, and bifoliate bryozoans in addition to incrusting genera. Also present near this interval are algal-bryozoan intergrowths (sample B35) which contain spongiostrome algal layers and phylloporinid and incrusting bryozoan forms. Biomicritic portions contain a diverse fauna.

While in some places the bryozoan boundstone facies appears to directly overlie the stromatoporoid layer, in other places a thickly-bedded grainstone/packstone (samples B36-38) seems to occupy that position. The grain/packstone forms a prominent ledge in the field

and displays a pronounced fining-up in grain size. The lowermost beds are well-sorted, very coarse, unabraded pelmatozoan sands with occasional to common flat-floored, partially micrite-filled interparticle pores (e.g., sample B37, Fig. 3-11h). Diverse pelmatozoan ossicle types occur in these sands (samples B36-38) including holdfasts. Other fauna includes several bryozoan types, lithistid sponge fragments, brachiopods, gastropods, worm tubes, and trilobites. Syntaxial cementation is dominant and may project sharp crystal faces into the mud which sometimes floors interparticle pores. These features suggest that the pelmatozoan sands were only slightly transported by waves or currents, trapped some fines in interparticle pores during quiet periods, and were winnowed of fines subsequently. Syntaxial cementation then reduced interparticle porosity almost completely.

The major differences discussed thus far between B Section and A Section are the occurrence in B Section of a stained sediment surface of hardground (sample B8), an oolite bed (sample B25), and a stromatoporoid horizon or biostrome (sample B33). The other major difference is the presence of varied facies (B19-27) above the laminated-diverse sand cycles in the lower half of B Section (samples B1-16). In lithologic terms, these include occasional grainstones, bimodal sparry packstones, muddy packstones, very poorly sorted and oncolitic muddy packstones, and rare wackestones. Two major ecofacies are especially well-represented--Ecofacies 3 and 5. Ecofacies 3 samples are B39, 40, 50, 52, 57, and 60. These are bimodallly sorted fossiliferous

facies, with varying amounts of silt-sized matrix grains in addition to the larger allochems. These samples often show primary depositional features such as shelter porosity or horizontally-oriented particles and usually have a high petrographic fossil diversity (Fig. 3-12a; Fig. 3-4, p. 68).

Another common ecofacies which is better represented in B section than in A Section is Ecofacies 5, which includes samples B16, 25, 45, 49, and 58 (Fig. 3-12b,c). These most resemble the very poorly sorted, often oncolitic facies developed toward the center of sample interval A19-31 in A Section. Some samples contain ooids (B25, 45, 49, 58). and multiple incrustations (B45) as well as coated grains and oncolites. All lack primary features such as shelter pores or horizontal particles and have jumbled particle fabrics. Yet, obvious bioturbation is not a common feature in these samples. It may be that postdepositional bioturbation is less noticeable using the criteria used here mud burrows, spar burrows, swirled particles) in coarsely fossiliferous and poorly-sorted facies than in finer grained packstones and wackestones. All of these samples from Ecofacies 5 contain a diverse assemblage of fossils, usually with a PFD greater than 10 (e.g., B45 = 12, B65 = 16).

The samples from the stromatoporoid biostrome up to the muddy, bioturbated zone at sample B62 are faunally and florally diverse regardless of their ecofacies. In addition to Girvanella and Hedstroemia, the algal flora of this interval includes dasycladacean algae and the problematic alga Nuia. One float specimen (B59) from

Figure 3-12. Photomicrographs and thin-section photographs of the Hogskin Formation (or Member of the Lincolnshire Formation) and Upper Lincolnshire Formation. Ecozones I and II.

A. Thin-section of bimodally sorted biosparite B60, Ecofacies 3. Contains primary depositional features: shelter pores (cement-filled) and perched sediment. Also matrix channel pores. Hogskin Formation. Bar is 1 cm long. Arrow indicates up direction.

B. Thin-section of oncolitic, poorly-sorted grainstone/packstone B45. Ecofacies 5. Hogskin Formation. Bar is 1 cm long.

C. Thin-section of poorly-sorted biomicrite/poorly-washed biomicrite B49. Ecofacies 5. Fossils present include cephalopod (arrow marks septa), Rhaphistoma [gastropod (R.)], and recrystallized algal(?) fragments (A). Hogskin Formation. Bar is 1 cm long.

D. Photomicrograph of B59, showing scaphopods in cross-section and burrow filled with fecal pellets. Hogskin Formation. Bar is 1 mm long.

E. Thin-section photograph of calcareous silt B44, displaying planar and small ripple cross-lamination. Ecofacies 2. Hogskin Formation. Bar is 1 cm long.

F. Thin-section photograph of bioturbated wackestone/mudstone B70, displaying mud-filled burrows and concentric arrangement of particles around burrows. Ecofacies 4. Ecozone II. Bar is 1 cm long.

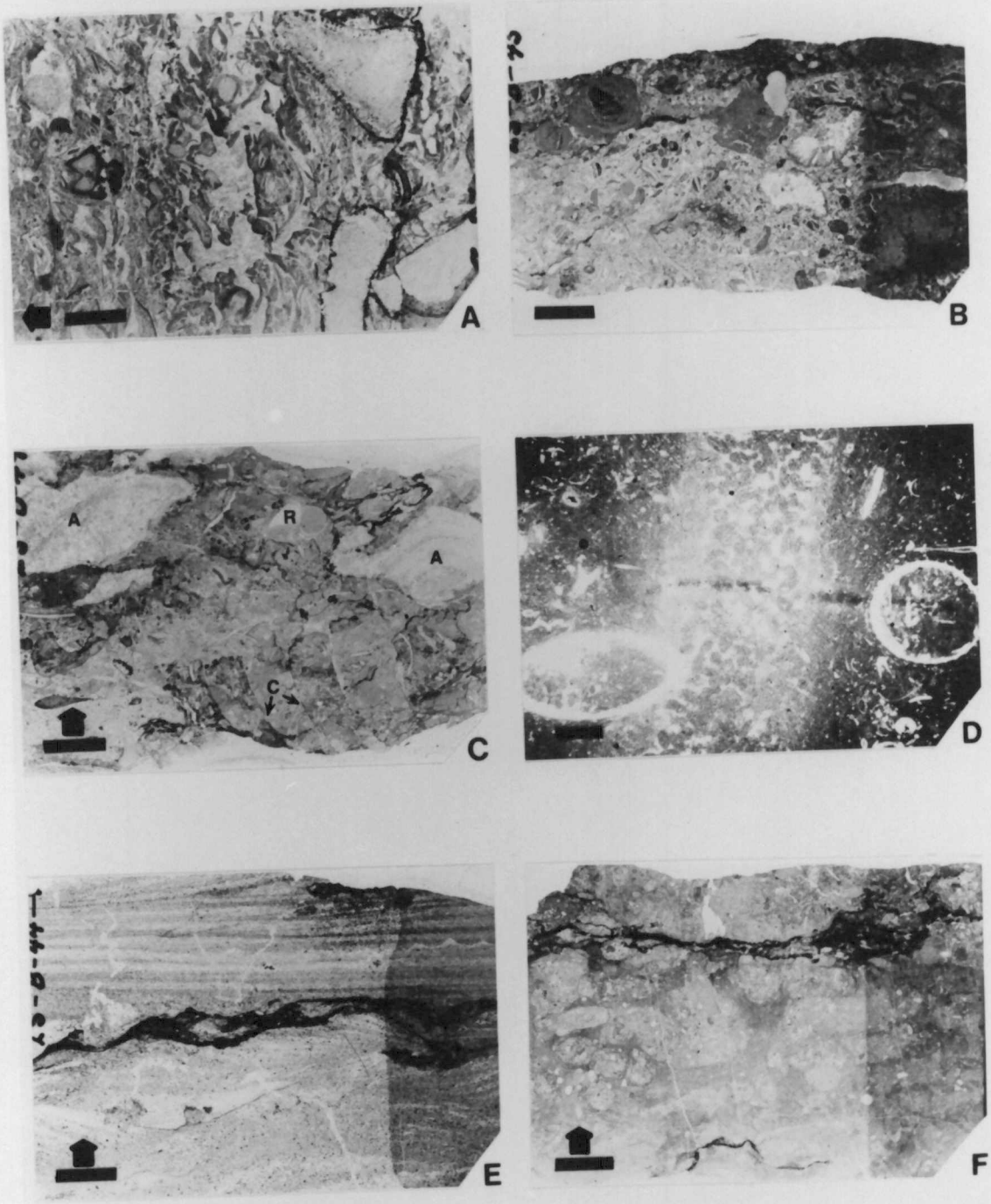


Figure 3-12.

the poorly exposed interval between samples B50-62 contains little more than the Receptaculites algal thalli, scaphopod shells, and burrows filled with fecal pellets (Fig. 3-12d). Another float specimen near the covered interval, B49, contains sparry recrystallized fossils of up to several centimeters across which appear to be algal or tabulate coral in nature (Fig. 3-12c). Bryozoan diversity is high, with all the major groups represented (i.e., phylloporinid, bifoliate, incrusting, arborescent trepostome, nicholsonellid, heloporid). Gastropod diversity seems to increase as the muddy zone is approached, with two samples containing three recognizably different types (B58, B64). Chitinophosphatic inarticulate brachiopods increase in abundance in this upper part of Zone IB (see Appendix D, Table D-5, for fossil types recognized in thin-section). Lithistid sponges as well as loose spicules are common above sample B33, as are rhynchonellid and impunctate (orthid?) brachiopods.

Zone I(B): Depositional Environments

Most of B Section below the stromatoporoid horizon (sample B33) resembles the shallowing-up cycles of A Section. For instance, B Section begins with laminated samples (B1-3) which are capped by a fenestral dismicrite sample (B4) just as the laminated series A39-50 is capped by dismicrite (samples A51, 52). These are followed by massively bedded, variably muddy sands of a subtidal character just as is the laminated sample intervals A17-19 or A36-50. The muddy sand samples in B Section (B7-16) are succeeded by a covered interval (a proposed zone of faulting) and another laminated sequence which

includes a laminated silt and sand with vertical burrows (sample B19) and a fenestral dismicrite bed (sample B23). Such cycles were previously interpreted with reference to the A Section as subtidal to supratidal shallowing-up units which reflect a progression of environments. Possible environments in such a progression include a tidal flat complex, near-shore subtidal sand bars, offshore barrier islands, and lagoonal settings shoreward of the islands. The sequence of facies toward the top of A Section suggested the presence of island windward facies of diverse skeletal sands and bryozoan/pelmatozoan boundstones. For further discussion of possible environments, see the earlier section (Part A).

Two facies exposed in this lower cyclical part of B Section which are not exposed in A Section are the stained hardground sample B8 and the poorly-sorted oolite sample B25. The hardground sample B8 is in a very similar stratigraphic succession to those described in the northwestern thrust belts in Virginia by Read and Grover (1977). Like the Virginia examples, sample B8 is developed above a fenestral limestone and below more open marine skeletal carbonates in a series of such cyclic units called the Blackford-Elway-Five Oaks Formations (Read and Grover, 1977). Like the Virginia examples, sample B8's stained surface is partially incrusted, in this case by a smooth, gray micritic coating similar to that on some coated skeletal grains. Unlike the northern surfaces however, this one is stained dark brown, has burrows or borings, and is apparently not a scalloped or a planar surface (although the outcrop is too overgrown and moss-covered to

see a larger picture). Read and Grover (1977) suggest that the Virginia surfaces are related to the periodic submergence of prograded tidal flat deposits characteristic of the Blackford-Elway Formation. Features of the Virginia surfaces suggest that these tidal deposits were lithified when submerged. While incrustation of the surface of sample B8 does suggest solidity, the burrows/borings in the spicular micrite have diffuse walls rather than sharp ones, indicating that sample B8 was not completely lithified when it was burrowed. The burrows contain the overlying muddy packstone which is rich in Nuia.

The poorly-sorted oolite of sample B25 contains a rich and diverse fauna and flora, including frequent coated grains and relatively large (2 cm across) solenoporid algal grains as well as Hedstroemia and dasycladacean algal types. Ooids present are both superficial and regular well-developed types, with the former more abundant. The nuclei of the superficial ooids include a diverse fossil assemblage, indicating that ooid formation occurred in fossiliferous areas quickly, before much abrasion and disarticulation could affect the fossils. The frequently thin oolitic coats suggest that these ooids were agitated only a short time prior to deposition, since there seems to be a correlation between the time an ooid spends in agitation and the thickness of its oolitic coats (Bathurst, 1975). These factors and the stratigraphic position of the oolite bed between laminated zones between samples B19-23 and samples B25-27 are consistent with a depositional setting which resembled the tidal deltas at the mouths of interisland tidal passes in the Persian Gulf, rather than the thick Bahamian type

of ooid shoal. Tidal deltas are usually somewhat thick deposits, however, often with large cross-laminae (Enos and Perkins, 1977). Oolite B25, on the other hand, is less than 10 m thick and lacks conspicuous cross-laminae. It must therefore result from a different inter-island or near-island setting, perhaps a sheet deposited by a rapid but short-lived transgression or storm which formed in a low place between islands and received diverse fossils and ooids from a more windward setting.

The presence of a stromatoporoid layer immediately above an interval containing laminated sediments (between samples B25-27) suggests another possible biotic means for causing leeward sedimentation, in addition to sediment stabilization. Algal and bryozoan boundstone (e.g., B34) and pelmatozoan particle incrustation (Fig. 3-11b, p. 109) in samples in and above the stromatoporoid layer suggest that sediment stabilization occurred in B Section and in roughly the same stratigraphic position as in A Section (i.e., above a laminated sequence). It may be that the formation of rigid, massive skeletal frameworks (e.g., stromatoporoid "framestone") in conjunction with the above-mentioned processes of sediment stabilization were instrumental in formation of offshore islands and subsequent leeward coastal accretion. In this view, a community composed of lamellar stromatoporoids, incrusting and erect bryozoans, pelmatozoans, sponges (lithistid and other), and calcareous algae formed a patchwork of windward subenvironments of variable composition and size which initiated the accretionary process described for Section A. In B

Section, these communities were lamellar stromatoporoids incrusted by pelmatozoans, sponges, and incrusting bryozoans (B33, Fig. 3-11b,c, p. 109); bryozoan boundstone composed of incrusting and erect trepostome bryozoans (sample B34), algal bryozoan boundstone composed of spongiostrome algae, incrusting trepostome and phylloporinid bryozoans (sample B35).

Environments above the biostrome/boundstone horizon between samples B33-38 seem to be represented by three basic types of facies. One facies type, described as Ecofacies 3, has a bimodal particle size distribution and often retains some type of primary depositional feature, such as horizontal fossil particles or shelter pores. Also in this post boundstone interval are the echinodermal sand samples B36-38, which were classed as Ecofacies 1 and 3. Both of these facies types display some features caused by grain transport due to waves or currents, as does sample B44, Ecofacies 2, a cross-laminated fine sand (Fig. 3-12e). The echniodermal sands, while not extensively abraded, display grading from bottom beds to top. This suggests sediment modification or adjustment to hydrodynamic processes, as do horizontal fossil particles (Johnson, 1960). Many of these samples also have substantial interstitial spar or cement (e.g., sample B44). These features, along with their close stratigraphic proximity to laminated intervals with peritidal features (e.g., intradismicrites like sample B23, dolomitic silts and laminated lithologies in samples B26-27) suggest their formation in very shallow near-shore subtidal environments. The echinodermal sand could have been sand shoals, spits, or

other sand bodies. The bimodal sands could have formed marginally deeper, retaining some larger skeletal remains and yet showing the effects of frequent water turbulence. Anderson has indicated that the retention of primary depositional features in skeletal sands suggests continuous or frequent water turbulence (1974). The generally high fossil diversity of these facies further suggests relatively unrestricted, open marine conditions (Laporte, 1968; Smosna and Warshauer, 1978). Good circulation or constant agitation seems to be confirmed by the general lack of blackened or pyritized particles in this interval immediately above the biostrome (i.e., between samples B34-40), as shown in the feature distribution, Fig. 3-3a (p. 64). Sulfides are a common constituent of micritic sediments in the restricted inner shelf region of Florida Bay and the Keys (Ginsburg, 1957).

Interfingering with these facies which preserve primary depositional features and becoming more common up-section are more micritic facies which often do not preserve primary features. One of these two facies in particular, Ecofacies 5, has features with apparently incompatible interpretations. For instance, these sediments are poorly-sorted, often with an entirely micritic matrix, and containing whole fossils and those with delicate parts preserved (e.g., the cephalopod with septae, Fig. 3-12c, p. 114). These features suggest that water movement or grain transport in the environment of deposition was not extensive or constant. Yet some sediment particles in these samples can only have been formed by grain transport or agitation, such as the common large oncolites, multiple incrustations on particles, and

ooids. Borings in fossil particles are a feature in all facies in this upper part of Zone IB and is consistent with long particle exposure at the sediment-water-interface prior to burial. Thus some fossil particles in this zone were exposed at the sediment surface for some time prior to burial, during which time many were bored in addition to being agitated, transported, and incrusted several times. Primary depositional features which might indicate the nature of transporting currents or waves are often absent in the more micritic facies, such as Ecofacies 5 or 4, because of bioturbation. The combination of features found in facies in upper Zone IB (mainly in Ecofacies 5) suggests that they resulted from normally gentle water turbulence consistent with micrite deposition and occasional more severe conditions necessary for oncolite formation and concentric incrustation. These more turbulent periods were not of long enough duration to extensively abrade of fragment skeletal particles. This part of Zone IB experiences an increase in blackened or pyritized particles (Fig. 3-3a, p. 64) which may indicate nearby areas of poor circulation or lack of strong, regular currents as the inner Florida shelf (Ginsburg, 1957). A somewhat deeper environmental setting is proposed for this ecofacies (5), perhaps at the near-shore edge of micrite deposition since only micritic lithologies are found in the overlying Zone II (Ecofacies 4). Conceivably this poorly-sorted, oncolitic and micritic facies formed in a transitional zone or series of subenvironments, with sparry, oncolitic sands occurring shoreward and carbonate muds with occasional to common oncolites found in a seaward or lagoonal direction. Logan

et al., 1964, found oncolites in modern environments to be characteristic of permanently submerged shoal water areas or ares low in the intertidal zone. Ginsburg (1972) noted the distribution of modern "oncolites" occurs in the south Florida area from the intertidal zone to depths of 3 m. So this transitional, oncolite-rich facies may have formed in similar depths. The last facies in this postbiostromal or upper Zone IB interfingers with the previously described ecofacies (5) and becomes the dominant rock type above sample B62 even though there are occurrences of Ecofacies 5 above it (e.g., B65). This facies is micritic and is characterized by bioturbation and particle fragmentation or degradation.

Zone II

Zone II includes the strata from sample B62 thru sample C10. It is the most homogeneous zone in the Lay School section, being composed of only one ecofacies--No. 4 or the bioturbated facies. Samples from the remainder of B Part are from thick-bedded ledges exposed between covered intervals on the hill that is B Part or B Section. Samples from the strata on the hillside opposite Hogskin Valley Creek (C Section) from the B Section hill are in thick to massive beds. Lithologies present are packstones and wackestones, usually with smaller skeletal particles than in the previous zone. Sorting of skeletal particles is poor to moderate. Flattened nodules, stringers, and irregular masses of chert are present and cause ledges to stand out in relief in the field. Bioturbation is always present, occurring as

both mud and spar-filled burrows as well as concentric and swirled particles (Fig. 3-12f, p. 114).

Other information relevant to particle histories in this environment of deposition are displayed in the stratigraphic plot of features in Fig. 3-3a (p. 64). This shows the uncommon occurrence of the Poorly-sorted features, with the exception of Poor-sorting itself. On the other hand, features of the Micritic Feature group are well-represented, including Coated Grains, and Adhered and Infilled Micrite. Blackened particles are abundant, although they occur less frequently in the middle part of the zone. Fragmentation and apparent abrasion are present throughout the zone, while good-sorting is not. Since primary or early depositional features have been obliterated by bioturbation, it is not surprising that the Shelter Group and Porosity Group of features are absent. Most cement-filled pores present are intraparticle in nature. Oncolites are the most frequently occurring feature in the Bimodal Feature Group, with Borings in fossils present mainly in the lower half of the interval. Finally, as mentioned earlier, there is an almost total lack of layering or horizontal fossils.

Fossil diversity in this zone is highest in the lower part, from B62-72, where values range from 11 to 16. Elsewhere, diversity is generally moderate (Fig. 3-4, p. 68). Algal diversity (Fig. 3-5a, p. 70) is also highest in the lower part, with dasycladacean algae only occasionally appearing after B70. Nuia and Girvanella, however, occur throughout this zone. Bryozoan diversity declines after highs in the lower part of the zone, with occasional highs elsewhere (Fig. 3-5a).

Phylloporinids, arborescent (radially-arranged zooecia) trepostomes, nicholsonellids, rhomboporids, and Coeloclema are noticeably rare. Only incrusting forms (e.g., batostomids), bifoliates, and heloporids occur with any frequency. Other faunal elements include loose sponge spicules, occasional lithistid sponges (in samples B65, C7), and high-spired smooth gastropods (especially between samples B63-C7). Low-spired gastropods become more common in the upper part, from samples C7 to sample C10. Bivalves (especially between samples B63 and B77), brachiopods, pelmatozoans, ostracodes, and trilobites also contribute to skeletal particles.

The fauna most characteristic of this zone probably left no skeletal remains at all, that is, the deposit-feeding benthos responsible for the intense bioturbation. In the Ordovician, deposit-feeding organisms included: protobranch bivalves, ophiuroids, agnath fish, trilobites, and annelids (Thayer, 1979). The rate of infaunal deposit feeding, as well as the kind of organism itself, is directly related to the cross-sectional area of the animal (Thayer, 1979). The cross-sectional area of the animals responsible for bioturbation in this interval can be grossly estimated from the burrows and concentric particle rings present in thin-section. Sample B70 (Fig. 3-12f, p. 114) is a good example of burrowing in the zone. Burrows range from 3-5 mm in diameter and are round in cross-section. The burrows are abundant and most commonly are horizontal in orientation, although many are found in all orientations. This suggests that the animal was mobile and active, which probably excludes ophiuroids from

consideration as the responsible organisms since they have a blind gut and are essentially sedentary (Thayer, 1979). Trilobites are not a good candidate organism since tracks suggest that they were most likely surface feeders (Thayer, 1979). The agnath fish were also surface feeders. Since most protobranch bivalves were larger in cross-section than the 3-5 mm size range and were not round in cross-sectional shape as are the burrows in this interval, this suggests that annelid or other worms were responsible for Zone II bioturbation.

Zone II Depositional Environments

Some of the particle history information displayed in Fig. 3-3 (p. 64) may be useful in reconstructing the environment of deposition of this zone. Features which result from epifaunal biogenic diagenesis or modification indicate that particles found in this zone were exposed at the sediment-water interface prior to burial for less time than those in the preceding zone. There are far fewer 1-layer incrustations, for instance, than in upper Zone IB. Also, there are no 2-layer incrustations at all in Zone II, while there are several instances in the previous zone. Borings in fossil allochems are less common in this bioturbated interval than in the last zone. These facts suggest more rapid burial of skeletal particles than previously seen. Since the hard substrate provided by larger epifaunal remains would provide valuable sites for further colonization in this soft and muddy sediment area, the above features also imply that benthic communities that did succeed in establishing themselves were short-lived, if present at all.

Many of the particles of the sediment in this zone show extensive fragmentation and apparent abrasion. Fragments of all kinds are usually smaller than in the preceding zone. This could indicate that much of the coarser sediment was transported into Zone II from adjacent areas. Some portion of the extensive particle diagenesis seen in the zone could have resulted, however, from biologic instead of hydrodynamic processes. Many particles, for instance, have micritic coatings which could be the result of the degradation of the particle by endolithic boring algae as well as by bacteria and fungi. A good example of particle degradation was found in zone IA, sample A30 (Fig. 3-13a). In that case, micritization was a destructive organic process mimicking physical abrasion rather than a constructive, agglomerative algal-sedimentary process such as that seen in oncolite formation. Furthermore, in modern carbonate settings, fragmentation by scavengers and predators accounts for a large amount of diagenetic particle size reduction (Ginsburg, 1957). Thus, the extensive fragmentation and apparent abrasion seen in this zone is consistent with effects produced by transportation of the skeletal particles into the area by episodic turbulent events. However, much of the particle diagenesis could also have been produced by biologic or organic agents (e.g., degradation by endolithic algae and fungi), either in adjacent habitats or in situ.

The abundance of fine-grained carbonate particles in these sediments indicates that water turbulence was low in this environment and that micrite was deposited faster than it was removed (Bathurst,

Figure 3-13. Photomicrographs and thin-section photographs of the Elway Formation (Ecozone I) and the lower Rockdell Formation (Ecozone III).

A. Photomicrograph of skeletal grain degradation, Sample A30, Elway Formation. Bivalve fragment with micritic coating. Bar is 1 mm long.

B. Thin-section photograph of biosparite/poorly-washed biomicrite C15, lower Rockdell Formation, flanking facies, mud-pod zone (Ecozone III). Features include shelter and matrix channel pores (cement-filled), horizontal grains. Ecofacies 6. Bar is 1 cm long.

C. Photomicrograph of matrix channel pores (cement-filled) in poorly-washed biomicrite C36, lower Rockdell Formation, Ecozone III. Pores are inter-particle, extend beyond possible sheltering particles, and have smooth floors. Flanking facies, Eco-facies 6. Bar is 1 mm long.

D. Photomicrograph of rhomboporid bryozoans in poorly-washed biomicrite C17, flanking facies, lower Rock-dell Formation, Ecozone III. Bar is 1 mm long.

E. Photomicrograph of cavities (cement-filled) in mud-pod facies, Sample C21, lower Rockdell Formation, Ecozone III. Upper cavity lined with radiaxial cement (R) which is also present in cavity floor debris. Center of cavities filled with blocky, equant cement. Ecofacies 7. Bar is 1 mm long.

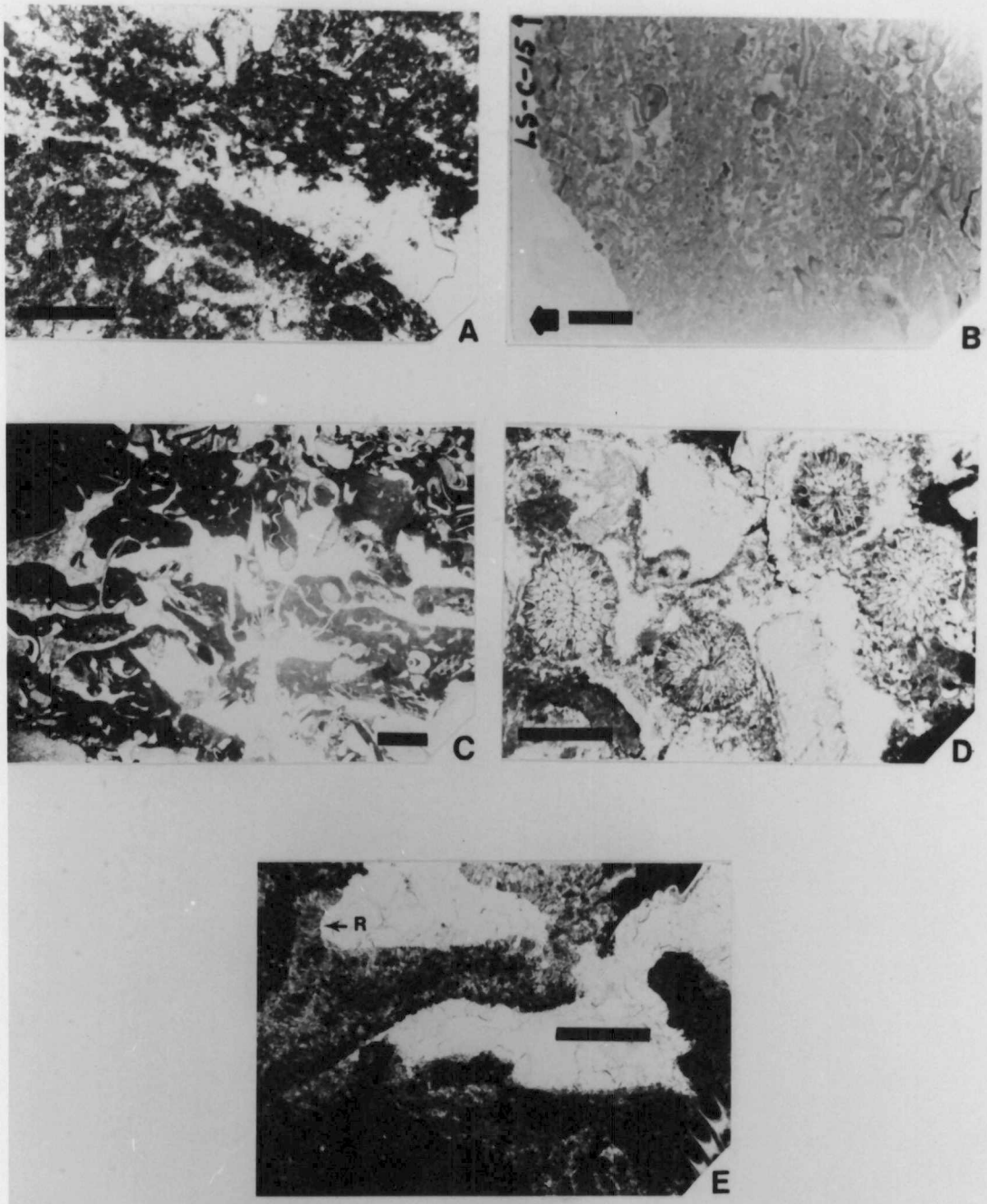


Figure 3-13.

1975). The bulk of the sediment was deposited by settling from suspension in quiet water conditions. Low turbulence or quiet water was also probably ultimately responsible for the common occurrence of blackened and pyritized particles in many of the samples. Pyrite forms with other sulfides below the redox potential discontinuity (RPD) in the sediment (Levinton, 1982). This discontinuity marks the depth where Eh potential (oxidation) decreases from positive to negative, or below which H_2S can exist in the absence of oxygen. Sulfides are generated in marine muds by bacterial reduction of sulfates near the discontinuity. Where dissolved H_2S exists, pyrite is the stable phase in which iron occurs, although it is indirectly produced through the reaction of early metastable monosulfides with elemental sulfur formed by the oxidation of H_2S near the RPD by inorganic processes or by sulfur-oxidizing bacteria (Berner, 1970). The biogenic reworking of the muds in this interval may, therefore, have aided in the precipitation of sulfides through the transfer of reduced compounds (e.g., monosulfides) from below the RPD to more aerated waters in sediment pores nearer the sediment-water interface (Levinton, 1982).

The effects of Zone II bioturbation make it less likely that there was extensive development of sessile epifaunal suspension-feeding communities in the biotope. Mud bottoms that are actively burrowed by large numbers of deposit-feeders have a higher water content than those with few (Rhoads, 1970; Rhoads and Young, 1970). The high water content has the effect of "fluidizing" the mud substrate, making it difficult for suspension-feeding organisms to attain a stable living

position above the mud (Levinton, 1982). Zone II has relatively few of the nonincrusting, erect forms of bryozoan colonies, such as arborescent trepostomes, nicholsonellids, phylloporinids, or bifoliates. This fact is consistent with a soft substrate setting since these forms would be unable to support themselves above the mud without a firm skeletal or sediment base. Another fact suggesting a very soft or fluid substrate in this zone is the lack of clearly recognizable fecal pellets or pelleted mud, even though the sediment is extensively burrowed. The process of biogenic sediment reworking also contributes to the resuspension of fines, resulting in increased turbidity near the sediment-water interface (Rhoads and Young, 1970). This turbidity can clog the filter-feeding devices of some suspension-feeders and inhibit growth (Rhoads and Panella, 1970; Rhoads, 1973). Other effects of deposit-feeding benthos which inhibit or prevent establishment of suspension-feeding communities are accidental ingestion of suspension-feeders by deposit-feeders and "bulldozing" (or overturning and burial) of suspension-feeders (Thayer, 1979).

The above particle history and sedimentologic information and implications suggest an environmental setting similar to some areas on the inner shelf and inner shelf margin of the Florida platform. The Zone II sediments also resemble in some ways the muddy sediments of the inner platform west of Andros Island on the Great Bahama Banks. The muddy bottom habitats on the Florida shelf occur in the lee of the shelf edge sand shoals and extend shelfward to the rocky intertidal shoreline (Enos and Perkins, 1977). They consist of grass-covered

and bare mud bottoms. Where the bottom is greater than 8 m deep, there are large areas of soft, bare mud which are continually disturbed by fish, benthonic organisms, and burrowers. This habitat has the highest turbidity on the inner shelf. Grass-covered mud bottoms (less than 8 m deep, on average) also have relatively high turbidity. Circulation in the bare mud habitat is restricted and water turbulence is at a minimum for the shelf margin (Enos and Perkins, 1977). The large shallow areas extending from the shoreline to 30 miles west of Andros Island on the Great Bahama Bank are areas of carbonate mud accumulation in a setting of sluggish circulation (Bathurst, 1975). This region, the most sheltered from trade winds and strong tidal activity, has water depths of 1-6 or 7 m. Epifauna and flora are relatively sparse and there are large areas without Thalassia grass cover, although a thin subtidal algal mat often covers the mud substrate.

Zone II of the Lay School section shares many features with these two modern areas of carbonate mud accumulation, namely fragmented skeletal debris, intense bioturbation by deposit-feeders, soft or fluidic nature of substrate, and possible turbidity near the sediment-water interface. Differences include different burrowing organisms than those in modern habitats, presence of oncolites and coated grains in the Lay School samples, and lack of recognizable fecal pellets. Both of the modern mud areas form in the lee of some sheltering topographic relief, such as sand shoals, banks, islands, or reefs. This suggests that there may have been some such protecting topographic features seaward of this zone at Lay School.

Stratigraphic Position of Zone II

The stratigraphic position of Zone II, on the whole, resembles that of the Lincolnshire Formation in the western thrust belts of Virginia as described by Read (1980). Zone II overlies the cross-laminated fine-grained grainstone sample B44, thick-bedded grainstone/packstones samples B36-38, bryozoan boundstone sample B34, and oncolitic samples B45 and B65 in the upper part of Zone I. In Virginia, the Lincolnshire Formation overlies the cyclic Elway units and consists of basal facies containing oncolites, skeletal and pelletal grainstones, and bryozoan boundstone pods. The lithologies of the major portion of the formation are dark gray, cherty skeletal muddy packstones, wackestones, and mudstones that contain abundant burrows (Read, 1980). This describes the facies in Zone II very well, and suggests that the formational boundaries of the Lincolnshire at Lay School begin at the stromatoporoid horizon (at sample B33) and extend to sample C12 in Part C of the section. Since Cooper (1956) named the Hogskin Formation (or member of the Lincolnshire Formation) for exposures of fossiliferous, yellowish brown, shaly strata on the northern side of Hogskin Valley, this study calls the interval of diverse lithologies (B33-62) below Zone II the Hogskin Member of the Lincolnshire Formation. Zone II itself is called the Upper Lincolnshire Formation since it conforms so closely to that formation as described from Virginia exposures (Read, 1980).

The Lincolnshire Formation in Virginia is interpreted as a shallow marine facies deposited in progressively deeper water on the shallow

portion of an eastward or southeastward dipping ramp (Read, 1980). According to that interpretation, the basal oncolitic and related facies were deposited in waters up to a few meters deep while the muddy, bioturbated portion of the formation was formed below wave based in a quiet, partly restricted or protected setting. The restriction of circulation which caused deposition of fines was partly due to the distance of these sections onto the ramp, but could also have resulted from buildups seaward of the Lincolnshire (Read, 1980). Since small mud mound buildups occur in the overlying Zone III at Lay School, their small topographic relief on a shallow shelf or ramp with a very gradual slope seems a more reasonable explanation for this near-shore muddy zone. It would be more difficult to explain how sediments deposited in a meter or two of water could immediately underlie sediments deposited below wave base. Fair weather wave base in a shallow sea unprotected by reefs or shoals (e.g., the North Sea) has been estimated at 18 m (Reinick and Singh, 1975).

Zone III

Zone III begins at the first grainy sample (C12) following the heavily bioturbated Lincolnshire Formation of Zone II (Fig. 3-1, p. 59). Samples C12, 13, 14, 15, 17, and C22, 30, 36, and 37 represent facies which underlie and flank a facies which consists of micritic pods or small, irregular masses. The micritic bodies consist of a lithology termed "mud-pod" facies by Read (1980) which accurately describes the manner of their occurrence. Flanking facies samples

mainly consist of bryozoan and pelmatozoan-rich grainstones and packstones of the Ecofacies 4, 5, and especially 6 (Fig. 3-2, p. 63). The packstones usually contain some spar in their matrices and several samples contain winnowed or washed textures, such as matrix channel pores (in samples C15 and C36, Fig. 3-13c, p. 128), and interparticle spar increasing upward in a sample (sample C22). Several facies present retain primary depositional features, such as shelter phenomena (in samples C13, 14, 15, 17, 22) and horizontal particle orientations (in samples C15, 22, 30, 36, 37) which caused them to be classed in Ecofacies 5 or 6. Lithologies with either horizontal particle orientation alone or with both horizontal orientation and shelter phenomena are classed via clustering in Ecofacies 6 (e.g., samples C15, 22, 30, 36). Those with shelter phenomena alone were clustered into Ecofacies 5 (e.g., samples C12, 13, 37). Other features of those in Ecofacies 6 include good to moderate sorting (contrary to most other subfacies in Ecofacies 6), and low fragmentation and abrasion. Exposure or epifaunal diagenetic features are present, such as 1-layer incrustations, coated grains, and borings in fossils. Blackened or pyritized particles are noticeably absent.

Those facies surrounding the mud-pod facies contain a relatively diverse flora and fauna. Petrographic Fossil Diversity (PFD), for instance, varies from 11 types (in sample C14) to 20 (in sample C37), see Fig. 3-4 (p. 68). Algal diversity is relatively low, although abundance or frequency is high. Girvanella occurs throughout the zone while Nuia is common only in the lower beds. Dasycladacean algae

increase in abundance in the interval, from occasional showings (as in sample C15) to grain/sparry packstones in the upper part where they are a major grain type (as in sample C37). Oncolites occur occasionally in the flanking beds, but are not as common as in the previous zone. Pelmatozoans, another major particle type, are present as diverse kinds of ossicles and holdfasts, which appear in both the flanking and mud-pod facies. Bryozoan diversity is high, with bifoliates and rhomboporids especially abundant (Figs. 3-5a, p. 70, 3-13d, p. 128). Both types form a major portion of grains in thin flanking beds, such as samples C17 and C22. Other kinds of bryozoans present are Phylloporina, incrusting forms, a few arborescent trepostomes, heloporids, and frequent nicholsonellids. Lithistid sponges (as in sample C14), articulate brachiopods, several types of gastropods, bivalves, trilobites, and ostracodes complete the faunal catalog of the flanking facies.

Environmental Setting of Flanking Facies

An environmental reconstruction from the flanking facies must be consistent with several facts that suggest increased or more constant water turbulence than in the previous zone. The sparry nature of many samples suggests current winnowing of fines, which is corroborated by features such as matrix channel pores (sample C36, Fig. 3-13c) and interparticle spar increasing upward in a sample (sample C22). The relatively good sorting of these samples, especially in comparison with the previous zone, could indicate some grain movement. Lack of much abrasion of the exozone regions of the bryozoan

colonies or fragmentation (e.g., presence of bryozoan particles smaller than colony size), on the other hand, implies only minimal grain transport. Retention of primary depositional fabrics, such as shelter phenomena or horizontal particles, has been suggested to indicate constant current activity in grainy facies since effects of occasional turbulence are often obliterated by biological agents (Anderson, 1974). The lack of pyritized particles in the zone as a whole also implies a better circulation or more turbulence since pyrite is found in sediments deposited in quiet or restricted water conditions (Ginsburg, 1957; Levinton, 1982). The above features argue for a shallow depositional setting above wave base. The occurrence of dasycladacean algae in this zone agrees with a shallow depositional environment. Paleoenvironmental studies of various eras have found dasycladacean algae to be associated with very shallow, sometimes protected shelf setting. See, for example: Jamieson, 1970, for a Devonian study; Flugel, 1977 (a Permian study which found dasyclads associated with both inner and outer shelf sediments); Conrad, 1977, Cretaceous; Wray, 1970, all eras; and Wray, 1972, early Cenozoic. All of the above evidence suggests that these facies formed at shallow depths, above water base, in well-circulated waters that may have been even shallower than the previous zone (if water turbulence is a key to depth interpretation).

Mud-Pod Facies

The other characteristic lithology of Zone III is the mud-buildup or mud-pod lithology (samples C18, 20, 21, 23, 27, 31, 32, 34, 35, and 41). The list includes some skeletal-rich or grain-supported

lithologies which contain few cavities but still have pelmatozoan holdfasts and algal crusts.

Wackestone and mudstone are the dominant lithologies in the mud-pod group of samples. While skeletal allochems vary greatly in abundance, they usually are not grain-supported. The mud-rich facies contains three types of cavities. Stromatactoid cavities, as defined by Pratt (1982), are digitate-roofed cavities with flat or undulose floors, and filled with isopachous radiaxial cement. Such cavities, are rare at Lay School section although some cavities are partly lined (Fig. 3-13e, p. 128). Most cavities are filled with blocky equant cement and may have graded sediment floors and digitate or irregular roofs (Fig. 3-14a). Occasionally, the internal cavity sediment displays fracturing and brecciation, suggesting early lithification. Bioclasts may protrude from cavity roofs. This cavity type has been described as fenestral by Pratt (1982). A third, presumed type of cavity consists of numerous tube-shaped or elongate, spar-filled cavities which are frequently present in the internal sediment of cavity floors (Fig. 3-14a). These were also noted by Read (1982) and Pratt (1982) who described them as having a vermiform shape.

The majority of Lay School cavities are filled with blocky calcite cements including those with a stromatactoid shape (i.e., irregular or digitate roof, flat or undulose floors). While brownish radiaxial cement is more often present welding together crustose algal debris (Fig. 3-13e) and partially lining a cavity, it never completely fills one. The processes of marine cementation were thus arrested before complete

Figure 3-14. Photomicrographs of features of the Mud-Pod Facies, Zone III, lower Rockdell Formation.

A. Photomicrograph of cavity fill, displaying graded sediment, crustose-clotted particles, and vermiform (V) pores/particles(?). Sample C21, Ecofacies 7, lower Rockdell Formation. Bar is 1 mm long.

B. Photomicrograph of round algal bodies (R) associated with spongiostrome alga (S). Sample C32, mud-pod facies, Ecofacies 7, lower Rockdell Formation. Bar is 1 mm long.

C. Photomicrograph of spongiostrome algae of C32, displaying intergrowth of Girvanella tubules. Mud-pod facies, lower Rockdell Formation. Bar is .5 mm long.

D. Photomicrograph of incrustation of stromatolitic layers by pelmatozoan holdfasts (H). Sample C32, mud-pod facies, lower Rockdell Formation. Bar is 1 mm long.

E. Photomicrograph of dasycladacean algal fragment (D) and coated fossil allochem (C) in Sample C31. Mud-pod facies, lower Rockdell Formation. Bar is 1 mm long.

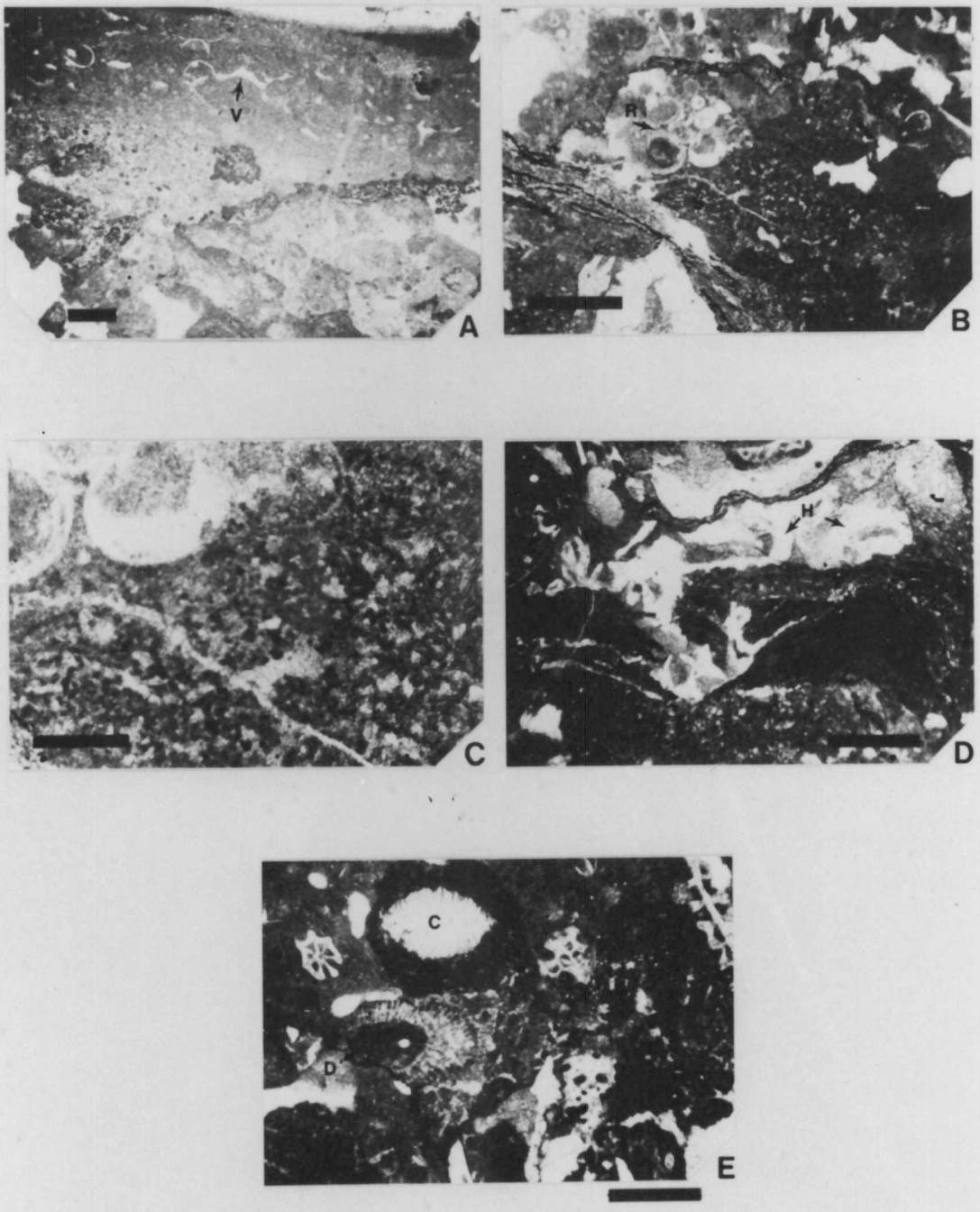


Figure 3-14.

pore filling could occur and the remaining pore spaces were filled by freshwater or blocky cements. The Lay School section may represent a point most shoreward on the middle Ordovician shelf/ramp at which marine cementation was common. Radiaxial cement is believed to represent replacement of early marine fibrous cements (Bathurst, 1959, 1975). If this is true, then sections farther to the west or northwest (closer to shore) of Lay School should be dominated by blocky or freshwater cementation, while those east or southeast of Lay School should contain more radiaxial cementation (originally marine cementation) and true stromatactis.

These cavities occur in a rough framework of clotted, presumed algal crusts (Pratt, 1982), incrusting and bifoliate bryozoans, pelmatozoans, and sponges. The crust-like material is often quite clotted or spongiostrome in nature and can be unlayered (Fig. 3-14a,b) or stromatolitic (Figs. 3-14d, 3-15a). Occasionally, distinct Girvanella-type tubules are visible in the spongiostrome layers (Fig. 3-14c). Both layered and nonlayered algal masses may be incrusted by benthic organisms (Figs. 3-14d, 3-15d) demonstrating the firmness of the crusts. Among the types of stromatolitic layering are crusts with relatively smooth laminae, close-linked hemispheroids (LLH-C), and spaced-linked stacked hemispheroids or digitate forms (LLH-S, Fig. 3-15a), following the classification of Logan et al., 1964. Concentric stromatolitic layering or oncolites occur primarily in the flanking facies, and in general are not common. Coated grains are more common, especially in the flanking facies (Fig. 3-14e).

Figure 3-15. Photomicrographs and thin-section photographs of the mud-pod facies, Zone III, lower Rockdell Formation and Zone IV, Rockdell Formation.

A. Photomicrograph of stromatolitic layering (LLH-S) of spongiostrome algal crusts in mud-pod facies. Sample C-32, Ecofacies 7, Ecozone III, lower Rockdell Formation. Bar is 1 mm long.

B. Photomicrograph of cavities (cement-filled) (C) around Phylloporina bryozoan colony (P) and pelmatozoan holdfast (H). C31, mud-pod facies. Ecozone III, lower Rockdell Formation. Bar is 1 mm long.

C. Thin-section photograph of mud-pod facies, Sample C21, displaying smooth-floored cavity with irregular roof (C) and lithistid sponge (S) incrusted by pelmatozoan holdfasts. Ecozone III, lower Rockdell Formation. Bar is 1 cm long.

D. Photomicrograph of multiple incrustation sequence, C32, mud-pod facies. Hedstroemia/Solenopora(?) (R) incrusts stromatolitic layers at right. Bryozoans (B) incrust Hedstroemia(?) and are incrusted by another algal growth (H). Ecozone III, lower Rockdell Formation. Bar is 1 mm long.

E. Thin-section photograph of biomicrite C41, Ecofacies 7. Holdfasts and cement-filled cavities present. Receptaculites fragment (R) at lower right. Ecozone IV. Rockdell Formation. Bar is 1 cm long.

F. Thin-section photograph of biosparite C46, Ecofacies 1. Displays layering and blackened particles. Ecozone IV, Rockdell Formation. Bar is 1 cm long.

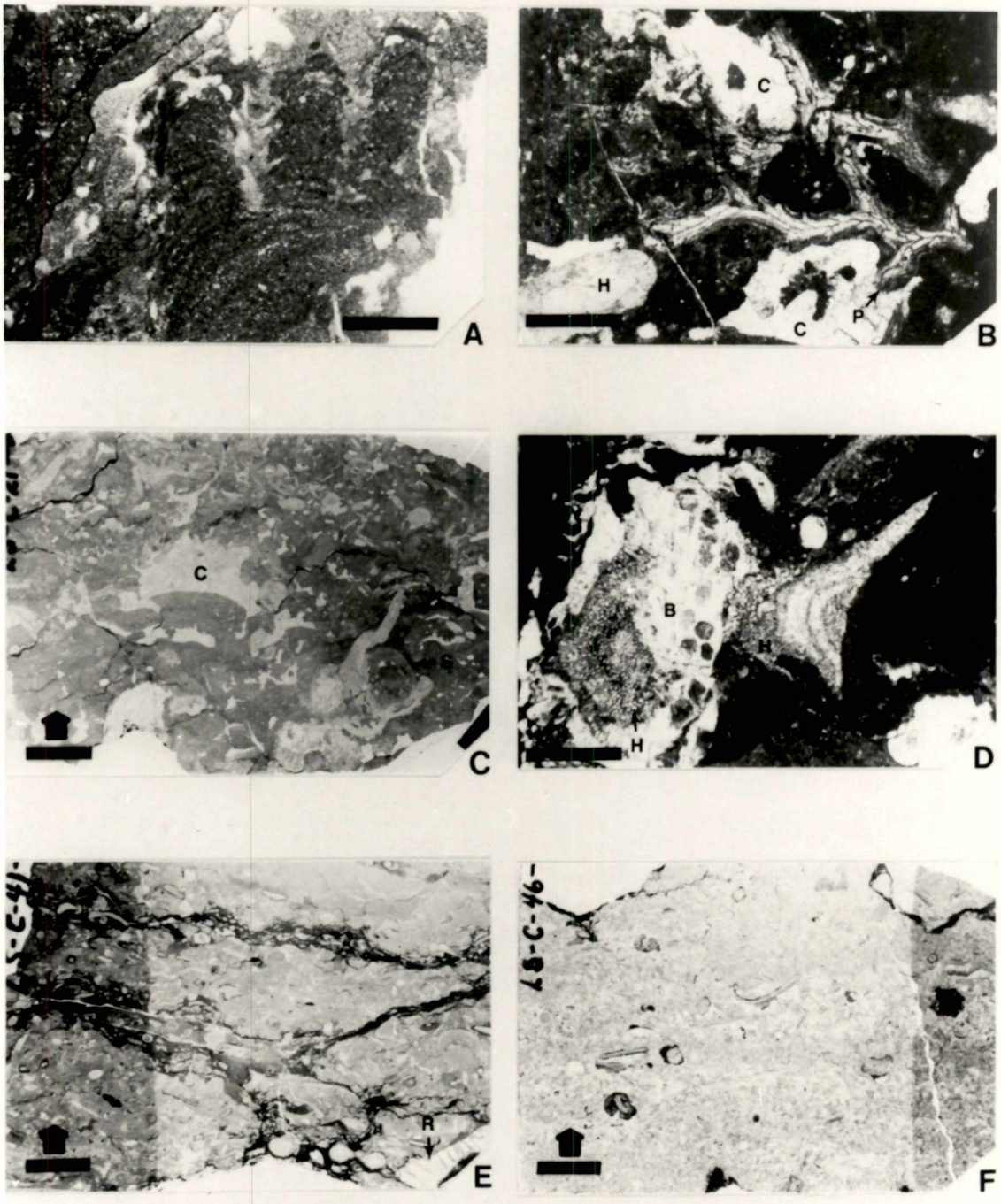


Figure 3-15.

The mud-pod facies is characterized by a combination of environmental effects grouped by sample clustering as Ecofacies 7. Among the features are poor-sorting, holdfasts, vug porosity (cement-filled), radiaxial cement, and incrusted surfaces. Other features present are frequent whole fossils and fossils with delicate parts intact, 1-layer incrustations, coated grains, infilled and adhered micrite, a few mud and spar-filled burrows. Shelter-related features, frequent in the flanking beds, are less common in the pods. The same is true for matrix channel pores. Moldic porosity (cement-filled) occurs in both facies, while skeletal borings are more common in flanking beds. Similarly, the horizontal particle orientation common in flank facies does not occur in the mud pods.

Overall diversity in the mud-pod facies is slightly less than that in the flanking facies. Petrographic Fossil Diversity greater than or equal to 10 types occurs in 7 of 10 samples in mud-pod facies and 8 of 9 sample (88%) in the flanking facies. Algal diversity is slightly greater in the mud-pod facies, while bryozoan diversity is higher in the flank beds. There are a variety of algal types present in the mud-pod facies. In addition to the spongiostrome form which sometimes contains Girvanella tubules, there are also Girvanella grain coatings (Fig. 3-14e) and unattached crusts. While Solenopora is not a major constituent, it does occur in the mud-pod facies at two locations (samples C31 and C32). Dasycladacean algae, on the other hand, are present throughout the interval and become even more common in the succeeding Zone IV (Fig. 3-14e). The Nuia ceased to

appear in the flanking facies after C14 and does not appear in the muddy facies until sample C41 in the allochem-rich uppermost beds in the zone. Lastly, the alga Receptaculites also occurs in the uppermost beds of this zone (samples C39, 41) and in the overlying zone.

Bryozoan faunas in the mud-pod facies are dominated by incrusting trepostome types, phylloporinids (Fig. 3-15b), bifoliates, and nicholsonellids. Rhomboporids are less common than in the flanking facies and radial arborescent trepostomes are also not common. Coeloclema occurs in several samples from the middle to upper part of the zone. Heloporids are also present. Brachiopods seem to decline in diversity and abundance in this zone and in the mud-pod facies especially. Pelmatozoans are present mainly as holdfasts in the mud facies, except for the upper transitional part of the zone, where other ossicle types form a major part of the allochems. Lithistid sponges are a very noticeable element of the fauna in the pod facies (Fig. 3-15c). Bivalves, gastropods (more common in upper beds), ostracodes, and trilobites complete a brief faunal survey of the facies.

Environmental Setting

Most mud mounds discussed in Wilson (1975) and Pratt (1982) occur in downslope, deep water setting. They may contain Girvanella but usually do not have much other algae. Waulsortian buildups, for instance, have been considered to form at depths below the euphotic zone because they lack algae (Wilson, 1975). Surrounding limestones may be fine-grained, argillaceous and cherty, and have lamination, graded bedding or nodular bedding. The Lay School mud pods, on

the other had, occur in a relatively shallow depositional environment. Several types of algae occur in flanking and core facies, including dasycladacean algae. Frequent winnowed textures and sparry packstones in the flanking beds may attest to the proximity of fair weather wave base at this point on the shelf. The underlying muddy, bioturbated Lincolnshire Formation (Zone II) also contains algae (Girvanella, Nuia) and has a coarsely oncolitic, Solenopora-rich basal portion (Hogskin member) which also has dasycladacean algae and ooids. These are very shallow, shoal water depth features. The Lincolnshire Formation itself immediately overlies laminated, peritidal sequences (Zone IB, Elway Formation). Thus the Lay School mud buildups occur in a shallow shelf or ramp setting rather than a deeper setting downslope.

The Lay School buildups resemble the shallow ramp mounds and pods described in Virginia by Read (1982). They also have been described in Tennessee in a similar stratigraphic position (Ruppel and Walker, 1982) but apparently from locations more seaward on the mid-Ordovician shelf/ramp than the Lay School section. The shallow ramp Virginia mounds and pods occur in the Rockdell and Ward Cove Formations and lie on cherty, skeletal wackestones and packstones of the Lincolnshire Formation. The Rockdell and Ward Cove buildups are overlain and interfinger with the fossiliferous shaly limestone of the Benbolt, which is interpreted to have formed in a deeper ramp setting (Read, 1982).

The core or mud-pod facies of these Virginia buildups are underlain and flanked by skeletal grainstones and packstones composed of

pelmatozoan and bryozoan grains. The core facies of these buildups are very similar to those at the Lay School section. They are dominated by carbonate mud (micrite) with scattered stromatactoid and other cavities (cement-filled), graded internal sediments, incrusting bryozoans and pelmatozoans, and fibrous radiaxial cements. More blocky, freshwater cements occur in the shallow ramp buildups than in the downslope mounds. Many skeletons are mutually incrusting or incrust lithified mud substrates. Like the Lay School pods, Virginia facies contain lithistid sponges and Solenopora but no or rare stromatoporoids or corals (Read, 1982).

East Tennessee mud buildups occur in two formations, the Rockdell and the Holston. Both mud-mound or wackestone/boundstone facies are in an area to the east of Lay School, or in a position more basinward on the mid-Ordovician platform. The Rockdell Formation is confined to an area in the northern part of East Tennessee, mainly west of the Saltville fault. The Holston Formation underlies the Rockdell in the eastern part of this area northwest of the Saltville fault, and also occurs in thrust belts east of the fault. It extends southward almost to the Tennessee-Georgia state line (Ruppel and Walker, 1982).

The Rockdell Formation in East Tennessee contains similar facies to those described in Virginia, namely, light-colored grainstone and sparry packstone, muddy packstone, and lime wackestone masses with scattered stromatactis. The formation becomes muddier to the west and northwest. The wackestone facies is characterized by incrusting

bryozoans, rare sponges, and spongiostrome algae. Some may be bryozoan/algal biolithites or boundstones. The dasycladacean alga Contexta may also occur, but is less common than in the surrounding grain/packstone facies. Irregular "birds-eyes" also are present (Ruppel and Walker, 1982).

The Holston Formation contains similar lithofacies to those of the Rockdell, i.e., grainstones/sparry packstones, muddy packstones, and wackestones/boundstones. A major difference between the two formations is the red color of the Holston Formation. Another distinction is the abundance and variety of stromatactoid cavities and other cavity types found associated with the wackestone/boundstone facies in the Holston. Unlike the Lay School stromatoctoid cavities, Holston cavities may be laminar and continuous alternations of red lime mud and cavities filled with radiaxial cement. This has been called zebra limestone elsewhere (Lees, 1964; Ross et al., 1975). The laminated stromatactoid facies is sometimes associated with bryozoan wackestone/boundstones containing irregular stromatactis and blocky cement-filled cavities with geopetal sediment and burrows. Both facies, as well as the grainstones and packstones of the Holston, contain no recognizable algae of any kind (Ruppel and Walker, 1982).

There are two categories of theories concerning processes and agents responsible for the formation of mud buildups containing cavities (including stromatactis) like those in the Rockdell Formation. One group of theories emphasizes the importance of the interplay of hydrodynamic processes, organic stabilization, and early cementation. One

such theory suggests that many mud accumulations were initiated by thickets of bryozoans and pelmatozoans which formed wave-protected sites for mud baffling analogous to the mud accumulated in Thalassia grass patches on the Florida inner shelf today (Ruppel and Walker, 1982). According to this reconstruction, the Rockdell Formation sediments formed a skeletal sand bank complex with localized mud mounds forming in favored sites among the sand banks. Mud bodies which thus developed from suspension settling were further colonized by incrusting, lamellar bryozoans and calcareous algae and were thereby stabilized and protected from erosion (Ruppel and Walker, 1982). Read (1982) emphasizes the possible role of marine cementation in the interplay of physical and organic processes responsible for mound development. In Virginia examples of mud mounds or pods, hard grounds, radiaxial cement in cavities, and mound surfaces incrusted by organisms provide evidence of early lithification which may have aided organic colonization and prevented erosion. Likewise, Bathurst (1982) argues that early marine cementation or "crustification" is the dominant process in the formation of stromatactoid cavities in these mud mound facies.

Another theory relevant to the origin of stromatactis-bearing mud mounds in general argues for an algal-sedimentary interplay as an explanation for their development. According to this theory (Pratt, 1982), mud mounds accumulate at a moderate to deep depth by the trapping and binding of carbonate mud by organic mats composed of cyanophytic or blue-green algae. This trapping and binding of

sediment is accompanied by concomitant marine cementation which is directly caused by the algae's metabolic activities. Unbound and uncemented sediment beneath algal crusts may be fully or partially winnowed depending on the local hydrodynamic situation, leaving stromatactoid cavities to be fully cemented by early fibrous cements. Whether the algal crusts are laminated, with marine-cemented sheet-like cavities (e.g., Zebra limestone) or are irregularly reticulate depends on the quantity and cyclicity of sediment floods which smother the algal mat in this theory. The porous, crustose buildup so formed is then colonized by incrusting pelmatozoans, bryozoans, sponges, and other benthic organisms which require a hard substrate.

The Lay School mud-pod facies samples contain examples which strongly suggest the existence of a hard, crustose "framework" in the mud pods. The clotted, crusty nature of cavity walls (Fig. 3-14a, p. 139), the presence of brown radiaxial cements in the crusts and extending into cavities (Fig. 3-13e, p. 128), and the incrustation of these surfaces by bryozoans and pelmatozoans (Figs. 3-14d, 3-15d, p. 142) are indicative of early lithification. The presence of cryptalgal stromatolitic layering in addition to the clotted or spongy textures and the presence of Girvanella has also been documented (Figs. 3-14c,d; 3-15a). These two groups of features suggest a close association between algal activity, marine cementation, and mud-pod formation. The possibility of algal binding of sediment in the Rockdell Formation mud facies has also been suggested by Ruppel and Walker (1982).

Paradoxically, a major difference between the mud-mound examples examined in the study by Pratt (1982) and those of the Lay School section is the relative abundance of recognizable calcareous algae in the latter. Most of the mud-mounds described in the study by Pratt lack "skeletal" algae in the core/framework facies or in their flanking beds. Girvanella is the only exception, and most quoted examples do not contain it. The Lay School mud-pod zone has a diverse algal flora, including loose Girvanella crusts, cryptalgal stromatolitic layering and oncolites, dasycladacean algae, spongiostrome crusts, and Solenopora. The Nuia occurs in rocks below (Zone II, Lincolnshire Fm.) and immediately above (Zone IV, Rockdell Fm.) the buildup and flanking beds. Thus, any theory of stromatactis and mound formation must explain why stromatactoid cavities, similarly-shaped blocky cement-filled cavities, and marine cementation occurs in both algal-rich facies such as the lower Rockdell beds at Lay School (Zone III) and in the Holston facies further east, which not only lacks recognizable algae but also stromatolitic or other cryptalgal fabrics (Ruppel and Walker, 1982).

The early lithification of these Rockdell mud buildups at Lay School suggested by petrographic evidence also provides the possibility that these pods or mounds acted as small ecologic reefs and provided partial barriers to circulation on a shallow shelf or ramp setting. The presence of a muddy, bioturbated interval immediately below the mud buildup zone (Zone II, Lincolnshire Fm.) or landward of it in a stratigraphic reconstruction, could be explained by a zone of small buildups which locally provided protection from waves and currents. This is

also suggested to have occurred on a smaller scale further to the east (Ruppel and Walker, 1982) and as an explanation for the development of the muddy Lincolnshire Formation in Virginia (Read, 1982).

In summary, evidence at Lay School suggests that the mud-pod and flanking bed facies in Zone III (lower Rockdell Fm.) were deposited in relatively shallow waters in the euphotic zone at or above fair weather wave base by a combination of hydrodynamic, organic, and chemical processes. Early establishment of mud-rich areas occurred in the lee of bryozoan and pelmatozoan thickets and skeletal sand banks formed by currents and by winnowing of fines from such mud-rich thickets. Algal structures, especially subtidal algal mats, may have formed over protected muddy areas and trapped and bound sediment. Concomitant early marine cementation occurred, often in winnowed cavities of the algal crust, and may have been caused by algal metabolic activities. Due to the shallow setting of the Lay School on the mid-Ordovician shelf, this early cementation was incomplete. Further development of these mud buildups was aided by colonization by benthic, sessile suspension-feeding organisms which favored hard substrates (e.g., bryozoans, pelmatozoans, sponges). These mounds may have impeded circulation or provided some protection from open marine conditions.

Zone IV

The zone overlying the mud-buildup interval consists of thin to thick-bedded grainstones, sparry packstones, and muddy packstones. The zone may be conveniently divided into a lower (samples C42-63)

and upper half (samples C64-D20). The lower half is primarily thin to medium bedded packstones with thick-massive beds of grainstone/ sparry packstone (samples C60-63) and a thin-bedded grainstone/ sparry packstone at sample beds C55-56. Bedding in the upper half is less well exposed and consists of thick-bedded ledges separated by covered intervals. Weathering is more cobbly in the upper part and wackestones and mudstones become the most frequent lithofacies. Some of the ledges exposed in the upper part have small stringers and nodules of chert (in field section D).

Ecofacies of all kinds appear in Zone IV, the most heterogeneous zone in the section (Figs. 3-1, 3-2, pp. 59 and 63). In the lowermost parts, presence of cement-filled cavities and holdfasts cause samples to be clustered into Ecofacies 7 (Sample Cluster 7) (e.g., C41, Fig. 3-15e, p. 142). In the lower half in general, grainstone and sparry packstone samples were clustered into Ecofacies 1 (C46, Fig. 3-15f), Ecofacies 3 (C62; Fig. 3-16a) and Ecofacies 5 (C56). Muddier packstone samples were classed as Ecofacies 4, 5, and 6 (e.g., C52, Fig. 3-16b). Samples in Ecofacies 1 and 3 usually display some type of grain transport feature or primary depositional fabric, such as the horizontal particle orientation seen in C46 or C62. These also have a rough layering of coarse and finer-sized skeletal allochems. Other possibly transport-related features developed in these facies are a bimodal size distribution, fragmentation, abrasion, and sparry matrices. The Ecofacies 5 sample (C56) retains shelter phenomena as a primary depositional feature, but lacks layering or oriented grains.

Figure 3-16. Photomicrographs, thin-section photographs, and field photographs of Ecozone IV, Rockdell and Benbolt Formations.

A. Thin-section photograph of grainstone C62, Ecofacies 3. Horizontal grains and shelter features are present. Ecozone IV, Rockdell Formation. Bar is 1 cm long.

B. Thin-section photograph of muddy, fine-grained packstone C52, Ecofacies 4. Bioturbation features present. Ecozone IV, Rockdell Formation. Bar is 1 cm long.

C. Thin-section photograph of mudstone or sparse biomicrite C70, Ecofacies 2. Mud-filled burrows present. Zone IV, Benbolt Formation. Bar is 1 cm long.

D. Photomicrograph of dasycladacean algal grainstone/packstone D17, Ecofacies 5. Ecozone IV, Benbolt Formation. Bar is 1 mm long.

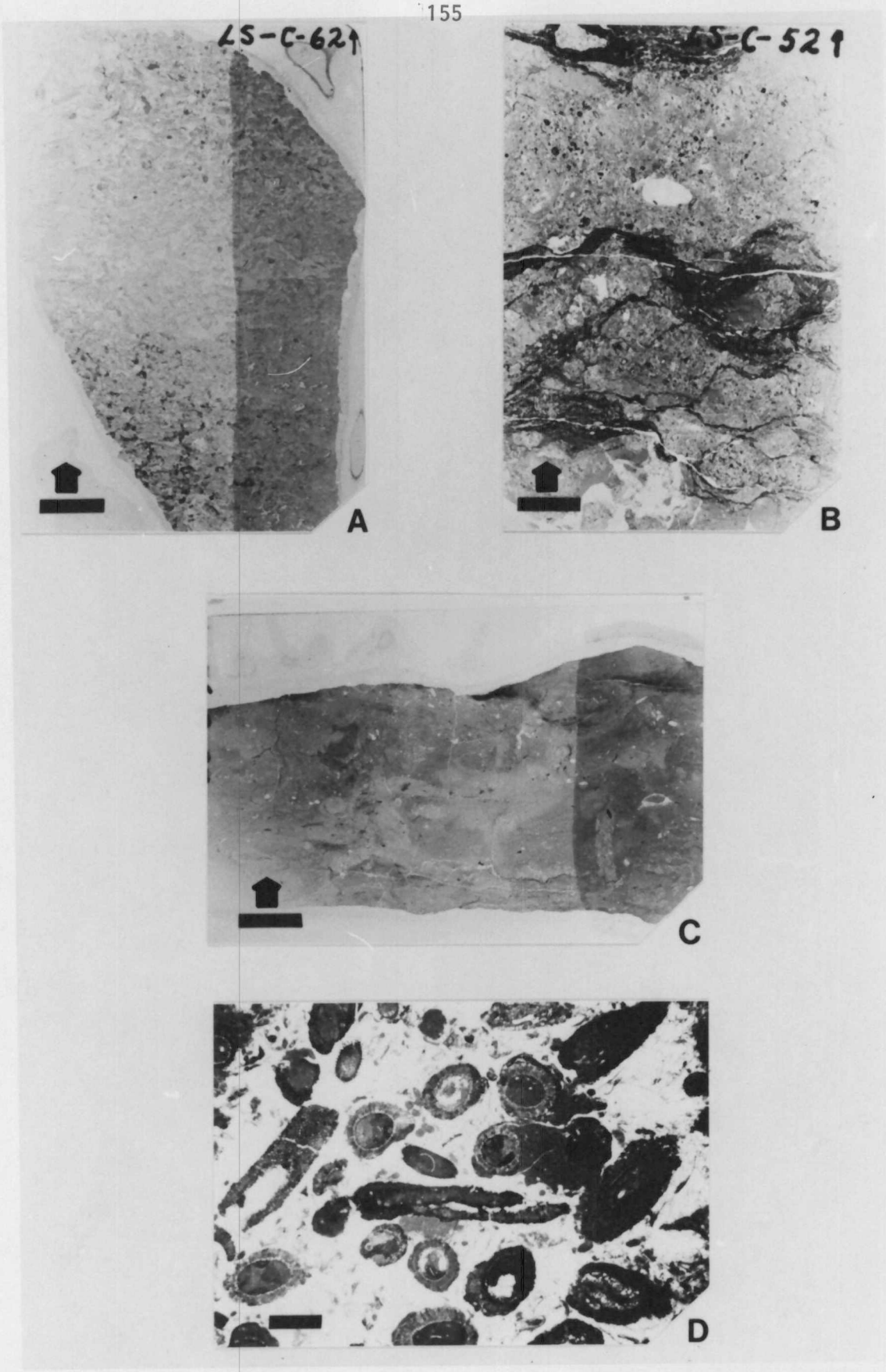


Figure 3-16.

The grains themselves are often coated or oncolitic as well as having bryozoan incrusted particles. Dasycladacean algae thalli form a significant number of allochems. The samples from transported particle ecofacies (1, 3) came from medium to massive beds (samples C46, 62) while the less-transported facies sample (C56) was collected from thin-bedded and shaly rocks more characteristic of the lower half. Sparry packstone samples in the lower half of Zone IV are mainly classed in Ecofacies 4 (C44, 52, 63) and Ecofacies 5 (C42, 49, 58). Those in Ecofacies 4, as well as more muddy packstones, usually display some form of bioturbation. Grain sizes of allochems decrease in the upper half of Zone IV as wackestones and mudstones become more common (e.g., C70, Fig. 3-16c). As might be expected, the increase in mud-supported facies brings about a decrease in grain-supported features, such as horizontal or layered allochems and shelter phenomena. This is reflected in the common occurrence of Ecofacies 4 and 5 in this upper part of the zone. Those two ecofacies usually lack layering or grain alignment, and in this interval, also lack shelter phenomena.

There are several noticeable trends in the feature groups established by R-mode clustering and whose stratigraphic distribution is shown as Fig. 3-3a and b, p. 64. The Poorly-sorted Feature Group (1) is not well represented in this zone. Poor-sorting is the most frequent feature and 1-layer incrustations the least common feature of the group. The Micritic Features (2) are best developed in the lower half, and include coated grains, adhered and infilled micrite, intraclasts, and blackened grains. These become less frequent in the

mud-supported fabrics of the upper half of the zone. The Well-sorted Group (3) is surprisingly strong in Zone IV, with a slight decline in the upper half due to the disappearance of pelloids along with intraclasts (of the previous group). The Bioturbation Group (4) increases upward in the zone in response to the increase in mud-supported lithologies, as the Shelter Feature Group correspondingly decreases. The Bimodal and Horizontal Groups, including oncolites, bimodal fabrics, layering, and horizontal grains are well represented in the lower half of the zone and only reappear in the anomalous grainstones and packstones which briefly occur at D13-19.

Biotic Characteristics of Zone IV

Overall diversity of skeletal remains is fairly high in this zone. The Petrographic Fossil Diversity is always above 10 types in the lower half of the zone and erratically declines in the upper half as wackestones and mudstone become more common. The more sparry samples in uppermost Zone IV (D13-19) mark a more diverse interval in an otherwise less diverse area (Fig. 3-4, p. 68).

Algal diversity (Fig. 3-5b, p. 70) is high in the lower half of the zone and declines to a low point of zero at the beginning of the upper half. Thereafter, it remains low until the upper packstones are reached (samples D13-20). Girvanella appears throughout Zone IV, as does dasycladacean algae. Dasyclad algae form an important part of the sediment in several beds in the lower half (C55, C56) as well as in the upper interval beds (e.g., sample D17, which is essentially a dasyclad grainstone, Fig. 3-16d). The problematic algae Nuia occurs

in the lower portion of the zone, thru C56, and reappears in the sparry facies D16-20. Finally, Receptaculites is present in the lower parts of the lower half of the zone (D39, 41) and disappears by the upper half.

Bryozoan diversity (Fig. 3-5b, p. 70) similarly declines from a high of 6 at the base of the lower half to a low of 0 (<61) at the base of the thick sands at samples C61-63. Diversity increases in the sand but thereafter remains low, with a few fluctuations. There are few fenestrate or phylloporinid bryozoans in this zone. Bifoliates, nicholsonellids, and heloporids are the most common bryozoan types with rhomboporids and incrusting forms occasionally present in the lower, more sparry half of the zone. Diplotrypa/Mesotrypa is present only in the upper half of the zone, and does not reappear until the upper part of the next section (Zone V). The more robust erect forms of bryozoans, such as arborescent trepostomes, are noticeably absent.

There is a fairly diverse sampling of other fauna in Zone IV. While lithistid sponges are relatively rare (especially when compared to the previous zone), loose spicules and hexactinellid or hyalosponges do occur (e.g., sample C67). Usually at least one kind of articulate brachiopod is present and phosphatic inarticulate brachiopods also occur at mid-zone (C64, 66, D1). Gastropods are common, with two and three different types recognizable in thin-section, including the calcitic Rhaphistoma (sample C60). Bivalves (pelecypods) are another molluscan group that occur commonly in this part of the Lay School section. Ostracodes and trilobites are commonly present.

Environmental Setting

Sediments were deposited in this zone in settings which included those of fairly constant turbulence. The occurrence of three grainstone horizons in the lower half (samples C46, 56, 62, Fig. 3-16a), and one in the upper (D16-19) suggest sufficient turbulence for non-deposition or removal of fines. Features related to grain transport occur in these rocks and are shown as peaks on the grain transport curve of Fig. 3-6b (p. 73). These features include fragmentation and abrasion, bimodal size distribution, and layering. Primary depositional features such as shelter phenomena and horizontal particle orientation also occur, and these primary features are suggestive of relatively constant turbulence (Anderson, 1974). The above indicates that the sediments were deposited at or above wave base. Features related to reworking or exhumation by turbulence show that there was considerable such reworking of micritic sands and sandy muds in the lower half of Zone IV, but this decreased with the general decrease in turbulence in the upper half (reworking curve, Fig. 3-6b). Sheltering protected some calcareous mud from erosion (shown as Sheltered Micrite or Sheltering under Biogenic Sedimentation in Fig. 3-6b). Epifaunal biogenic modification or diagenesis of skeletal particles is most common in the lower half and is a noticeable feature of some sparry horizons (e.g., samples C54-56, 63, 64). This is doubtless due in part to the reduction in skeletal allochems available for incrustation or coating in the upper part of the zone.

The variably sparry packstones of Ecofacies 4 and 5 represent settings which were less turbulent and possibly partially protected by

sand shoals. Their proximity to more turbulent subenvironments is suggested by the common presence of coated grains and oncolites. Presence of dasycladacean algae throughout most of this zone and forming an important constituent in several instances, indicates a depositional setting in the euphotic zone and confirms the shallow nature suggested by the other sedimentologic features. Studies of rocks of several eras have pointed to a generally shallow water preference by dasyclad algae (see p. 136). Oncolites are most abundant in modern shelf environments from the intertidal zone to depths of about 3 m (Ginsburg et al., 1972).

The increase in wackestones and mudstones in the upper half of this zone implies a progressive lessening in turbulence that could be the result of increasing water depth. Both algae and fauna decrease in diversity with the introduction of the finer-grained sediments. Facies of the rocks in the overlying strata, Zone V, are on the whole even finer-grained and algal-poor than the upper part of this zone. Thus the upper part of Zone IV seems to be transitional between the shallow, algal-rich sands and muddy sands of lower Zone IV and the overlying mudstones and shales of Zone V. This is consistent with a depositional setting downslope from algal-rich sands marking a shelf edge or a zone on a ramp which marks the effects of fair weather wave base. A near shelf edge and downslope setting for the two parts of this zone agrees with environmental interpretations of the Rockdell and Benbolt Formations in Appalachian regional studies of the lower Middle Ordovician carbonate sequences in Tennessee and Virginia. In

southwest Virginia and northwest Tennessee, the Rockdell Formation is overlain by the shaly Benbolt Formation which was interpreted to have a deep ramp setting by Read (1980) or deep water open platform setting by Ruppel and Walker (1984). The environmental setting of the Benbolt will be discussed further in the next part of this chapter.

The bottom of the Rockdell Formation is placed in this study at the sands and muddy sands underlying the mud-pod interval at the beginning of Zone III. The top of the Rockdell is more judgmental in nature. Since the overlying Benbolt Formation is generally considered to be predominantly micritic, shaly, or fine-grained, the top of the Rockdell Formation is most conveniently placed above the last, thick sands at samples C60-63. These wackestones and mudstones appear at about samples C66-70, so the formational boundary should be at C70. Thus the total thickness of the Rockdell Formation at Lay School is 60 m, from 220 m to about 280 m of cumulative thickness above the Knox unconformity.

Zone V

Zone V is an interval in the Lay School section which is well-exposed by the road cut of the Hogskin Valley road and is that part of the section adjacent to the old Lay School. The rocks consist mainly of brown to yellow-brown nodular-bedded mudstones and wackestones with common packstone layers. There is a grainstone/sparry packstone horizon in the lower part (sample E27) and the upper part (E49-56) (Fig. 3-17a) of the section, with the thick upper sparry beds

Figure 3-17. Photomicrographs, thin-section photographs, and field photographs of Ecozone V, Benbolt Formation.

A. Field photograph of upper grainstone/packstone horizon E54-57, Benbolt Formation, Ecozone V. Measuring rod is 1.8 m long.

B. Thin-section photograph of biomicrite-shale layers of E4, Ecofacies 7. Ecozone V, Benbolt Formation. Bar is 1 cm long.

C. Thin-section photograph of muddy packstone E13, Ecofacies 6. Articulated brachiopods, horizontal fossils, and shelter features present. Bar is 1 cm long.

D. Thin-section photograph of faintly laminated mudstone E62, Ecofacies 2. Displays stylolites. Ecozone V, Benbolt Formation. Bar is 1 cm long.

E. Photomicrograph of fecal pellets preserved in shelter of articulated brachiopod. Mud-filled burrow (B) beneath brachiopod. Sample E13, Ecofacies 6. Ecozone V, Benbolt Formation. Bar is 1 mm long.

F. Thin-section photograph of poorly-washed biomicrite lithology developed over wackestone (biomicrite) containing large Receptaculites (R) fragment. Upper lithology contains oriented fossil particles, shelter and matrix channel pores (cement-filled). Sample E8, Ecofacies 6. Ecozone V, Benbolt Formation. Bar is 1 cm long.

G. Thin-section photograph of poorly-washed biomicrite E50, Ecofacies 5. Displays oriented fossils, sheltered micrite (M), shelter pores, bimodal particle distribution. Ecozone V, Benbolt Formation. Bar is 1 cm long.

H. Thin-section photograph of graded biosparite E27, Ecofacies 1. Displays fossils with adhered micrite (M), shelter pores (cement-filled), and blackened intraclast (I). Ecozone V, Benbolt Formation. Arrow marks up direction. Bar is 1 cm long.

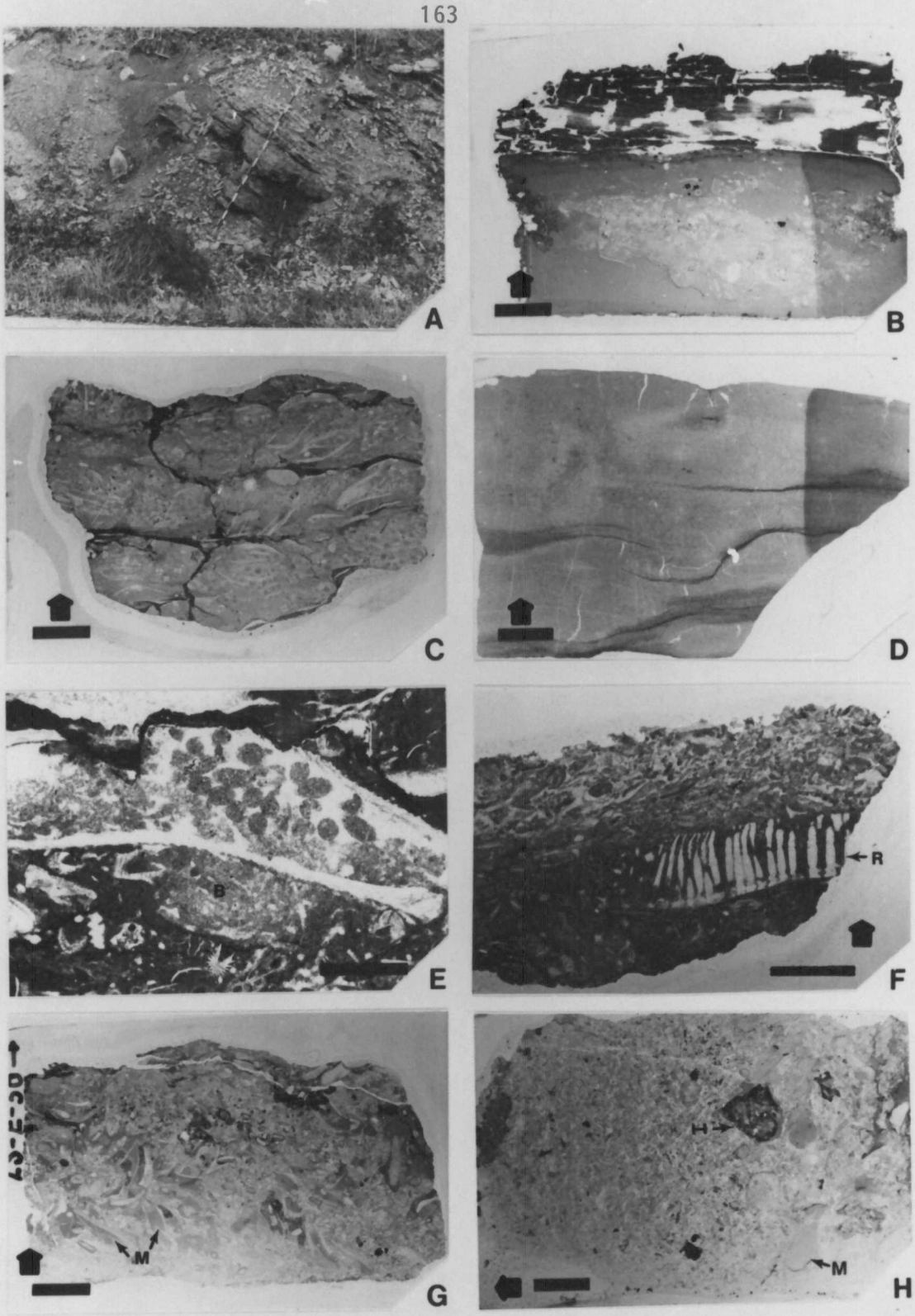


Figure 3-17.

being part of a thinning-upward sequence. Many nodular carbonate layers are interlayered with shales (E4, Fig. 3-17b) or have boundaries of clay-rich stylolites (E13, Fig. 3-17c, E62, Fig. 3-17d). This is a very fossiliferous part of the Lay School section and the abundance of clays in the lithofacies causes deep cobbly weathering which results in loose bioclastic slabs and fossils. This was the most sampled part of the section.

The types of ecofacies found in this interval are shown in Fig. 3-2 (p. 63). Ecofacies 6 occurs most frequently, followed by Ecofacies 5, 4, 7, 3, 2, and 1 in descending order of frequency. Ecofacies 6 is particularly common in the lower half of the zone (e.g., E13, Fig. 3-17c). It often contains whole fossils with little abrasion, frequent 1-layer incrustations, common horizontal allochems with infilled and adhered micrite, but relatively few coated grains and no oncolites. In fact, this zone is algal-poor save for its upper portions. Shelter phenomena are particularly common in Ecofacies 6 samples in the lower half of this zone (Fig. 3-17e,f).

Ecofacies 5 is most frequent in the upper half of this zone. It frequently has a jumbled particle fabric rather than horizontally-oriented particles present in Ecofacies 6. Some samples from this facies have a patchy or irregular distribution of micrite in otherwise sparry areas (e.g., E34, 35, 36, 38, 50) instead of more-layered sparry and micritic areas characteristic of Ecofacies 6 in the lower half of the zone (e.g., E5, 8, 13, 16, 19, 22). Ecofacies 5 samples in this zone often retain shelter features as well as having a high number of micritic features (e.g., E50, Fig. 3-17g).

Other common ecofacies in Zone V include Ecofacies 4, which usually contains facies rich in micrite, bioturbation effects, and few primary depositional features. The two major grainstones in this zone, sample E27 (Fig. 3-17h) and sample E56 (Fig. 3-18a) were clustered into Ecofacies 1, whose samples often have well-sorted particles. Since many of the grains in these facies are sorted, there are fewer larger or longer allochems to form large shelter pores or oriented fabrics. This results in a jumbled or randomly oriented particle fabric. These samples will be discussed further in a later part.

Stratigraphy of Feature Groups in Zone V

The Poorly-sorted group of features (No. 1 in Fig. 3-3b, p. 64) attains its maximum expression in Zone V. Many samples have fossil particles with all three attributes: poor sorting, unfragmented and unabraded fossils, and often incrusted by bryozoans (1-layer). Additionally, articulated brachiopods are common in this interval. These features are consistent with a high proportion of little-transported, nearly indigenous fossils (Johnson, 1960). Grainstone horizons (samples E27, E56) with clearly transported grains are especially noticeable as the few points of low magnitude in the group summary curve. Zone V witnesses a sharp increase in these features from the previous zone, suggesting little grain transport or quiet-water conditions.

Micritic Feature (Group No. 2, Fig. 3-3b) occur erratically but often are abundant or frequent. Coated grains (cortoids) and pyritized or blackened particles increase upward in the interval. Adhered and infilled micrite, as well as intraclasts suggest

Figure 3-18. Photomicrographs and thin-section photographs of Ecozone V, Benbolt Formation.

A. Thin-section photograph of graded biosparite/biomicrite E56, Ecofacies 1. Rounded, sometimes blackened allochems at base grade up to burrowed biomicrite at top. Ecozone V, Benbolt Formation. Bar is 1 cm long.

B. Thin-section photograph of biomicrite E74, displaying in situ Tetradium colony at base. Overlain by dasycladacean algal biomicrite at top. Ecofacies 7, Ecozone V, Benbolt Formation. Bar is 1 cm long.

C. Thin-section photograph of bryozoan boundstone(?) E24. Ecozone V, Benbolt Formation. Bar is 1 cm long.

D. Thin-section photograph of transverse view of unknown organism in sample E10. Organism incrusted by lithistid sponge at top of sample. Benbolt Formation. Bar is 1 cm long.

E. Thin-section photo of longitudinal and transverse views of unknown organism in sample E10. Benbolt Formation. Bar is 1 cm long.

F. Thin-section photograph of wackestone/sparse biomicrite of sample E59. Ecozone V, Benbolt Formation. Bar is 1 cm long.

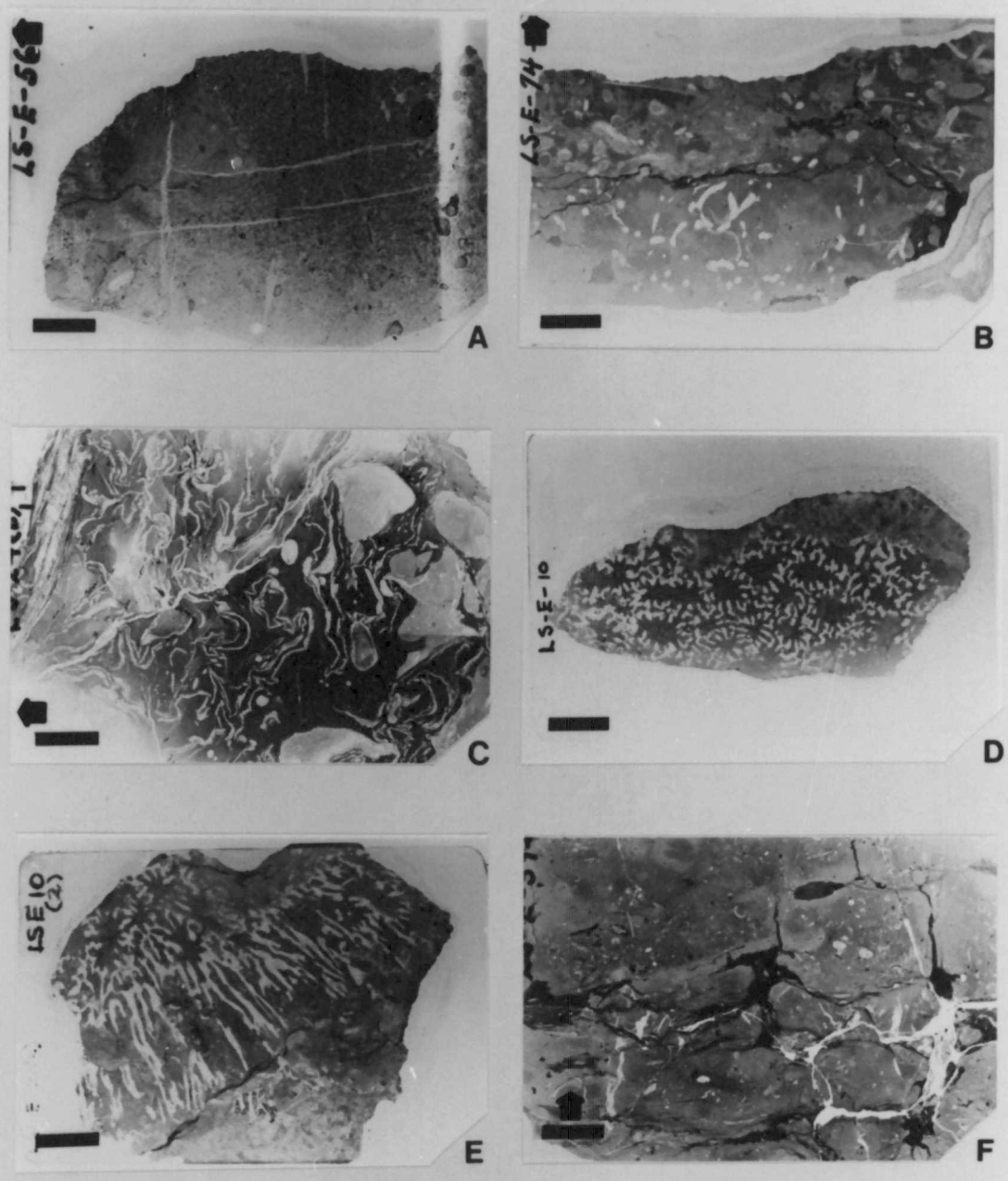


Figure 3-18.

resuspension or reworking of coherent muds deposited in quiet-water conditions (Kreisa, 1981). Pyritized particles were formed in the fine-grained carbonate mud, near the redox potential discontinuity (Levinton, 1982).

The Well-sorted group of features (No. 3 in Fig. 3-3b, p. 64) declines in importance in this zone when compared to the previous zone (IV, Rockdell Fm.). The sum of features curve shows an erratic increase up the interval, indicating more grain transport or other effects of increasing water turbulence. The Bioturbation Group of features (No. 4 in Fig. 3-3b) is also less important in this zone than in the next lower one. Although most lithologies show some form of burrowing, there are many more spar-filled burrows than mud-filled ones. This unusual relation could be related to properties of the original mud, which is now richer in clay minerals than in previous zones. The abundance of fecal pellets (in the Shelter Feature Group) and pelleted mud (in the Mixed Feature Group) in this zone also attest to the presence of bioturbation and deposit-feeding benthos.

Shelter phenomena (Shelter Group or No. 5 in Fig. 3-3b) are a major characteristic of Zone V. The co-occurrence of shelter pores and sheltered micrite in this interval indicates that sheltering of mud as an organo-sedimentary process only happens when increased water turbulence causes resuspension of particles above a sheltering allochem. This increased turbulence causes some transport of the reworked particles and the formation of shelter pores when the particles are redeposited. The R-mode cluster analysis of features,

shown as a dendrogram in Appendix C, shows that this close association of sheltered micrite and shelter pores is true for the Lay School section as a whole. Articulated brachiopods serve as shelters for fecal pellets in this ecozone.

There are several features of the Porosity Group (No. 6 in Fig. 3-3b, p. 64) present in facies in this zone. Pelmatozoan holdfasts occur in some samples in the lower half of the zone and indicate sites of growth. This is consistent with the previously-mentioned indigenous nature of much of the fauna in this zone. Unlike some of the lower zones in which water turbulence was significant (IV, III, I), Zone V has no moldic porosity (cement-filled). Overall, the clustering of cement-filled moldic porosity with particles that are extensively modified by epifaunal biogenic diagenetic agents (e.g., 2, 3-layer incrustations) suggests an association of moldic porosity and transported sediment that also implies a close relation to water turbulence. Particles with multiple incrustations are most often found in very shallow water sediments with many grain transport or other turbulence-related features (e.g., in the shallowest subtidal shoal zones adjacent to peritidal sequences in Zone IA and IB, Fig. 3-3b). Zone V has far fewer grain transport or other features related to water turbulence than do the lower zones. The multiple incrustations found in a few Zone V samples may be due to a relatively long pre-burial epifaunal particle exposure period due to low rates of sedimentation rather than time spent in transport. The great abundance of particles in this zone with 1-layer incrustation supports this possibility.

Another particle feature which suggests a long preburial epifaunal exposure period in this zone is borings in fossil skeletal particles, part of the Bimodal Group (No. 8 in Fig. 3-3b, p. 64). Borings in fossils are far more common in this zone than in the previous one, unlike oncolites, which are rarer than in Zone IV. The increasingly sparry nature of facies in the upper half of the zone (e.g., the upper grainstone/sparry packstone of samples E49-56) and the increase in transported-grain features (e.g., graded beds) accompany the increase in facies with bimodal particle distributions seen in this part of the zone. Bimodal facies are also associated with those features in some lower zones (IA, IB) and in some ecofacies with grain transport features (e.g., Ecofacies 3).

Finally, the lower half of Zone V shows the common development of fabrics with horizontal or subhorizontal orientation of fossil particles (feature of the last or Horizontal Group, No. 9 in Fig. 3-3b). The possible significance of this feature and its genesis is discussed in the following environmental reconstruction.

Flora and Fauna of Zone V

The flora and fauna of Zone V is diverse and often well-preserved. The Petrographic Fossil Diversity, as shown in Fig. 3-4 (p. 68), is for the most part higher than in the previous zone. In fact, diversity of skeletal particles in Zone V is the highest in the Lay School section above the mud-pod interval (Zone III). Diversity declines in the zones above Zone V. The algal contribution to the overall diversity is small, except for the upper part of the zone. At

sample E42, Girvanella and dasycladacean algae reappear and again become common. Nuia also is present in the upper zone grainstones/ sparry packstone samples E53-57. Dasyclad algae occur in several upper samples and are a conspicuous element in the uppermost sample E74, along with in situ tabulate corals (Fig. 3-18b).

Bryozoan diversity in Zone V is one of the highest in the Lay School section, with all major types represented (Fig. 3-5b, p. 70). Phylloporina is very common and appears in both muddy and sparry facies throughout the interval. Bifoliate cryptosome bryozoans are abundant and continue to be common in the next zone. Incrusting types, usually batostomids, are often found on larger skeletal allochems or, in one case (Sample E24) enclose micritic masses containing a fenestral or vermiform pore pattern. This sample resembles a boundstone but the fenestral spar-filled pores in this micritic masses could also be the remnants of sponges or other unknown organisms (Fig. 3-18c). Large colonies of Diplotrypa/Mesotrypa begin to occur in the upper half of the zone. Arborescent trepostomes increase steadily in abundance upward in the zone to a climax and then decrease in the next zone. Nicholsonellids are common in the upper half of the zone while heloporids seem more abundant in the muddy lower part. Rhomboporids occur throughout this zone.

Brachiopods are another common benthic invertebrate group in Zone V. Costellate and plicate impunctate types are present, as well as the pseudopunctate strophemínids. By contrast, rhynchonellids are rare. Chitino-phosphatic brachiopods also occasionally occur.

Mulluscan phyla are represented in Zone V, as well. Gastropods are present throughout the interval but seem to occur more regularly from sample E27 upward in the zone. Bivalves become common in the upper half, which is also where the only cephalopod in the zone was found (E63). Echinoderm pelmatozoan ossicles are also very common in the Benbolt and are often unbroken and unabraded. Ossicles of all types occur, including holdfasts, columnals, and plates. Worm tube epibionts or incrustations are more frequent in the lower part of the zone, below E48. Trilobites and ostracodes are present, as always. Finally, a fossil of unknown affinity, resembling in some ways sponges was found at several parts of this section (E10, E20(1), E59(1), E59(2)). The largest example is specimen E10(1) and E10(2), Fig. 3-18d,e, p. 166.

Environmental Setting

Some general characteristics of the environmental setting in which Zone V sediments were deposited have already been deduced through examination of ecofacies and the distribution of feature groups. Zone V rocks were deposited under quiet-water conditions, as evidenced by abundance of features associated with low turbulence (low turbulence curve, Fig. 3-6b, p. 73) and only occasional presence of grain transport or other features related to high turbulence (grain transport curve, Fig. 3-6b). The common occurrence of micritic allochems and variable amounts of interparticle spar also suggest that reworking of sediment particles was as a normal event in some parts of the zone (reworking curve in Fig. 3-6b). Despite a relative lack of algal

degradation or diagenesis of particles, much of the macrobiotal skeletal remains was colonized by epifauna prior to burial (epifaunal diagenetic curve, Fig. 3-6b, p. 73). Infaunal diagenesis was substantial and not surprising, given the muddy nature of the sediment of this zone. Retention of horizontal particles and shelter phenomena in the lower part, despite bioturbation, is further evidence for reworking (post bioturbation reworking).

It is within this general framework of conditions that specific interrelations of sedimentary textures, fabrics, and facies may be examined in order to reconstruct an environmental model which explains their formation. The lower half of Zone V, for instance, contains the most examples of Ecofacies 6 in this section. Among this ecofacies' characteristic features are horizontal particles and shelter phenomena. Sheltering of mud from reworking (sheltered micrite) is very frequent in the lower part of the zone (sheltering curve, Fig. 3-6b). The interrelation of horizontal particle fabrics, shelter pores, and sheltered micrite suggest certain environmental models of formation of the Ecofacies 6 in this zone.

Oriented or horizontal particles may be related to a jumbled particle fabric in several ways in this part of the section. The mud-supported lithologies (mud, wackestones) and many muddy packstones in this part of the section have particles with a jumbled fabric with no shelter phenomena (E19, E4, E59, Fig. 3-18f, p. 166). A horizontal or oriented fabric may be developed by the winnowing of the inter-particle micrite in a jumbled muddy packstone and redeposition of

reworked particles. A poorly-washed packstone results, with matrix channel pores remnant from winnowing and oriented larger particles overlying the jumbled muddy packstone (E8, Fig. 3-17f, p. 162). An oriented sparry fabric may also underlie a jumbled muddy facies as in sample E22(1), where the sparry grain-supported facies grades into a mud-supported one. Sample E60 also has oriented allochems at the base of a sparry grain-supported layer which grades up into a mud-supported, jumbled upper facies (Fig. 3-19a). In the first instance, the oriented sparry fabric indicates renewed or increasing turbulence reworking already-deposited muddy sediment. The second two instances (E22, E60) display the fabrics resulting from the decay of a turbulent event or the edge of a turbulent subenvironment, such as the outer edge of a sediment tongue or shallow channel.

The last two examples also show a common relation between oriented bioclasts and sparry layers. Frequently, horizontal particles are found either at the base or the top of a grainstone or sparry packstone layer. The former relation is especially noticeable when the sparry layer overlies a muddy facies disconformably, i.e., the sparry layer is developed over a sharp or erosive contact. Bioclasts at or near the contact are often oriented (e.g., sample E60) and shells may be oriented convex-up. Sparry layers may have randomly oriented particles near their centers or within the bed as a whole if it is thick enough (e.g., samples E18, 27, 28, 49, 54). This observed feature can be explained by the flume experiments of Brenchley and Newall (1970) on the transportation of shells and other objects on sandy and

Figure 3-19. Photomicrographs and thin-section photographs of Ecozones V and VI, Benbolt Formation.

A. Thin-section photograph of biosparite/poorly-washed biomicrite E60, Ecofacies 4. Biosparite with micritic areas overlies biomicrite with erosive surface separating lithologies. Sheltered micrite and pores (cement-filled) in sparry areas, with oriented bioclasts and bimodal size distribution. Grades up to burrowed micrite. Ecozone V, Benbolt Formation. Bar is 1 cm long.

B. Photomicrograph of shelter features and fecal pellets, Sample E35. Burrow (B) in sheltered micrite containing fecal pellets. Overlying brachiopod shelter (S) and mollusk shelter (M) preserve fecal pellets (P). Bar is 1 mm long.

C. Thin-section photograph of variably sparry lithology developed over lower micrite, with diffuse contact. Sample E52, Ecofacies 6. Ecozone V, Benbolt Formation. Bar is 1 cm long.

D. Thin-section photograph of grainstone/packstone E49, Ecofacies 4. Rounded allochems, sometimes blackened. Arrow marks up direction. Ecozone V, Benbolt Formation. Bar is 1 cm long.

E. Photomicrograph of dasycladacean algae, sample E80. Ecozone V, Benbolt Formation. Bar is 1 mm long.

F. Thin-section photograph of sample E42, displaying patchy, irregular distribution of muddy and sparry facies. Ecofacies 3, Ecozone V, Benbolt Formation. Bar is 1 cm long.

G. Thin-section photograph of biomicrite sample E98, displaying sponge (S). Ecofacies 4, Ecozone VI, Benbolt Formation. Bar is 1 cm long.

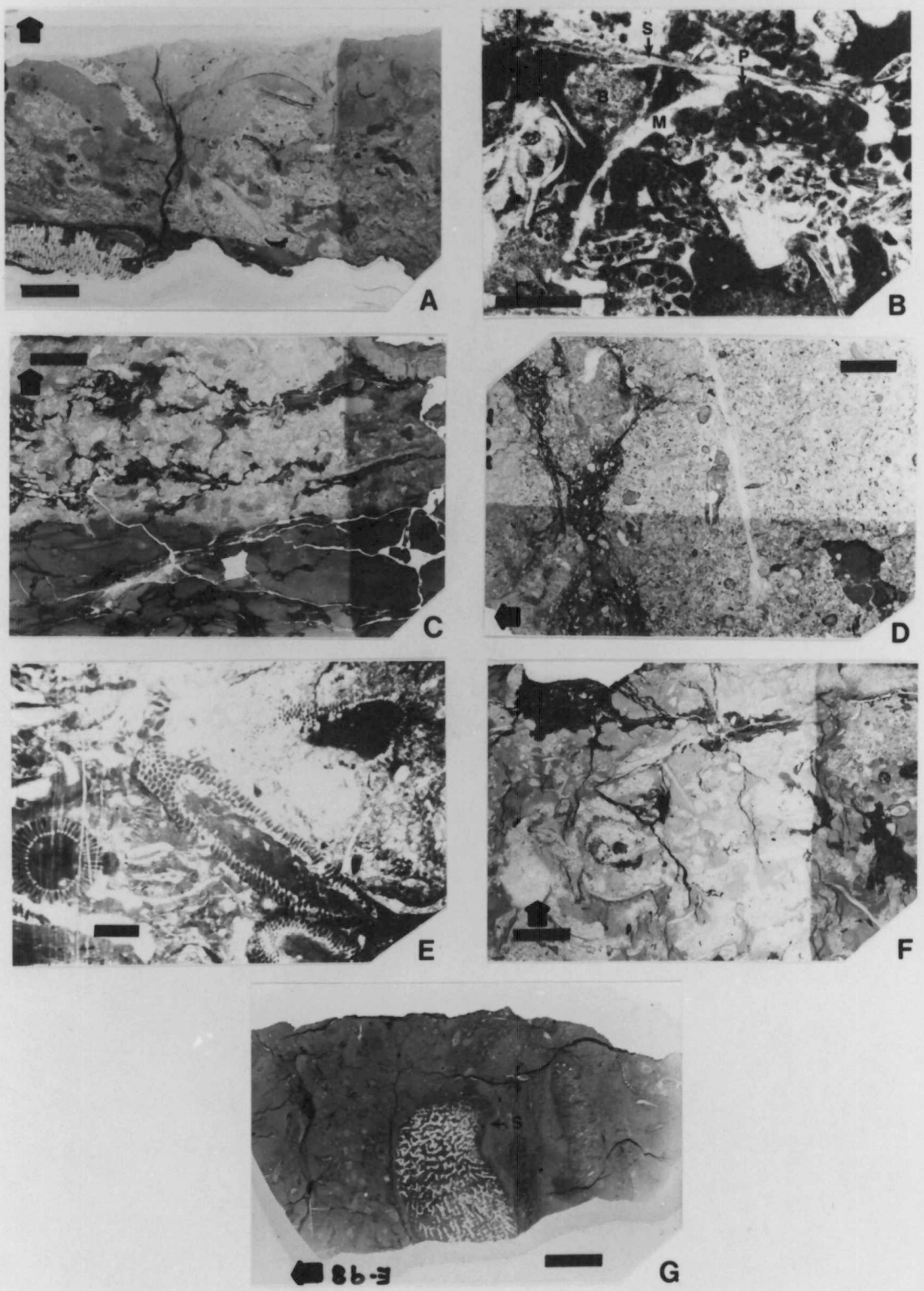


Figure 3-19.

muddy substrates. Shells transported on a sandy substrate are often buried by the scouring caused by the traction carpet of sand and may be buried at any angle. Shells and other objects on a muddy substrate, on the other hand, quickly assume a stable horizontal or convex-up configuration when swept by currents. Thus, poorly-sorted skeletal sediments deposited on a muddy, coherent bottom may develop oriented bioclasts at their base, where drag caused them to revert to a stable configuration.

Observed relations between fabric type, layer or bed thickness, and ecofacies in Zone V suggest that oriented particle fabrics may develop only in thin beds or in certain parts of thick beds (assuming both types have grain-supported lithologies). In Zone V, horizontal grains are most common in the thin bioclastic layers between muddy strata in the lower half of the zone (E8-34) where rocks with Ecofacies 6 are most frequent (Fig. 3-1, p. 59). These layers often grade from sparry packstones to muddier facies (or vice versa) within the thickness of a thin-section (5 cm). Bed thickness increases upward in the zone and this is true for both sparry packstones and grainstones as well as muddier facies. Horizontal particles disappear with this increase in thicker beds (Fig. 3-3b, p. 64). Also, sparry facies increase in frequency up the zone and the thicker sands (e.g., E54-57) generally have a jumbled particle fabric. There may be several related reasons for the association of oriented fabrics and thinner beds or layers. First of all, thicker sands are often more sparry and better sorted in the Lay School section than thin ones. Better sorted

sediments have fewer large or elongate particles to be oriented than poorly-sorted sediments. A more fundamental reason may relate to the strength and continuity of water turbulence and its relation to the traction carpet of transported sediment. Horizontal particles are also characteristic of Ecofacies 2, the laminated facies. Traction transport of sediment grains is very important in the formation of laminated sediments (Blatt, Middleton, and Murray, 1972) and the laminae are, by definition, thin (less than 1 cm--A.G.I. Dictionary of Geological Terms, 1976). The bioclastic layers in lower Zone V, where horizontal grains are common, are usually less than 5 cm thick. The thickest grainstone in this lower interval, on the other hand, is 35 cm thick and grades from very coarse micritic and skeletal allochems at the base to a medium sand at the top. The lower two-thirds of sample A27 has a jumbled particle fabric, but at the smallest grain size horizon there is a thin layer of horizontal particles (including brachiopods) and codeposited micrite. Above this hiatus, grain size again increases and the fabric is again randomly oriented (Fig. 3-17h, p. 162). This suggests that the horizontal grains were deposited at a low point in water velocity and consequent thin traction carpet. The lower part of E27 could have been deposited by a higher velocity current which carried coarser particles and a thicker traction carpet or bed load whose movement jumbled its larger bioclasts or micritic particles.

These relationships among ecologic facies, bedding thickness, and stratigraphic position are consistent with an environmental model in which the sediments of Zone V are deposited in a relatively deep,

quiet water setting. Normal sedimentation in this setting involved settling of fines from suspension and the formation of its characteristic muds. These muddy sediments were periodically disturbed and slightly reworked, possibly by storms which also caused occasional invasions of shallower environment sediment tongues (e.g., the graded biosparite E27, Fig. 3-17h, p. 162). Characteristics of the strata in the lower half of Zone V include:

1. A high proportion of fine-grained sediment beds to bioclastic or macrobiotal layers.
2. Bioclastic layers are generally thin.
3. Bioclastic or skeletal layers often grade up into muds.
4. Sparsity of calcareous algae consistent with deep water setting.
5. Large amounts of fine-grained sediment, also consistent with deep water, below wave base settings.

Other characteristics of lower Ecozone V (or Benbolt Formation) which may reflect depositional conditions include:

1. Skeletal layers with horizontal particles.
2. Skeletal layers with poor sorting.
3. Skeletal layers with frequent shelter porosity and sheltered mud.
4. A high proportion of micritic allochems and micritic features (Feature Group 2, Fig. 3-3b, p. 64).
5. Strata between skeletal concentrations or accumulations have jumbled particle orientations and mud-supported lithologies.

The lower interval of Ecozone V, in summary, consists of facies that seem consistent with an environment characterized by normally quiet water sedimentation which was periodically disturbed by turbulent events. During quiet periods, indigenous fauna died and was buried. Bioturbation soon destroyed any primary depositional features, such as horizontal particle orientation. Occasionally, storms would partially exhume and rework fossils and semicoherent micritic allochems in these areas, imprinting a second cycle of primary depositional effects on the sediments (e.g., shelter phenomena, horizontal grains, etc.). This resulted in facies with both bioturbation and primary depositional features, two feature groups that are often mutually exclusive (as in Ecozone II, Upper Lincolnshire). Bioturbation features include spar-filled burrows and frequent preservation of fecal pellets under shelters. Rarely, storms would cause the movement of larger sediment tongues into the area from shallower settings up ramp (e.g., E27, Fig. 3-17h, p. 162). These would have the previously mentioned fabric characteristics related to development of jumbled and horizontal particles.

The upper half of Zone V (samples E34-76) shares some characteristics with the lower part. Samples in between sparry bioclastic layers are micritic, often mud-supported facies with randomly-oriented fossils (e.g., E58, 59, 62, 64, 69, Fig. 3-19b). Some sparry layers deposited on muddy sediments may have large intraclasts with irregular shapes and diffuse borders (E50, 52, 60). Bottoms of sparry layers may be diffuse (E5, Fig. 3-19c) or sharp (E60, Fig. 3-19a).

Blackened or pyritized skeletal and micritic grains may be among the coarser basal particles in graded grainstones in both halves (E27, E56). On the other hand, grain-supported, sparry skeletal layers increase in frequency and thickness in the upper part of the zone. Some of the characteristics of these sparry layers include shelter porosity and sheltered mud; more facies with a better sorted, small size fraction; graded beds (E56, Fig. 3-18a, p. 166); some grainstones with transport features such as abraded or rounded particles (E49, Fig. 3-19d; E56, Fig. 3-18a); a higher proportion of skeletal grains in some grainstones; jumbled particle fabrics; and the reappearance of algae, including Girvanella, Nuia, and dasycladacean algae (Fig. 3-19e). Some samples contain almost equal proportions of sparry areas and muddy areas but mixed into an irregular, nonlayered mosaic, possibly caused by compaction (sample E42, Fig. 3-19f). An environmental setting consistent with the above characteristics consists of two subenvironments; a normally quiet-water setting of muddy overbank and interfan areas, and increasingly turbulent locales of sandy shoals, blankets, and fans. The skeletal sand blankets and shoals fed the sediment fans which moved shallow shelf or ramp biogenic particles downslope along topographic lows in the muddy, fossiliferous substrate. The increase in sparry facies in the upper part of Zone V indicates and increase in water turbulence that could be the result of fair weather wave base upon the ramp or shelf as the section experienced a shallowing upward trend. The reappearance of calcareous algae supports a shallow water, euphotic setting for upper Zone V.

This zone resembles in several ways the Benbolt Formation as described in northwestern strike belts of Virginia (Read, 1980) and in strike belts in east Tennessee (Ruppel and Walker, 1982; 1984). It is a mud-rich, fossiliferous interval immediately following the shallow sands and muddy sands with small mud-rich buildups known as the Rockdell Formation. The increase in finer-grained sediments, including clays, following the Rockdell is interpreted by Read (1980) to be the result of rapidly increasing water depth, or the "drowning" of that part of the shelf or ramp. The disappearance of algae is consistent with greater water depths, although such mitigating factors as turbidity could have caused the elimination of benthic algae at depths considerably shallower than the 100 m limit of the modern photic zone (Ruppel and Walker, 1984). In Tennessee, the formation if recognized by its yellowish-brown color, nodular to shaly weathering characteristics, fossiliferous nature, and grainstone horizons in its upper portions (Ruppel and Walker, 1984). In Virginia, the Benbolt is a gray, shaly, whole fossil limestone which in southwest Virginia contains mudrock interbeds and is considered the first formation in an offlap or regressive package of stratigraphic units of the upper Chickamauga Group (Read, 1980). The Benbolt Formation attains a thickness of about 100 m in the area between the Lay School strike belt and the Saltville Fault in northern East Tennessee (Ruppel and Walker, 1984). At Lay School, the Benbolt extends from 280 m to 365 m of cumulative thickness above the Knox unconformity, or from sample C70 to E114, a thickness of 80-85 m.

Zone VI: General Characteristics and Ecofacies

Zone VI is the thick-bedded with two thin-bedded intervals (E103-113 and E122-140). The thick-bedded intervals extend from samples E76-103, E113-120, and E140-149. In general, the thicker bedded intervals are dark, micritic carbonates with both mud-supported and muddy grain-supported lithologies. Thin-bedded sequences are lighter in color and have a variety of lithologies, including mudstones, muddy and sparry packstones, and laminated calcareous silt and fine sand-sized rocks. Each of the five sub-intervals in Zone VI has some distinctive characteristics that distinguish it from the others and suggest a different environmental setting. Features present in this zone and which cause it to be distinguished from other zones are bioturbation features. Ecofacies 4, the facies shared by samples with bioturbation effects and no primary depositional fabrics, is the most frequent in the zone (Figs. 3-1, 3-2, pp. 59, 63). As in the lower part of the Lay School section, this zone with bioturbation features is adjacent to one containing common sedimentary structures (e.g., cross-lamination) and peritidal features (e.g., fenestral dismicrites), that is Zone VII. The bioturbated zone (Zone II) in the lower part is adjacent to Zone IB, which also has the above-mentioned hydrodynamic and subaerial exposure features. Many samples with other ecofacies, seen in Fig. 3-2 are from the varied thin-bedded zones.

Many of the rocks in the lower part of this §one have a mud-supported fabric and lack shelter pores or other primary features.

There are occasional oncolites and coated grains. In addition to bioturbation effects, other common features are whole fossils with delicate parts (e.g., E84, E98, Fig. 3-19h, p. 175), blackened grains, and borings in skeletal particles. A few samples seem to contain transitional lithologies which represent changes depositional environments or subenvironments. E80 (Fig. 3-20a), for example, displays layers which are increasingly sparry upward to the center of the slide, and then decrease in interparticle spar toward the top. E80 contains common dasycladacean algal remains in progressive states of disintegration (Fig. 3-20b). Lower portions of the bed represented by E80 contain whole dasyclad thalli, a micrite matrix, and jumbled particles (Fig. 3-19e). Intermediate layers have partially disintegrated thalli, loose silt-size dasyclad cells as matrix particles, interparticle spar, matrix channel pores washed around larger particles, shelter pores, and some horizontally-oriented fossils. The most sparry layer is a grainstone/sparry packstone with silt-sized dasyclad cells but no whole thalli, bimodal particle size distribution, shelter pores, and jumbled fabric. This layer grades up into a wackestone. Thus, bed E80 seems to record the passage of traction sedimentation in a more turbulent subenvironment, such as a small algal-colonized channel or tongue, into and out of quiet-water setting dominated by suspension sedimentation of micrite. Sample E87 contains both micritic and sparry facies but in this case the two are mixed in an irregular, nonlayered manner (Fig. 3-20c). The extensive burrowing in E87 could be partly responsible for this mixing of a bimodal, sparry bioclastic facies with

Figure 3-20. Photomicrographs, thin-section photographs, and field photographs of Ecozone VI, Benbolt and Wardell Formations.

A. Thin-section photograph of E80, showing development of several variably sparry facies over mudstone basal layer. Lower grain-supported facies display horizontal particles, channel and shelter pores (cement-filled). Central sparry facies disrupted by burrowing. Grades upward to burrowed mudstone. Ecofacies 4, Ecozone VI, Benbolt Formation. Bar is 1 cm long.

B. Photomicrograph of E80, showing disintegration of dasycladacean algal thalli into pelloid-sized particles. Bar is 1 mm long.

C. Thin-section photograph of Sample E87, showing irregular distribution of muddy and bimodal sparry facies. Ecofacies 4, Ecozone VI, Benbolt Formation. Bar is 1 cm long.

D. Field section photograph of thinning-upward sequence at the beginning of the first thin-bedded subzone, Ecozone VI. Benbolt Formation. Rod is 1.8 m long.

E. Thin-section photograph of mud-supported facies displayed in Sample E84, lower thick-bedded subzone, Ecozone VI. Benbolt Formation. Bar is 1 cm long.

F. Thin-section photograph of sample E109, a thicker bed from the lower thin-bedded subzone. Muddy packstone layer with horizontal fossils and convex-up shells present over mudstone. Arrow marks up direction. Bar is 1 cm long.

G. Thin-section photograph of biosparite/poorly-washed biomicrite E113, Ecofacies 5. Beginning of oncolitic/coated fossil subzone of Ecozone VI. Wardell Formation. Bar is 1 cm long.

H. Thin-section photograph of oncolitic sample E117, Ecofacies 4. Ecozone VI, Wardell Formation. Bar is 1 cm long.

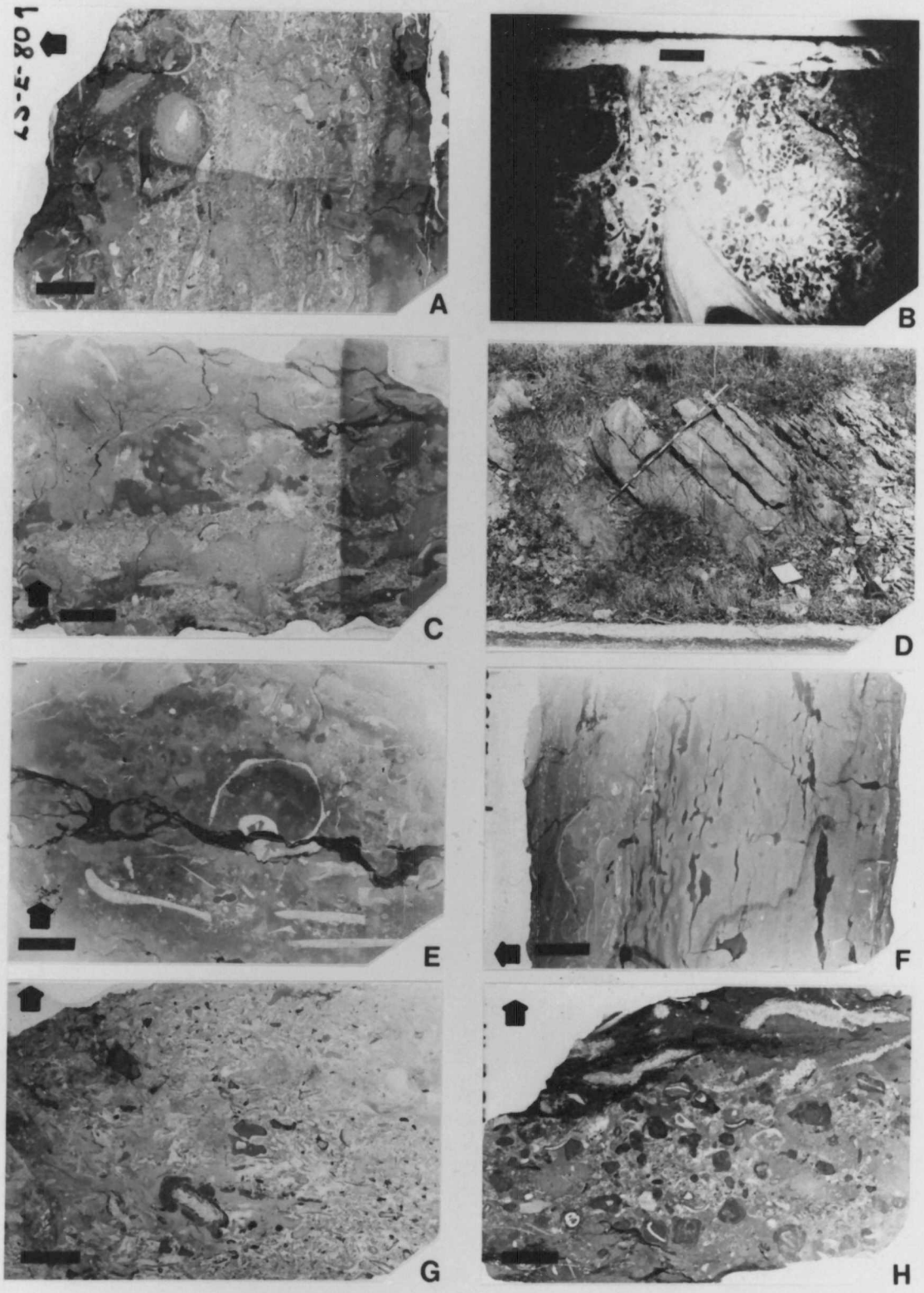


Figure 3-20.

mud-supported facies more typical of the lower part of Zone VI. Sample E87 is part of a thinning-up sequence of beds near the top of this generally thicker-bedded subzone which is a precursor to the thin-bedded subzone at E105-113. This thinning-up sequence (Fig. 3-20d) begins with thick beds of wackestone and mudstone (E81-83), continues into medium beds (samples E84, 86), and becomes thin-bedded or slabby from samples E87-96. Facies in this sequence remain mud-supported for thick to thin beds, with the exception of sample E87 which contains some sparry areas. E98 (Fig. 3-12g, p. 114) is an example of the mud-supported facies above the thinning-up sequence, in the last of the thicker beds prior to the lower thin-bedded subzone at E105-113.

Biotic Character of Lower Thick-Bedded Subzone

Petrographic Fossil Diversity decreases slightly in this lowest part of Zone VI, possibly due to an increase in mud-supported facies after the thick sand at the top of the previous zone (Zone V). The overall diversity is, nevertheless, relatively high, with only one sample having a diversity lower than 10. Algal diversity in particular continues to be high, with Girvanella, Nuia, and dasycladacean algae present (Fig. 3-5b, p. 70). This subzone marks the last sequence with a relatively diverse algal flora until the last thick-bedded part of this zone (VI). Only Girvanella continues into the sediments of the intervening thin-bedded and middle thick-bedded subzones. Bryozoan diversity erratically declines from the previous zone. Phylloporinids, incrusting forms, rhomboroporids, and Coeloclema are very rare.

Arborescent trepostomes, nicholsonellids, heloporids, and Diplotrypa/ Mesotrypa occur only occasionally. Only bifoliates occur with an frequency. Lithistid sponges are a noticeable part of the fauna (E98, Fig. 3-19h, p. 175), as they were in the previous zone. Scattered unidentified tabulate corals, and common impunctate and pseudo-punctate brachiopods are present as is a fairly diverse gastropod fauna (Fig. 3-20e, E84; E80). Bivalves are also a common skeletal constituent as are the usual trilobites, ostracodes, and echinoderms.

Depositional environment. This part of Zone VI has a depositional setting in the euphotic zone and yet deeper than the zone of abundant oncolites at 0-3 m on modern shelves (Ginsburg et al., 1972). The continued presence of dasyclad algae from the top of the preceding Zone V indicates that this subzone was in the euphotic zone. After this subzone, dasyclad algae disappear and do not recurr. If the thick grainstone/packstone beds near the top of Zone V mark the position of wave base on the ramp/shelf, then these beds may have formed in a protected setting. The characteristic abundance of micrite-supported facies in this subzone suggests that turbulence was low for most of the time and that these facies were either deposited in a protected or below-wave base setting. The presence of coated grains and an occasional oncolite in these facies suggest relative proximity downslope (or ramp) from Oncolite-producing shallow shoals. Oncolite beds in fact occur in the middle thick-bedded part of this zone. Since oncolites form in modern carbonate shelves most abundantly from 0-3 m (Ginsburg et al., 1972), this subzone probably

formed at depths greater than 3 m. The environmental significance of the thinning-upward sequence at the top of this subzone is unknown. The thin beds have similar facies to the thick beds, i.e., mud-supported. The increase in bedding planes could represent increasing periods of nondeposition in a quiet water setting. Alternatively, the bedding planes could represent periods of turbulence not reflected in the facies because of early coherence or lithification of the muds, whose cohesion may resist resuspension by periods of renewed turbulence (Blatt et al., 1972).

Lower Slabby Subzone

Unlike the thin-beds in the previously-mentioned thinning-up sequence, beds in the lower thin-bedded sub§one (E105-113) have both muddy and sparry facies. The beds in the thinning-up interval of the previous subzone were clustered mainly into Ecofacies 4 (5 of 6 samples) whereas the slabs in this thin-bedded subzone were classes into various facies (Ecofacies 2, 3, 4, 6, and 7 in Fig. 3-1, p. 59). E106 is an example of the type of sparry facies developed in this subzone. E106 grades from a grainstone at its base to a wackestone top. It was classed in Ecofacies 3 by the cluster analysis and has a bimodal particle size distribution, with larger fossils in a variably sparry matrix of smaller allochems. A few of the larger allochems are horizontally oriented but most have shelter pores beneath them, especially those in the basal sparry portion. Many of the particles have adhered micrite and there are intraclasts and pelloids, all of which suggest reworking. Blackened particles are present and there

are borings in some skeletal particles as well as 1-layer incrustation of larger fossil allochems by bryozoans. This bioclastic layer was deposited on a wackestone.

Sample E109 is an example of a muddy lithology from this subzone (Fig. 3-20f) from a thicker slab (6 cm) than most in the interval, and was clustered into Ecofacies 6. Most of the bed is unfossiliferous mudstone, with a completely muddy packstone layer at the top. Fossils in this layer are horizontally oriented or, in the case of brachiopods, are convex-up. Fossil allochems include thin, umpunctate brachiopods, trilobite fragments, and whole, intact phylloporinid bryozoan fronds. Shelter pores are not present. Both spar and mud-filled burrows are present and are more noticeable in the particle-rich areas.

Most other samples in the subzone resemble one or the other of the two examples discussed above. E107, for instance, has good examples of adhered micrite on fossils, convex-up shells, and shelter pores in a slab of exhumed fossil allochems with a bimodal size distribution (Ecofacies 2). Sample E114 is the only exception. It contains oncolites, including hemispheroidal forms, as well as a muddy matrix with frequent horizontal burrows, abraded allochems, coated grains, and blackened particles. Large nicholsonellid bryozoan colonies are present, with large holes bored in them. E114 is a precursor of facies exposed in the overlying middle thick-bedded subzone of Zone VI.

Depositional environment. The many mud-rich slabs in this thin-bedded zone suggest that water turbulence was low most of the time, the sparry bioclastic layers marking exceptional turbulent events or subenvironments. The lighter brown color of these thin beds and relative scarcity of blackened grains, on the other hand, seem to suggest relatively good circulation. Lighter colors in carbonates indicate less organic matter and probably more oxidizing conditions associated with good circulation (Wilson, 1975). The lack of blackened particles could indicate relatively quick deposition of sediment. In one modern setting of micritic deposition, Florida Bay, blackened particles are usually associated with areas with slow depositional rates (Enos and Perkins, 1979). The frequent thin beds in this subzone could indicate numerous episodes of sedimentation, instead of more uniform conditions implied in thick or massive beds. Frequent episodes of turbulence of influxes of fine-grained sediment could result in turbidity inimical to algal growth. This could explain the scarcity of algae in this subzone, where dasyclad algae, Nuia, and most Girvanella are absent. This subzone immediately underlies the oncolite-rich middle part of Zone VI and itself contains scattered oncolites (e.g., E114). In modern environments, oncolites are most abundant from 0-3 m (Ginsburg et al., 1972). The above features are consistent with a setting of rapidly shifting low mud banks seaward of an oncolite-producing shoal zone. This setting would be deeper than 3 m and characterized by frequent periods of turbidity, possibly due to storms. Skeletal accumulations formed on the windward sides of these mud

banks and in interbank channels, as in modern Florida Bay (Enos and Perkins, 1979). The frequent turbidity and soft substrate were not conducive to algal growth.

Middle Thick-Bedded Oncolitic Subzone

The first major oncolitic zone in the upper part of the Lay School section begins after the lower thin-bedded subzone of Zone VI. The rocks in this subzone (E113-120) are thickly bedded and usually have micrite-rich lithologies. Since they often contain burrowing features, lack oriented particle fabrics, and contain oncolites or coated grains these samples were mainly classified into Ecofacies 4 by the computer cluster analysis. Oncolites range in size from small, coated grains of 1 mm to about 10 mm maximum, with oncolites of 5 mm diameter common. The basal beds of this subzone contain a sparry bed (E113) which may represent a turbulent setting more closely resembling conditions of oncolite formation in modern carbonate regimes than the muddy oncolite facies more prevalent in this zone. E113 (Fig. 3-20g, p. 185) is a grainstone/packstone containing coated allochems and belonging to Ecofacies 5. It is variably sparry and has common shelter pores under its constituent particles, some of which are horizontally aligned. There are some rounded or abraded particles, grains with adhered micrite, some blackened allochems, and micritic allochems. There is a good example of sheltered micrite under an algal-coated phylloporinid sheet or colony (Fig. 3-20g). Echinoderms, trepostome arborescent bryozoans, and especially bifoliate cryptosome bryozoans are the most common skeletal particles, although other fossil groups are represented

(Fig. 3-4, 3-5b, pp. 68, 70). Another basal sparry oncolitic bed is E111, which had two discrete layers. The bottom layer was sparry and contained numerous oncolites and a large, overturned Diplotrypa/ Mesotrypa bryozoan colony about 5 cm in diameter. This sparry layer was directly overlain by a bioturbated wackestone/minor packstone with fairly well-sorted skeletal particles no larger than 2 mm.

The more common oncolitic facies in this zone contains very little, if any interparticle spar in its matrix. On the surface, this seems to be inconsistent with effects expected from modern environments of oncolite formation. Oncolites form today in turbulent waters in the intertidal and shallow subtidal zones, where the prime requisite for oncolite growth its grain agitation and movement (Logan et al., 1964). Thus oncolites in a lime mud matrix must have formed in areas with at least moderate turbulence but were deposited in shallow standing or quiet water (Wilson, 1975). Examples of muddy oncolitic facies in this subzone consist of oncolite beds (E117, Fig. 3-20h, p. 185) or beds with a basal oncolitic layer which grades up to a wackestone or mudstone (E118; E119, Fig. 3-21a). These facies may be rich in blackened grains and the oncolites often have blackened laminae (E119, Fig. 3-21a). Allochems in these facies are often abraded, degraded, and fragmented. Those features, and the concentric laminae of oncolites and coated grains suggest both considerable grain movement and preburial grain exposure at the sediment-water interface (Johnson, 1960). Long preburial exposure of sediment particles is equivalent to a slow rate of deposition, which is also suggested for these allochems

Figure 3-21. Thin-section photographs of Ecozone VI, Wardell Formation.

A. Thin-section photograph of oncolitic sample E119, displaying blackened and coated particles in basal portion. Grades up to a burrowed wackestone. Ecozone VI, Wardell Formation. Arrow marks up direction. Bar is 1 cm long.

B. Thin-section photograph of burrowed mudstone E125. A thicker bed from the upper thin-bedded subzone, Ecozone VI. Wardell Formation. Bar is 1 cm long.

C. Thin-section photograph of sample E126, Ecofacies 6. Sheltered micrite under convex-up shells in lower sparry layer. Gastropod-rich layer present over middle muddy layer. Thin-bedded subzone, Ecozone VI, Wardell Formation. Bar is 1 cm long.

D. Thin-section photograph of muddy packstone E131, showing convex-up shell orientation. Upper thin-bedded subzone, Ecozone VI, Wardell Formation. Bar is 1 cm long.

E. Thin-section photograph of E135, showing convex-up shells and horizontal fossils in lower portion. Grades up to mudstone which is disconformably (unconformably?) overlain by laminated, burrowed calcareous silt. Thin-bedded subzone, Ecozone VI, Wardell Formation. Bar is 1 cm long.

F. Thin-section photograph of E140, upper thin-bedded subzone of Ecozone VI. Laminated calcareous silt with horizontal burrows unconformably(?) overlying mudstone. Ecofacies 2. Wardell Formation. Bar is 1 cm long.

G. Thin-section photograph of E142, showing a basal oncolitic, a middle laminated, and an upper wackestone layers. Ecozone VI, Wardell Formation. Bar is 1 cm long.

H. Thin-section photograph of E149 showing multigeneric grain coatings (algal?), articulated bivalves, and a jumbled particle fabric. Ecofacies 5, Ecozone VI, Wardell Formation. Arrow marks up direction. Bar is 1 cm long.

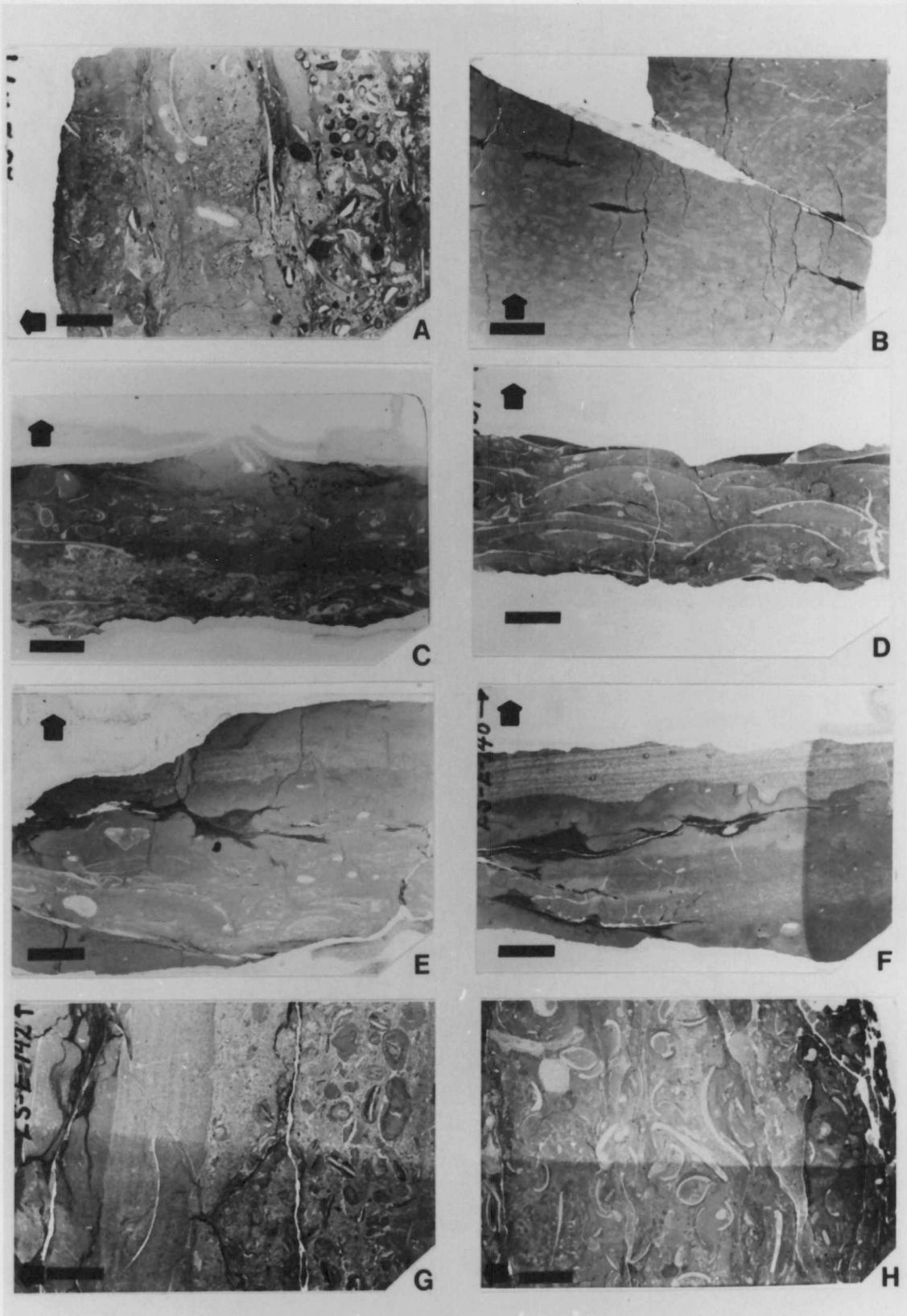


Figure 3-21.

by the presence of blackened particles (a feature of areas of low rates of deposition in Florida Bay; Enos and Perkins, 1979). Since some of these blackened oncolitic layers grade up into wackestones (E118, 119) whose particles are not blackened, it may be that the oncolitic layers represent lag deposits of small channels or pond edges which were buried by fines as the channel or pond migrated and the lag area was abandoned. Thus, the turbulent environment characterized by grain movement and slow accumulation was replaced by standing water and rapid, though episodic fine-grained sediment accumulation. One such modern depositional setting in which oncolite-floored channels occur is the tidal channel system developed bankward or leeward of oolite shoals in the Bahamas (Bathurst, 1975). There, sediments which accumulate in the lee of shoals become increasingly fine-grained away from the shoal. These sands and muddy sands are cut by tidal channels which are filled with variable thicknesses of sand and contain oncolites, often averaging 5 mm in diameter. Between major tidal channels, small ephemeral channels occur within the stabilized sand flat that are actually just topographic lows that localize water movement (Harris, 1979). Water depths on the sand flats are from 1-2 m, while the active tidal channels range from 2-4 m deep. Although the sediments in this part of the Lay School section were not deposited in an oolite shoal environment, this modern back-shoal complex is an example of an oncolite-forming area characterized by more turbulent, oncolite-forming channels and less turbulent interchannel areas where some oncolite deposition occurs. In a like manner, sparry oncolitic samples

such as E111 (bottom) and E113 could represent the passage of major tidal channels which produced the bulk of oncolites in this environment. Muddy oncolitic samples, such as E117, E118, and E119, many represent passage of minor ephemeral channels or ponds adjacent to major channels.

Upper Thin-Bedded Subzone

The thick oncolitic beds in middle Zone VI are followed by the upper thinly bedded interval (E121-140). Lithologies in this interval include mudstones (samples E121, E125) (Fig. 3-21b), laminated calcareous siltstones (E127), laminated calcareous siltstones which grade into mudstones (E137), and various combinations of sparry bioclastic layers with mud-rich layers.

These samples are all lighter-colored than those of the previous interval and contain facies clustered into Ecofacies 2 (E121, 125, 127, 137, 140), Ecofacies 3 (E130, 135), Ecofacies 6 (E124, 126), and Ecofacies 7 (E131). See Appendix D, Table D-1, for the table of the features in this closely sampled interval.

The examples of mudstones in this interval (E121, E125) are remarkably free of skeletal allochems. E125 (Fig. 3-21b) contains numerous mud-filled burrows 1-2 mm in diameter, horizontal or subhorizontal in orientation, and filled with lighter-colored mud than the surrounding substrate. Not far above E125 is the thin bed of sample E126, which contains separate layers of mudstone, muddy packstone, and sparry packstone (Fig. 3-21c). The basal sparry packstone contains fossils with adhered micrite, convex-up shells, horizontal

particles, and frequent shelter features. Shelter features include shelter pores and good examples of fossils sheltering micrite or mud from sparry lithologies which overlie those fossils. The muddy packstone layer is composed mainly of intact gastropod shells and unbroken trilobite segments. At its base, some fossils are horizontally oriented or convex-up (especially ostracode valves, another common constituent). This fossil layer grades up to a mudstone. These features suggest that this fauna was indigenous to a quiet water habitat with a relatively firm mud substrate which was commonly swept by small turbulent channels containing transported fauna as well as reworked indigenous fossils (e.g., gastropods and brachiopods with adhered mud). Other completely muddy packstones occur at samples E131 (Fig. 3-21d), E132, and E135 (Fig. 3-21e). These also have a high proportion of convex-up shells and horizontal particles. Other packstones in this subzone have layers which grade up into mudstones (E124, 126, 132, 135). This suggests that the passage of small, ephemeral channels, pond edges, or other possible turbulent sub-environments was common in this environment. Another characteristic of this environment is the lack of calcareous algae. Most of the samples lack coated grains or oncolites and only E126 contains any Girvanella (Fig. 3-6b, p. 73). Dasyclad algae last appear in E102 in the lower thick-bedded portion of Zone VI.

Another facies which appears in this upper slabby subzone is the laminated calcareous silt, which first occurs at E127, just above the sparry and muddy packstone E126. Laminated silts are developed over

erosive surfaces on mudstones in E127, 135 (Fig. 3-21e), and E140 (Fig. 3-21f). E137 begins with a laminated silt and mud, and grades into a mudstone. Laminae in all of these samples lack fenestral cement-filled pores, cracks, or other subaerial features. Most laminae are not disrupted by bioturbation, although some samples contain mud-filled horizontal burrows (e.g., E127). Convex-up shells and horizontal particles are common when larger particles are present (e.g., E127).

Depositional environment. This thin-bedded interval consists of mudstones, thin muddy packstone layers, sparry packstone layers, and laminated calcareous siltstones. There are two basic associations of facies: a mudstone-muddy packstone-sparry packstone group and a siltstone or siltstone and mudstone association. These facies associations may represent two subenvironments of a setting generally characterized by algal scarcity and light brown color. The lighter color is a result of less dispersed organic matter, which may be a result of oxidizing conditions (Wilson, 1975). The lack of algae in the lower thin-bedded interval was previously postulated to be a result of frequent turbidity and that reason may also apply to this subzone. Another possibility is that some environmental factor related to water circulation, such as salinity, could have been involved. The stratigraphic position of this subzone is in the midst of an oncolite-bearing interval. As previously mentioned, oncolites are found in very shallow subtidal marine waters (0-3 m; Ginsburg, in Ginsburg et al., 1972). The rocks in the overlying Zone VII contain features such as fenestral

mudstones, mudcracks, bidirectional cross-lamination, and laminated sediments are often found in present day peritidal settings. Thus, this portion of the Lay School section displays features consistent with a progressive shallowing-up section as do many other sections in the upper Chickamauga Group in this strike belt (Sickafoose, 1979; Ashworth, 1982). An increase in salinity could have characterized the increasingly shallower environments in this section and would have left little trace in the sediments. Notably, petrographic fossil diversity declines dramatically in the next zone (VII) and is above 10 in only 3 of 10 samples in this thin-bedded interval (Fig. 3-4, p. 68; Appendix D, Table D-5). Salinity is an important factor in the distribution of calcareous algae (Wray, in Ginsburg et al., 1972) as well as the distribution of other benthic organism (Levinton, 1982).

The mudstones with variably sparry packstone layers seem to represent a subtidal muddy bottom habitat of normally quiet water conditions. This mud bottom attained firmness or coherence relatively quickly and a mobile epifauna of gastropods, trilobites, and ostracodes roamed over it. Relative firmness is suggested by the sharp contacts between muds and other lithologies (e.g., E127, 135, 140) as well as packstone layers which define bedding planes where sharp contacts are missing (e.g., samples E126, 132, Fig. 3-21c). In some areas, brachiopods colonized the bottom during quiescent periods. Episodically, turbulent events would transport, concentrate, or exhume this indigenous fauna as well as bring in more fine-grained sediments to settle out of suspension. These turbulent episodes caused shells to

assume a common convex-up attitude and other fossils to lie flat or horizontal. Despite burrowing in many samples, bioturbation was not extensive enough to disrupt those primary depositional features. This could also be related to the light color of the rock, since it implies less dispersed organic matter in sediment (Wilson, 1975).

The other facies association in this subzone is that of mudstones and laminated lime silts and sands. These could have developed during a drop in sea level or as a result of regression, where the quiet water mud flats were capped by laminated sediments which show the effects of shallow water turbulence. These sands and silts contain planar laminae which are occasionally interrupted by mud-filled horizontal burrows (e.g., E127, 140, Fig. 3-12f, p. 114) and lack any cement-filled fenestral fabrics. Horizontal burrows are a common feature of subtidal sediments (Walker and Laporte, 1970). Since fenestral pores ("birds-eyes") are indicative of subaerial exposure of carbonates in the intertidal or supratidal zones (Shinn, 1968), their absence in this subinterval also supports a subtidal setting for these rocks. Sorting of sediment particles, as in the laminated sands and silts, implies grain transport by currents or turbulence (Johnson, 1960) and may suggest a very shallow subtidal setting. Millimeter lamination, for instance, occurs in several subenvironments in the tidal flat complex of western Andros Island, Bahamas (Hardie et al., 1977). Planar lamination of lime sands and silts may occur in the shallow subtidal portions of grainy shallowing-up intervals overlying bioturbated lime mudstones and underlying intertidal deposits in some ancient

carbonate shoaling sequences (James, 1979). Once these sandy shoals became inactive, they were burrowed, sometimes obliterating the primary lamination. Samples E127 and E140 contain some mud-filled burrows in the laminated grainy portions (Fig. 3-21f, p. 194).

The planar laminated lime sand deposits in this subinterval are associated with oncolite beds as well as mud layers. Sample E142, for instance, is the first bed in the overlying oncolitic thick-bedded top of Zone VI. E142 is a transitional sample, containing a basal oncolitic layer, a middle laminated silt, and an upper lime wackestone (Fig. 3-21g). Since oncolites are most common in modern setting from the lower intertidal zone to subtidal depths of about 3 m (Ginsburg, in Ginsburg, 1972), this suggests that the laminated deposits also occurred in that depth range. The close association of these three sediment types in one bed indicates their past close lateral proximity, following Walther's Law (1898). These facies could represent the sequence of subenvironments resulting from the passage of a small oncolite-floored ephemeral channel of low relief, with the basal oncolite layer representing the channel floor, the laminated silt representing the channel levee, and the wackestone representing the interchannel low areas or subtidal "ponds." As previously mentioned, oncolite-floored tidal channels occur in the very shallow subtidal areas to the lee of oolite shoals and islands in the present day Bahamas (Harris, 1979; Bathurst, 1975). Thus this upper thin-bedded interval of Zone VI may have formed in a near-shore setting of subtidal mud flats, thin lime-sand shoals, and oncolite-floored tidal channels which lay offshore from the sediments which form the overlying Zone VII.

Upper Thick-Bedded Subzone

The uppermost portion of Zone VI is thick-bedded and oncolitic. The most frequent ecofacies in this subzone is No. 4 (samples E145-148) which is characterized by jumbled particle fabrics, lack of shelter features, micritic matrices, oncolites, and burrow features. In addition to oncolites and coated grains, this upper portion of Zone VI has particles with multilayered incrustations (e.g., E149, Fig. 3-21h, p. 194). These features result from biogenic modification or diagenesis of skeletal particles at the sediment-water interface (i.e., in an epifaunal setting) and suggest a relatively long preburial exposure time (Johnson, 196). The epifaunal biogenic diagenesis feature summary curve in Fig. 3-6b (p. 73) indicates that particles in the middle and upper oncolitic subintervals had more such "exposure" diagenesis on average than those in the preceding Zones V and IV. This fact is consistent with increased particle exposure time due to turbulence-related particle movement associated with an increasingly shallower depositional setting. The concentric nature of oncolites and some multiple-layer incrustations is also consistent with particle transport or agitation and differs from the epifaunal incrustations in Zone V (Benbolt Fm.) which have few multiple incrustations (2, 3-layered) or oncolites. Instead, Zone V has a high proportion of single-layer incrustations on skeletal grains and loose, or apparently unattached, single bryozoan sheets (Fig. 3-3b, p. 64). These features are associated with others which suggest much less particle transport (e.g., a high proportion of whole fossils, often with delicate features preserved).

Another aspect of Ecofacies 4, present in samples in this and the other thick-bedded portions of Zone VI is the occurrence of bioturbation features. Those can be seen as the Burrow Feature Group (No. 4) in Fig. 3-3b (p. 64) or as the Infaunal Biogenic Diagenesis summary curve in Fig. 3-6b, p. 73. Mud-filled horizontal burrows, spar-filled ones, and churned or swirled particles are present in these micritic samples of Zone VI and become rare above E149 (i.e., in Zone VII). As reported by Rhoads (1967), subtidal burrowing infauna move laterally through the sediment, leaving burrow mottling with an overall horizontal orientation. The presence of these horizontal burrows in Zone VI, therefore, suggests a subtidal depositional setting. Furthermore, the rapid disappearance of these bioturbation features in the overlying strata implies a change in environments.

Another facies present in this upper subzone of Zone VI which contains features consistent with substantial particle transport is Ecofacies No. 3 found in sample E144 (Fig. 3-22a). This sample contains a bimodal or polymodal particle size distribution, shelter features (including sheltered mud), skeletal particles with adhered micrite, and many horizontal and convex-up brachiopod shells. The presence in this oncolitic zone of horizontal fossils is an exception to the relation seen in the stratigraphic distribution of R-clustered feature groups (Fig. 3-3a,b) that oncolites and horizontal particles usually do not occur together. In fact, this rule is true for the rest of this interval above sample E144 since none of the other oncolitic samples (E145-149). have horizontal fossils (Fig. 3-3b). E144 is at the

Figure 3-22. Photomicrographs and thin-section photographs of Ecozones VI and VII, Wardell and Bowen Formations.

A. Thin-section photograph of E144, showing bimodal particle size distribution, adhered micrite on fossils, and sheltered micrite. Ecofacies 3, Ecozone VI, Wardell Formation. Bar is 1 cm long.

B. Photomicrograph of E158, showing long-tubule alga (Sphaerocodium?) and bimodal particle size distribution. Ecofacies 3, Ecozone VII, upper Wardell Formation. Bar is 1 mm long.

C. Thin-section photograph of E154, showing matrix channel pores (cement-filled) under and around fossils in bioclastic layer which grades up to a ripple-marked mud. Ecofacies 3, Ecozone VII, upper Wardell Formation. Bar is 1 cm long.

D. Photomicrograph of matrix-channel pores (cement-filled) in Sample E154. Pores are interparticle, extend beyond possible shelters, and have smooth, graded floors. Ecozone VII, upper Wardell Formation. Bar is 1 mm long.

E. Thin-section photograph of E155, showing erosive ripply developed over nearly planar-laminated calcareous silt. Ecofacies 2, Ecozone VII, upper Wardell Formation. Bar is 1 cm long.

F. Thin-section photograph of E157, displaying herringbone cross-lamination of calcareous silt. Possible U-shaped burrow (B). Ecofacies 2, Ecozone VII, upper Wardell Formation. Bar is 1 cm long.

G. Thin-section photograph of E158, displaying basal bimodal layer, middle laminated calcareous silt, and upper bryozoan layers. Worm tubes (W) present in center of bryozoan zooecium. Ecofacies 3, Ecozone VII, upper Wardell Formation. Bar is 1 cm long.

H. Thin-section photograph of reddish, laminated mudstone E159, displaying broken layers and chips. Ecofacies 2, Ecozone VII, Bowen Formation. Arrow marks up direction. Bar is 1 cm long.

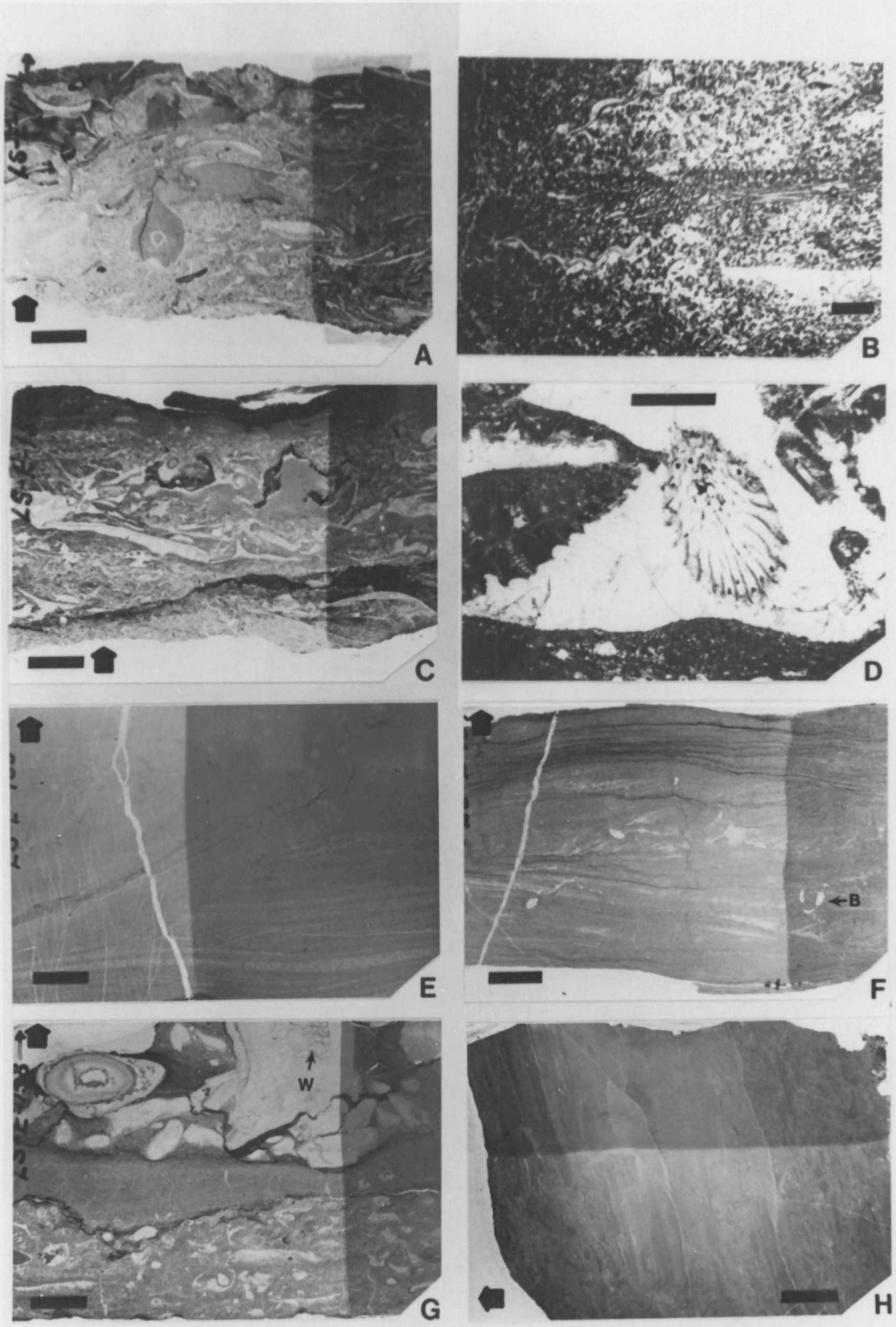


Figure 3-22.

base of this upper subinterval and is nearest E142, which also has horizontal particles. It may be that oncolites form in settings of more continual agitation than those in which horizontal fabrics are generated.

Biologic Character of Subzone

This uppermost part of Zone VI is the last interval of the Chickamauga Group at Lay School to have a relatively high Petrographic Fossil Diversity (Fig. 3-4, p. 68). Only one sample (E142) has a PFD less than 10. By contrast, the preceding thin-bedded subzone has 6 of 11 samples with PFDs less than 10 and the overlying Zone VII has only 3 of 14 samples with diversities greater or equal to 10. As noted in Walker and Laporte (1970) diversity of marine organisms decreases from offshore subtidal environments to tidal flat environments. Thus, the diversity of fossil organisms found in this subzone is consistent with a completely subtidal depositional setting, while the succeeding Zone VII may have been deposited in a different environment.

This subzone witnesses a recurrence of fossilized calcareous algae from the previous thin-bedded subzone (Fig. 3-5b, p. 70) and contains multigeneric oncolites similar to those found in upper Zone IA and IB. In addition to cryptalgal and girvanellid algae, complex oncolites and grain coatings contain a larger tubule, sometimes incrusting alga also found in the lower interval samples (Fig. 3-22b) in upper IA and IB zones. Sample E149, for example, contains large algal-coated particles up to 15 mm in length and which display a

variety of stromatolitic forms, such as LLH-S (digitate), LLH-C, and SH forms, as classified in Logan et al., 1964. A few samples above the mud-pod zone in Zone III also have coated particles with these stromatolitic forms (see C32, Figs. 3-14c, 3-15a, pp. 139, 142). Other algal types include Hedstroemia sp. and Nuia. This presence of several types of calcareous algae suggests that the depositional setting was in the euphotic zone and probably quite shallow, a conclusion consistent with the occurrence of oncolites in modern carbonate environments (Logan et al., 1964; Ginsburg, in Ginsburg et al., 1972). The dramatic reduction in algal variety and abundance after Zone VI suggests a change in depositional environments. A final biotic feature of interest in this subzone is bed E149 which contains abundant, articulated pelecypods (Fig. 3-21h, p. 194). These are robust, small bivalves which range in apparent height in thin-section from 5-7 mm and apparent thickness from 4-5 mm. They occur in a micritic matrix containing multigeneric oncolites and coated grains, commonly abraded fossils, and fossils incrusted by bryozoans and fossil algae (Girvanella and the unknown incrusting type, previously mentioned and possibly that type called Sphaerocodium in Weiss, 1981). Other fauna include punctate and pseudopunctate brachiopods, incrusting bryozoans, worm tubes, and gastropods (one of which is incrusted by bryozoans in Fig. 3-21h).

Environment of Deposition

A depositional setting similar to that of the middle, thick-bedded oncolitic interval is suggested for this upper interval. Most samples

contain similar grain types indicating extensive particle movement, such as abrasion and fragmentation of fossils, concentric incrustations, and oncolites. The greatest distinction between samples in this subzone is in the nature of the matrices, which may be sparry and contain a smaller-sized fraction of fossil and nonfossil particles (bimodal or polymodal character) or may be micritic or muddy. An overall setting in the shallow subtidal zone was suggested previously by the bioturbation in micritic samples, lack of fenestral pore fabrics, generally high fossil particle diversity, and frequent presence of calcareous algae. More specific geomorphic settings can be inferred from those features which are related to water turbulence. Rocks with sparry matrices suggest sufficient water turbulence for the removal of carbonate fines (Dunham, 1962). Additionally, oncolites are known to form in relatively turbulent settings in modern carbonate environments, from depths of 0-3 m generally (Ginsburg, in Ginsburg et al., 1972). One such setting is in shallow tidal channels in the stabilized sand and oolite habitats leeward of oolite shoals and islands (Bathurst, 1975; Harris, 1979). There, oncolites form on channel floors and may be transported to stabilized interchannel flat areas where they are deposited. Furthermore, those interchannel settings may have localized oncolite accumulations in more ephemeral depressions and topographic lows (Harris, 1979). By analogy with the above examples, sparry oncolitic facies present in this upper interval of Zone VI (e.g., E142, 144, 145) could represent more active or established tidal channels where the bulk of the oncolites were formed. Micritic facies,

on the other hand, could have formed in the interchannel areas where oncolites and other grains resulting from continuous agitation were episodically deposited. These shallow interchannel areas, in turn, were probably sufficiently agitated to continue some epifaunal particle modification or degradation such as algal grain coatings and yet sufficiently quiet most of the time to allow deposition of carbonate mud and deposition of pyrite on reworked particles near the redox potential discontinuity (RPD). The stratigraphic position of this interval below the relatively unfossiliferous sediments of peritidal aspect in Zone VII suggests a setting just offshore of a zone of tidal flats.

Stratigraphic Position of Zones V and VI

The Benbolt Formation in equivalent strike belts in western Virginia is up to 100 m thick and consists of interbedded whole fossil limestones and terrigenous mud rock (Read, 1980). The formation is a dark, nodular and argillaceous wackestone and mudstone elsewhere in Virginia, where the carbonate nodules are separated by stylolitic seams as they are in the Lay School section. Algae are generally absent except near the base and the top of the unit.

Tennessee exposures of the Benbolt Formation in the Hunter Valley Allochthon occur at Evans Ferry, 13 miles northeast of Lay School at Hogskin Valley. The Benbolt Formation at Evans Ferry is a nodular or cobbly-weathering unit containing micritic and argillaceous lithologies with a massive, cross-bedded calcareous sand ("Unit A") about 30 m from the base. The lower portion of the formation is more evenly argillaceous than the upper, while the upper part contains

intervals of pure carbonate separated by shaley beds. Algae are sparse in most of the lower parts of the formation. Dasyclad algae appear at about the middle of the unit and near its top. Oncolites first occur in the upper 10 m of the Benbolt. The top of the formation was placed below a horizon rich in oncolites (up to 75%). This oncolitic bed was considered the base of the Wardell Formation. All of the above information is from Sickafoose (1979).

This study follows the precedent set at Evans Ferry and places the top of the Benbolt Formation below the first major oncolitic horizon at E111. The Stanley Farm section lacked exposures of oncolite horizons and the formational boundary was placed at the level where bedding changed from cobbly-shaly to massive (Ashworth, 1982). The base of the Benbolt Formation was placed at the beginning of mud-supported lithologies at C70. With such formational boundaries, the Benbolt at Lay School attains a thickness of 90 m. In terms of the ecologic zones defined in this study, the Benbolt encompasses parts of two zones (IV, VI) and all of one zone (V) (Fig. 3-1, p. 59). The lower part of the Benbolt lies approximately in the upper half of Zone IV and includes the dasyclad grainstone (D17) and skeletal packstones (D19, 20) that appear in the middle of the otherwise mud-supported facies in D Section. The middle part of the Benbolt contains the entire Zone V, with its nodular mud and wackestones separating skeletal packstone layers and the thicker sands and muddy sands at E54-57. The upper part of the Benbolt lies in Zone VI and includes the first thick-bedded subzone at samples E76-103 and the

first thin-bedded interval at E103-111. Calcareous algae in the Benbolt, thus defined, occur in the lower part (samples D16-19) and the upper portions (samples E42-102). The Benbolt Formation at Lay School, therefore, contains several zones of facies with different environmental characters.

Zone VII: General Characteristics and Ecofacies

The uppermost ecologic zone of the Chickamauga Group at Lay School begins at a point (sample E152) where the nature of bedding in the carbonate rocks change. Below E152, bedding is characterized by lumpy bedding planes which are stylolitic surfaces containing clay minerals and dolomitic stylocumulate. Even massively bedded strata contain numerous such stylolitic seams which, upon weathering, cause disintegration of beds into lumpy slabs or crumbly nodules. Above E152, bedding planes become sharp, flat, or planar and there is a separation of clay-rich shales into distinct, fissile beds rather than evenly dispersed, wavy-bedded stylolitic seams within carbonate beds. Accompanying this change in bedding style are lithologic changes from oncolitic and skeletal muddy packstones and wackestones to finely laminated and cross-laminated mudstones, siltstones, and occasional bioclastic packstone beds. Silt-sized dolomite crystals become more common and in hand specimen, some carbonate layers may appear sugary or finely-crystalline. Shale beds increase in abundance upwards in this zone and continue up to the red, laminated mudstone beds at sample E159 (the Bowen Formation). Both thin-medium bedded

carbonates and shales occur from E159 up to a more thickly-bedded sequence above E163. Carbonate layers commonly have gently undulose or rippled bases and flat tops. E163 is the first fenestral dismicrite or mudstone sample from the zone. Above E163, there are fewer shale beds and more thin to medium bedded calcareous mudstones with occasional bioclastic layers, such as E165 (Fig. 3-23d). A thick interval of reddish residuum with scattered, weathered slabs follows sample E165 and continues for an estimated 30-35 m. This was considered to be the Moccasin Formation of the Chickamauga Group and no samples were taken from it since the objective of this study was to characterize the environments of the pre-Moccasin formations of the Group. Reddish mudstone and yellow shale beds follow the covered interval of residuum and contain mudcracks.

Zone VII is characterized by the presence of sedimentary structures and well-sorted sediments. Rocks with these features were placed in Ecofacies 2 by the Q-mode or sample clustering process. Zone VII, therefore, has the majority of its samples in Ecofacies 2 (Figs. 3-1, 3-2, pp. 59, 63). These include planar laminated rocks (E159, 163), rocks with gently undulose lamination or ripples with very low height (E153, 162), and rocks with several types of cross-lamination (E154, 155, 156, and 157). Another common Ecofacies in this zone is Ecofacies 3 (Fig. 3-2). Ecofacies 3 samples share a bimodal or polymodal particle size distribution, with a normally sparry matrix of well-sorted small skeletal and nonskeletal particles and a larger size fraction of mostly fossil particles (Fig. 3-22b, p. 205).

Figure 3-23. Photomicrographs, thin-section photographs, and field photographs of Ecozone VII, Wardell and Witten Formations.

A. Photomicrograph of ostracode valve accumulation in silty mudstone E160. Ecozone VII, Witten Formation. Bar is 1 mm long.

B. Thin-section photograph of bioclastic layer in E161, containing intraclasts (I), matrix channel pores (cement-filled), and bimodal size distribution. Grades up into faintly laminated mud. Ecofacies 3, Ecozone VII, Witten Formation. Bar is 1 cm long. Arrow marks up direction.

C. Thin-section photograph of dismicrite E163, displaying cement-filled laminoid and tubular fenestrae. Ecofacies 2, Ecozone VII, Witten Formation. Bar is 1 cm long.

D. Thin-section photograph of E165, displaying horizontal fossils, convex-up shells, sheltered micrite, and cement-filled matrix channel and moldic pores (upper layer). Ecofacies 3, Ecozone VII, Witten Formation. Bar is 1 cm long.

E. Photomicrograph of worm tubes (Spirorbis?) incrusting mollusk fragment (moldic), E158. Ecozone VII, upper Wardell Formation. Bar is 1 mm long.

F. Photomicrograph of screening of perched sediment, i.e., progressively less infiltered blackened grains perched on shelters in a downward direction. Bimodal sediment of E154. Ecozone VII, upper Wardell Formation. Bar is 1 mm long.

G. Field photograph of uppermost Witten Formation, Ecozone VII. Measuring rod is 1.8 m long.

H. Photomicrograph of shelter phenomena, burrows, and fecal pellets, sample E126. Fecal pellets (P) preserved in shelter pore under sheltering brachiopod (B). Spar-filled burrow (S) and mud-filled burrow (M) present. Wardell Formation. Bar is 1 mm long.

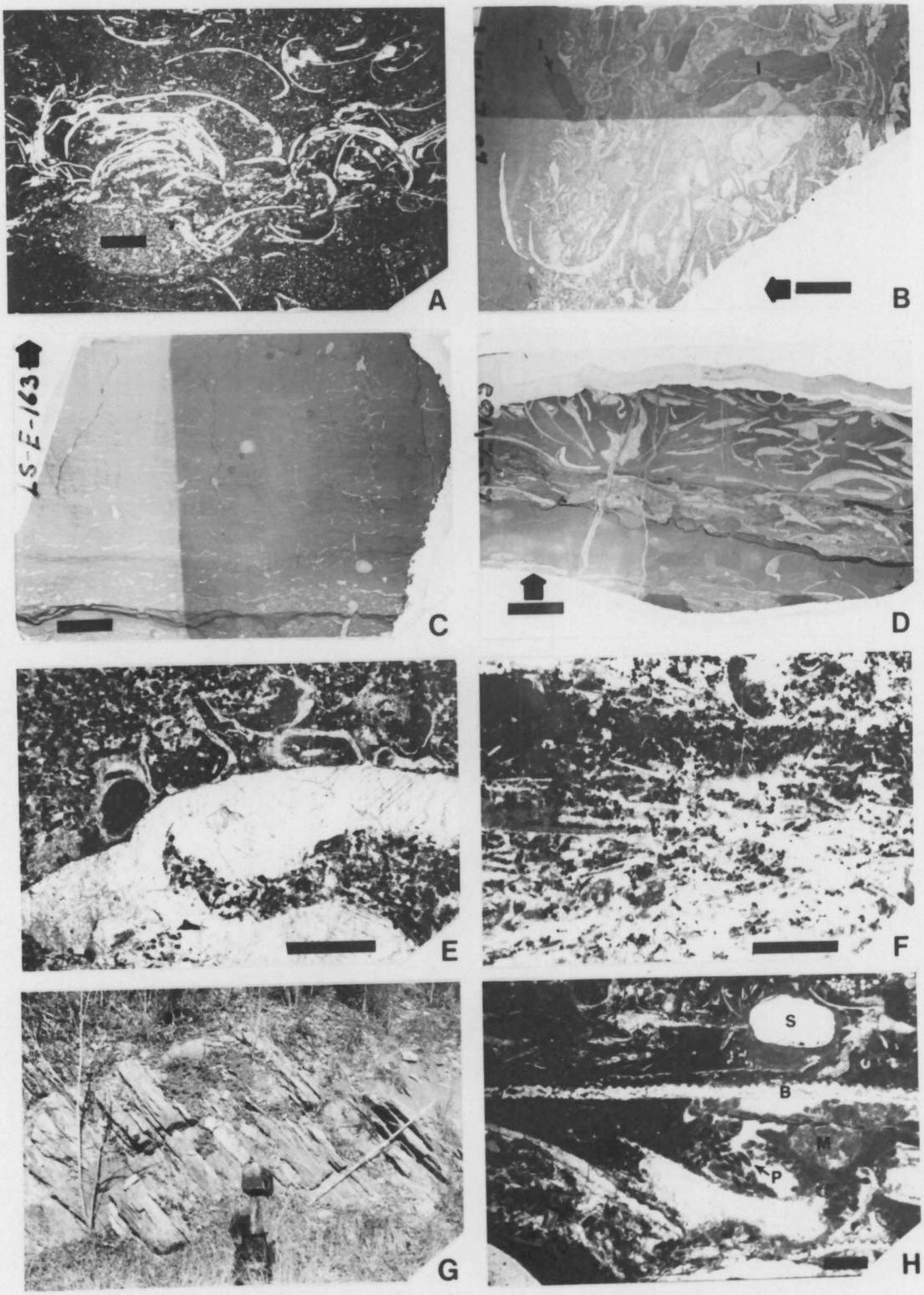


Figure 3-23.

Shelter features and horizontal fossils may also be present (see Table 2-1, p. 55, for a summary of features). Most of the bioclastic layers in the zone belong to this ecofacies (E154, 158, 161, 165). Zone VII most resembles the lowermost Zones IA and IB in having the majority of its ecofacies in Ecofacies 2 and 3 (Fig. 3-2, p. 63).

The lower half of Zone VII seems to be especially characterized by planar and cross or ripple lamination. After the basal mudstone of sample E152, almost planar, slightly undulose laminations are developed over convex-up brachiopod shells in the mudstone E153. Not far above, slab E154 (Fig. 3-22c, p. 205) contains coarser fraction fossils (brachiopods, bryozoans) with a matrix of silt-sized particles, pelloids, and areas of mud. This bioclastic part of the layer has cement-filled matrix channel pores washed from under and around the larger fossils (Fig. 3-22d). These pores have graded silt floors and extend beyond possible sheltering fossils. The layer grades up to a ripple-marked mud at the top of the bed. The ripple length (L) is 7 cm and height if 5-10 mm, following the classification of Reinick and Singh (1975). The rippled upper surface contains even smaller ripples or undulations whose length varies from 3 or 4 mm to 1 cm and which are covered by a clay layer. The clay layer is thickest in the trough of the larger (7 cm) ripple. Clay drapes over ripple marks are a feature which suggests small scale alternations in slack water and strong currents which are characteristic of tidally influenced sediments (Ginsburg, 1975, p. 92).

Next in the series of laminated rocks is amples E155 (Fig. 3-22e), which is an example of a laminated mudstone with an erosive ripple

(using terminology of Reinick and Singh, 1975) scoured out of nearly planar laminations of mud and silt. The mud laminae filling the trough so formed are form-concordant and become nearly planar at the top of the bed. The erosive ripple has a stoss side horizontal projection (L1) of 5.8 cm and a height of 1.5 cm.

Sample E156 is a mudstone with ripples of a different nature. These consist of many small, low-angle forsets of mud and silt which dip in several directions. Scoured troughs and small channels (1-2 cm) are present, as are horizontal, mud-filled burrows. Small, sometimes rounded mud fragments appear in some silt cross-laminae. Channels, scours, and mud fragments can suggest alternating erosion and deposition characteristic of peritidal settings (Ginsburg, 1975, p. 92). Unfortunately, contacts between many ripple-laminated layers are obscured by stylolites.

The last type of ripple lamination encountered in this lower half of Zone VII occurs in sample E157 (Fig. 3-22f, p. 205). This consists of long (6-7.5 cm) laminae, inclined at low angles to the horizontal, which contain numerous short (2-5 mm) forset laminae that dip in opposite directions. The close association of alternate cross-laminae dipping in opposite directions qualifies these as "herringbone" cross-laminae, although not of the kind usually illustrated (i.e., with equally-developed sets of laminae). Herringbone cross-bedding where opposite-dipping cross-laminated layers are separated by a thin mud layer is typical of tidal environments (Reinick and Singh, 1975). Ginsburg (1975) also characterizes herringbone cross-lamination as

diagnostic of siliclastic tidal flat settings. The modified herringbone laminations in this sample give way to planar laminated mud in the upper portion of the bed. A possible small, U-shaped spar-filled burrow is present in the cross-laminated portion of E157. This type of burrow may also be indicative of a peritidal setting (Walker and Laporte, 1970).

An interesting example of a bioclastic bed developed in this rock sequence below the red mudstone E159 (Bowen Formation) is sample E158 (Fig. 3-22g, p. 205). This rock consists of three layers of different lithologies. The basal layer is a bimodal biopelsparite with frequent shelter pores under the larger-size fossils, horizontally-oriented fossils, and incrustations by bryozoans and worm-tubes on skeletal allochems. The middle layer is a laminated, silt-sized biopelsparite which occurs over an erosive contact with the basal layer. The upper layer consists of large (e.g., 2 cm diameter) arborescent trepostome bryozoan colonies incrusted by worm tubes in a biopelsparite matrix. These bryozoan colonies lie in all orientations and thus are not in living position. These three facies are dominated by transported grain features (e.g., good sorting, bimodality, lamination, horizontal fossils) and their close vertical proximity in thin-section suggests a close lateral association of their environments (Walther, 1894), as in subenvironments of a channel.

A convenient point which divides Zone VII into lower and an upper half is the short sequence of red mudstones of which sample E159 (Fig. 3-22h) is a part. These reddish mudstones occur in a

1.8 m interval of cream-weathering shale and are easily distinguishable from the light gray carbonates and shales above and below them. In thin-section, this mudstone consists of laminated cream and red-colored mud layers which are often broken into areas of laminated chips. At Evans Ferry, the reddish clastics which appear in the otherwise gray-colored carbonates below the Moccasin Formation was called the Bowen Formation and that convention is followed here. The Bowen Formation of Stanley Farm consists of 5.8 m of tan to yellowish brown calcareous mudstone and shale (Ashworth, 1982).

An example of the strata which overlie the red mudstone beds is the unlaminated calcareous mudstone bed of sample E160, whose chief feature of environmental significance is its concentration of numerous ostracode shells (Fig. 3-23a). Further discussion of this biotic feature is reserved for the following treatment of the Zone VII biota.

Sample E161 (Fig. 3-23b) provides an illustration of the type of bioclastic layer which is separated by almost featureless mudstones (e.g., E162) in this upper half of Zone VII. This bed is mainly a biointrapelsparite which grades upward into a faintly laminated micrite. Larger particles are bioclasts of several types and nonlaminated intraclasts which occur in a matrix of silt-sized pelloids, dolomite grains, detrital quartz, and carbonate skeletal grains. Cement-filled moldic pores occur in and around the common mollusc fragments (usually bivalves) and some channel pores with graded silt floors also are present under and around larger allochems. Intraclasts are composed of pelmicrites, contain dolomite rhombs, and some have

cement-filled vug or fenestral pores. Moldic porosity develops primarily in the freshwater phreatic zone of diagenesis (Longman, 1980). Intraclasts are products of erosion and redeposition, processes which are characteristic of intertidal depositional environments due to rapid changes in current or wave velocity (Ginsburg, 1975). Intraclast formation can also be related to subaerial exposure, which causes hardening of the carbonate sediments into crusts that may be broken by later flooding in the peritidal setting and redistributed in intertidal or supratidal environments (Ginsburg, 1957; Walker and Laporte, 1970). No edge-wise or intraformational conglomerates were observed in this upper section of Zone VII as they were in Zone I level strata in B-section and in Jarvis Hollow, southwest of Lay School in Hogskin Valley. These intraclastic facies are diagnostic of the intertidal zone (Ginsburg, 1975).

Following the faintly laminated mudstone E162 which overlies bed E161, is the fenestral mudstone or dismicrite E163 (Fig. 3-23c). This rock contains cement-filled laminoid fenestral pores, using the fenestral pore terminology of Read (1973). Tubular pores, usually vertically oriented and irregular or vuggy pores (all cement-filled) are present as well. Many of the laminoid pores are long, with matching roofs and floors, and parallel the faint lamination of the mudstone. Fenestral pores, or "birds-eyes," are diagnostic of intermittent subaerial exposure and occur in intertidal and supratidal zones of tidal flat settings (Shinn, 1968; Walker and Laporte, 1970; Ginsburg, 1975).

Sample E164 is an unlaminated carbonate mudstone with a thin, irregular layer of mostly small fossils, including trilobites, ostracodes,

bivalves, gastropods, and worm tubes. Many of these are unabraded, whole, or articulated. The last sample in Zone VII is E165 (Fig. 3-23d, p. 214) which is a bioclastic slab composed of three layers and comes from beds just prior to the reddish soil-covered interval (Fig. 3-23g). E165 has several features in common with E161. The matrix in all three layers is pelmicrite, biopelmicrite, or a biopelintrasparite which grades upwards to a pelmicrite. Silt-sized dolomite is present. In all three layers there are common horizontal or convex-up fossils and shells (brachiopods, bivalves). Especially in the upper layer there are pores under these fossils which extend out beyond overlying shelters to pores under other fossils. Since these mainly occur under fossils, they may have originated as shelter pores but were enlarged and extended by winnowing or solution to become matrix channel pores as in E161. Some mollusc fragments are cement-filled, solution enlarged, moldic pores. Other features of significance include mud-filled and spar-filled burrows and fecal pellets.

Biologic Character of Zone VII

The diversity of fossil particles in Zone VII declines drastically despite bioclastic layers with Petrographic Fossil Diversities at or near ten (e.g., E154, 158, 161, 164, 165) (Fig. 3-4, p. 68). The lack of larger skeletal allochems in many of the calcareous mud and siltstones result in low diversities for those samples and cause the averaged diversity curve to be quite low. Low taxonomic diversity may be a reflection of the physiological stress placed upon organisms by the

environment (Sanders, 1968). Environmental factors which can effect marine benthic diversity include temperature, turbulence, turbidity, salinity, desiccation, oxygenation of waters, and trophic resource supply (Smosna and Warshauer, 1978). As mentioned in the discussion of the previous zone, diversity of organisms typically decreases when going from a normal, open circulation subtidal marine environment to a peritidal setting (Walker and Laporte, 1970).

The diversity and abundance of calcareous algae parallels the decline in overall diversity in Zone VII (Fig. 3-5b, p. 70). None of the major algal types present in the preceding zone occurs in this zone with the exception of the algae characterized by tubules much larger than Girvanella but which may also adopt an apparently unorganized growth mode (Fig. 3-22b, p. 205, E158). This alga may incrust other particles, as in examples in Zone I (Fig. 3-9e, p. 93, A60), or may form separate masses, as in E158, Fig. 3-22b. Although the alga at the bottom of the section may be a different type than that of this zone, they share the characteristic that the tubules are equivalent in size to those of Solenopora Type R (Nelson, 1978) or Hedstoemia but are of a less organized aspect. The tubules may extend up to 7 mm in length without bifurcating. The algal mass in E158 consists of a central axis of long tubules around which is wrapped an outer layer of tubules (Fig. 3-22b). In some respects the algal bodies of this type resemble algal specimens categorized as Sphaerocodium by Weiss (1981), which also occurred at a high level in the Chickamauga section. The only other algal types recorded in this zone are the appearances of Solenopora in E158 and E160.

Biotic elements which are important in this zone include brachiopods, bivalves, ostracodes, trilobites, worm tubes, and occasionally bryozoans. Sponges are absent and gastropods less numerous than in the previous zone, although examples occur in E164 and E165. Bivalves remain an important part of skeletal accumulations, though bioclastic layers in general decrease in abundance. Bryozoan diversity declines as does the algal diversity (Fig. 3-5b, p. 70) and bryozoans are not important contributors to skeletal sediments with the exception of the previously mentioned large arborescent trepostomes in sample E158 (Fig. 3-22g, p. 205). The central portion of the largest zooarium in this sample also contains worm tubes (Spirorbis sp.?). Worm tubes increase in abundance in this zone and a good example is shown in Fig. 3-23e, p. 214. They occur in 6 of 14 thin-sections (or 42.8%) in Zone VII compared to 6 of 44 thin-sections (or 13.6%) in Zone VI. Incrusting bryozoans occur only twice in Zone VII (Fig. 3-7, p. 76) and considering that worm tubes normally occur in this life mode, it may be that worm tubes (Spirorbis?) replace incrusting bryozoans in that niche in this part of the Chickamauga Group section.

Arthropods, such as trilobites and ostracodes, attain a more important proportion of the fauna in this zone by virtue of the reduction in number of other phyla. Ostracodes especially, become a major part of the fauna in some rocks, such as sample E160 (Fig. 3-23a). E160 is a pelintrabiomicrite of relatively low diversity (P.F.D. = 6) that contains numerous ostracode valves and some calcareous algae. Since Zone VII is also typified by a generally low diversity, it may be

that the environmental conditions that were present in E160 and the zone were too rigorous or stressful in some way to allow many types of organisms to flourish. Yet, if food resources are available, some types of organisms (e.g., opportunists or pioneer species) evolve the necessary adaptations to tolerate rigorous environments and take advantage of food resources. One such adaptive strategy to utilize uncontested food resources is a high fecundity, which results in large populations of such organisms (i.e., r-selection) (Valentine, 1973). Tidal flat environments typically have large populations of a few species that can take advantage of trophic resources, such as algae (Walker and Laporte, 1970). The calcareous algae present in E160 hint at the presence of such primary producers in the Zone VII environment, and there may have been other algal types that were not preserved (e.g., noncalcified forms).

Environment of Deposition

There are two categories of environmentally relevant features that have been observed in Zone VII--sedimentologic and biologic. Some sedimentologic features suggest a very shallow subtidal depositional milieu while others are consistent with a tidal flat setting. There are several types of ripple lamination in the zone, especially in the lower half. Small mud ripples of low height (<5 mm), or slightly undulose lamination, occur in E153 and E162. Mud ripples of greater height (10 mm) and length between crests (7 cm) cap a bioclastic bed at E155, where clay layers drape over the ripples. Bedforms or stratification such as ripples or cross-lamination are indicative of subtidal

deposition (Ginsburg, 1975). Clay drapes over ripplemarks, however, suggest small scale alterations in slack water and strong currents which are characteristic of tidally-influenced sediments (Ginsburg, 1975). Sedimentologic features which suggest formation in an intertidal setting include erosive ripples (E155) and small scale scours and channels (Ginsburg, 1975). These result from alternating deposition and erosion characteristic of tidally-influenced environments. Herring-bone cross-lamination, present in E157, forms from rapid changes in current direction, as occurs in tidal flat settings (Reinick and Singh, 1973).

Other features commonly found in tidal flat environments are present in the upper half of Zone VII. Fenestral pore fabrics, or "birds-eyes," result from the intermittent exposure of carbonate sediments to the air and are characteristic of the intertidal and supratidal zones of tidal flats (Shinn, 1968). These occur in E163. Intraclasts are a product of deposition, erosion, and redeposition and as such, are characteristic of peritidal settings (Ginsburg, 1975). They may also be generated by subaerial hardening and desiccation of sediment, followed by reworking due to intermittent flooding of tidal flats (Ginsburg, 1975). Intraclasts occur in E161 and the red laminated mudstone E159 contains broken layers and numerous small, laminated chips.

The preservation of sedimentary structures and bedforms in carbonates is itself unusual for offshore subtidal sediments unless they are continually reworked by turbulence (Walker and Laporte, 1970;

Anderson, 1974). Usually, primary depositional features such as structures or infiltration textures (e.g., Fig. 3-23f, p. 214) are destroyed by bioturbation unless abnormal salinities preclude sediment-eating infauna (Walker and Laporte, 1970). This could be the case for this zone, since the diversity of fossils is low, and high salinity is a factor which causes a decline in diversity (Smosna and Warshauer, 1978). On the other hand, no indications of high salinity in the rocks have been observed, such as evaporites or salt casts. Thus the preservation of the primary depositional structures in this zone may be due to the lack of a normal, soft-bottom deposit-feeding benthos because of the desiccating nature of a tidal flat setting or any of several other factors which fluctuate greatly in that environment.

Several features of a biologic nature in the rocks on Zone VII are consistent with a tidal flat depositional setting even if they do not prove it. The deline in fossil diversity from the previous zone is consistent with an environmental change from a subtidal offshore or lagoonal situation to a tidal flat setting, especially when the sedimentologic criteria are also considered. The decline in diversity and abundance of calcareous algae in this zone suggests a change from offshore, subtidal marine conditions. Finally, the occurrence of large populations of a single taxon is a biologic characteristic of tidal flat communities or other high-stress environments (Sanders et al., 1962). This results from the ability of some tolerant organisms to exploit a food resource denied to most normal marine organisms by means of a high rate of fecundity (Valentine, 1973). The large number of ostracodes in E160 may be an example of this phenomenon.

Stratigraphic Position of Zone VII

Ecologic Zone VII encompasses three regional formations of the Chickamauga Group, as defined in the introductory chapter. Following the conventions used by Sickafoose (1979) at Evans Ferry, 13 miles northeast of Lay School, the base of the Wardell Formation is placed at the first major oncolite horizon, sample E111. The top of the Wardell Formation in other regional studies of the Chickamauga Group is placed at the first, usually thin, reddish mudstones or other clastics below the Moccasin Formation known as the Bowen Formation (e.g., Sickafoose, 1979; Weiss, 1981). Thus the top of the Wardell Formation is the base of the 1.8 m thick unit of reddish mudstones previously mentioned as the Bowen Formation. This makes the Wardell Formation 40 m thick at Lay School. Its lower portion lies in Zone VI and is characterized by the middle thick-bedded subzone (E11-120, the upper thin-bedded subzone (E120-140), and the upper thick-bedded subzone (E140-149). The second or upper half of the Wardell is typified by rocks of a different character--the thin to medium bedded carbonate mud and siltstones with sharp or planar bedding and common sedimentary structures (i.e., the features of Zone VII).

The Bowen Formation consists of a 1.8 m interval of cream-weathering shales and laminated red mudstones (E159). The Bowen Formation at Evans Ferry is thicker (8 m) than that at Lay School. In southwest Virginia, the Bowen ranges from 0-23 m in thickness and consists of brown-weathering calcareous sandstone and red terrigenous mud rock in the lower part of the Witten Formation (Read, 1980).

The Witten Formation is here defined as the strata between the lower red mudstone horizon and the thick zone of reddish-brown residuum above E165. So defined, the Witten Formation is around 40 m thick at Lay School and has thin to medium bedded well-sorted carbonates and shales with occasional bioclastic layers and sharp bedding planes. The Witten Formation at Evans Ferry at 132 m thick is thicker than that at Lay School. At its thickest in equivalent strike belts in southwestern Virginia, the Witten formation is over 50 m thick (Read, 1980). The covered interval of reddish residuum and the overlying red beds were considered to be of the Moccasin Formation and beyond the scope of this study.

CHAPTER 4

SUMMARY OF ECOZONES, ECOFACIES, FORMATIONS, AND ENVIRONMENTS

The sequence of Chickamauga Group rocks exposed at Lay School, Hogskin Valley, present facies characteristic of increasingly deeper water marine environments from the base of the section to the Benbolt Formation (Ecozone V) (Fig. 4-1).

Tidal Flat Zone

Ecozone Ia, the Blackford Formation, begins with well-sorted, pink biosparites (Ecofacies 1) developed over the Knox Unconformity. A coastal tidal flat suite of ecofacies includes: laminated mud and siltstones (Ecofacies 2), dismicrites of fenestral mudstones (Ecofacies 2), bimodal biosparites (Ecofacies 3), and dark, cherty argillaceous mudstones (various facies). The well-sorted biosparites (Ecofacies 1) and bimodal biosparites (Ecofacies 3) represent more turbulent settings of the coastal tidal flat environment, such as beaches, near-shore sand bars, tidal channel bars, etc. Laminated mudstones and siltstones occurred in intertidal and supratidal settings in a tidal flat zone as did the light-colored fenestral dismicrites.

Lagoonal Zone

The bases of sequences that grade up to the island facies (Ic) of Ecozone I contain rocks of Ecofacies 1, 3, 4, and 5. These rocks occupied a lagoonal position (or Ecozone Ib) with respect to the

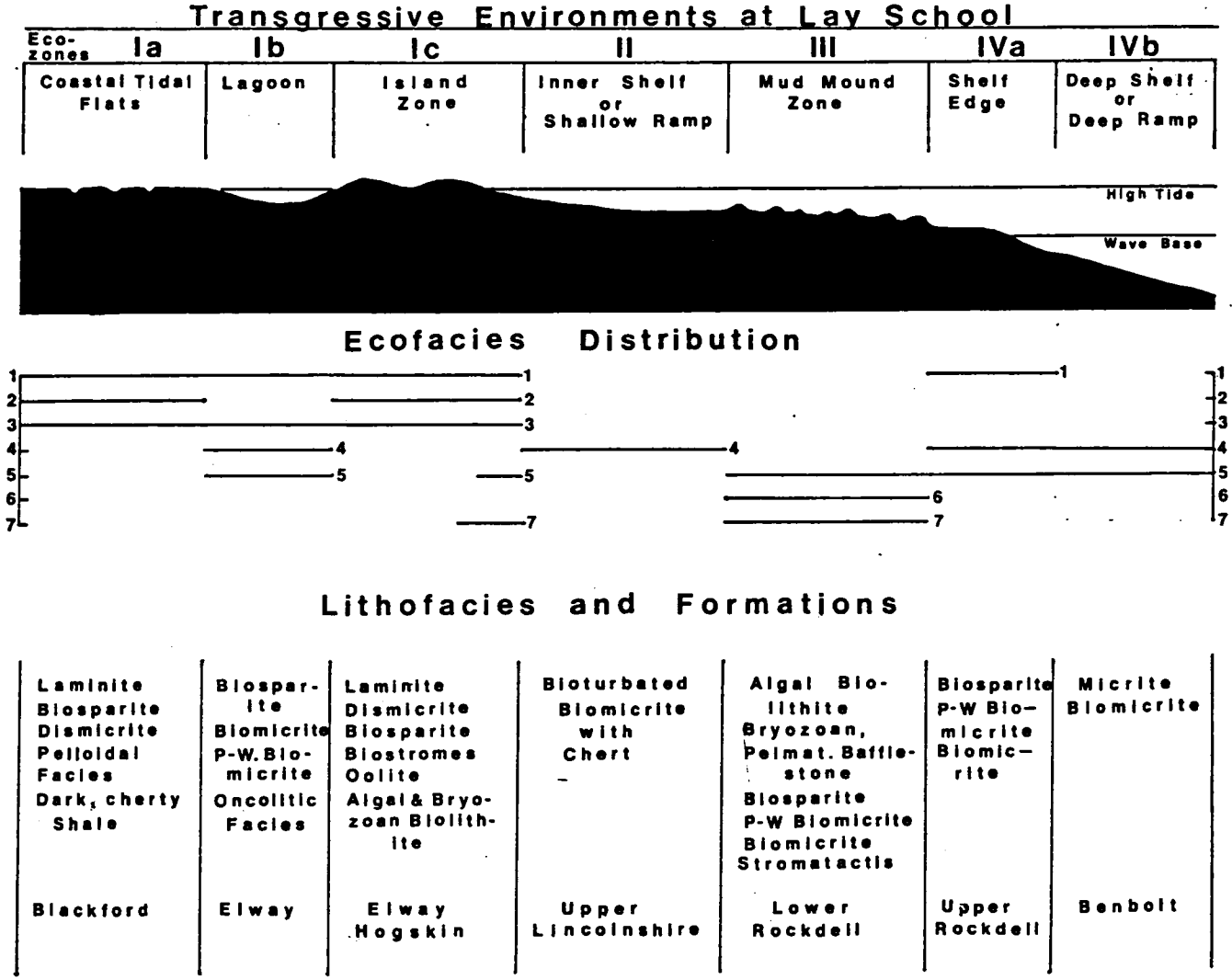


Figure 4-1. Ecofacies, lithofacies, and formations representing transgressive environments of the Chickamauga Group at Lay School.

overlying island ecozone. A typical sequence begins with Ecofacies 1 biosparites, that is, well-sorted and well washed skeletal sands. Ecofacies 3 samples follow that have a larger, poorly-sorted skeletal fraction, coated grains, some particles with adhered micrite, horizontal grains, and possibly remnant micrite preserved under shelters. The succeeding ecofacies are more micritic and poorly-sorted, and may or may not have primary depositional features preserved (Ecofacies 4 and 5).

Island Zone

The lagoonal series of facies is replaced by those of increasingly shallower aspect until replaced by intertidal-supratidal facies of the island ecozone (Ic). In terms of ecofacies, this is reflected by an increase in better-sorted, more sparry facies that retain primary depositional features (Ecofacies 3). These are succeeded by laminated mud and siltstone with vertical burrows, and dismicrite (both of Ecofacies 2).

The island facies are closely followed by a variety of facies that may have represented windward island fringe and inter-island environments. Inversely graded and other types of biosparites (Ecofacies 1 and 3) reflect the presence of continuously turbulent settings such as beaches, spits, and skeletal sand bars. Some of these agitated environments produced the only oolite bed in the Lay School section. Interfingered with skeletal sands are algal biolithites or boundstones which constitute Ecofacies 7, an ecofacies characterized by organisms and textures suggestive of in situ organic growth. Bryozoan

boundstones, bryozoan-pelmatozoan holdfast intergrowths, and spongiostrome-algal boundstones occur in this horizon. Associated with the above boundstones are more massive, lamellar incrusting stromatoporoid biostromes with both smooth-sided and irregular cavities in the upper surface which contain endocerid cephalopods. The cephalopods as well as other bioclastic cavity fill were colonized repeatedly by pelmatozoans, sponges, and bryozoans. In addition to Ecofacies 1, 3, and 7, this shallow subtidal, near-island subzone contains poorly-sorted fossils, oncolites, multiple bryozoan/algal concentric incrustations, and a varied algal flora. Ecofacies 5 samples of this type are variably sparry.

The lagoonal subtidal to inter/supratidal island sequence is typical of the Elway Formation or member of the Lincolnshire Formation. The varied island-fringe, near-island facies and lithologies are associated with the Hogskin or Elway-Hogskin members of the Lincolnshire Formation.

Inner Shelf or Shallow-Ramp: Ecozone II

The muddy facies present in rocks in this ecozone are subtidal sediments deposited in a normally quiet water, above wave base setting. Ecofacies 4 is the typical facies in this zone, and its major characteristic is intense bioturbation. Lithologies present are wackestones and fine-grained packstones (biomicrites) with common chert nodules. Other features include much fragmentation and apparent abrasion of fossils, poor to moderate sorting, micritic (algal?) coats on particles, occasional oncolites, blackened grains, and no

primary depositional features (e.g., shelter phenomena). These characteristics are very similar to the Lincolnshire Formation as exposed in southwest Virginia. This zone is called the Upper Lincolnshire Formation. The abundance of carbonate mud in a shallow, above-wave base setting suggests some form of seaward protection from open marine turbulence, either in the form of physical barriers to circulation or a considerable distance of shallow shelf or ramp.

Mud-mound Zone: Ecozone III

Micrite-rich pods with algal and biotic boundstone (biolithite) surrounded by variably sparry bryozoan-pelmatozoan sands overlie the bioturbated facies of the previous ecozone. These are sediments of the lower Rockdell Formation. The mud-pod facies (Ecofacies 7) contains algal-crust frameworks encompassing spar-filled cavities of several types. Some cavities have flat floors with graded sediment and digitate or irregular roofs. Radiaxial cement, possibly a recrystallized early fibrous marine cement, partially lines some cavities, whereas other cavities are completely filled with blocky, equant cements. Incrusting and bifoliate bryozoans and incrusting pelmatozoan holdfast systems are common. Sponges also occur, along with stromatolitic cryptalgal forms, spongiostrome algal forms, Girvanella, and dasycladacean algae.

Interfingering with and flanking the mud-pods are variable sparry bifoliate and rhomboporid bryozoan and pelmatozoan sands of Ecofacies 6. These facies commonly show horizontal grain orientation and shelter phenomena such as shelter pores and sheltered micrite.

Cement-filled matrix channel pores occur around some fossil particles, which include pelmatozoan holdfasts and other ossicle types, and cement-filled moldic porosity may also be present.

These mud-pods or mounds resulted from a combination of algal growth with concomitant early lithification and colonization by incrusting and binding benthic suspension-feeding organisms. Flanking sands consist of particles of these organisms and surrounding thickly inhabited areas of stalked or arborescent suspension feeders which were variably transported after death depending on the local topography. Migration of local sheltering topography caused variable winnowing and reworking of deposited skeletal grains. This zone of organically-controlled early lithification probably exerted some influence on bottom currents in a shallow shelf setting and may have aided in the formation of the previous muddy bioturbated zone.

Shelf-edge or Outer Ramp: Ecozone IVa

The upper Rockdell Formation represents quiet-water conditions or protected settings punctuated by turbulent environments which culminate in the thick sand near the top of the lower half of the zone. Quiet-water settings had sediments with Ecofacies 4 characteristics, that is, muddy packstones with bioturbation features and few primary depositional features. More turbulent environments yielded partially winnowed and reworked sediments of Ecofacies 5 (with poorly-sorted grains, variably sparry matrices, and shelter phenomena). The most turbulent conditions resulted in better-sorted sands (Ecofacies 1 and 3) with interparticle and shelter porosity as well as horizontal

particles. These turbulent environments occurred three times in the lower half of Ecozone IVa. This ecozone has a diverse algal flora.

Deep Shelf or Drowned Ramp: Ecozone IVb

The upper part of Ecozone IV, mainly field section D, represents a progressively quieter water setting indicated by the increase in fine-grained, mud-supported facies. Occasionally, sparry skeletal sand bodies occur, such as a dasycladacean algal grainstone (sample D17). This part of Zone IV lies in the Benbolt Formation. Mud-supported facies include Ecofacies 4 (with burrow Features), and Ecofacies 2 samples. The skeletal sands include the well-sorted Ecofacies 1 (samples D16, 19) and Ecofacies 5 (D17).

The mud-supported, fossil-poor facies in this part of Ecozone IV suggests a depositional setting which lay below wave base. Despite the occurrence of dasyclad algae in a few horizons, algal abundance and diversity declines in this subzone. This suggests that the sands near the top of the lower subzone (Ecozone IVa or upper Rockdell Formation) marked the position of wave base on the deepening ramp or drowned shelf. Thus the sediments of this subzone after the thick sand was deposited in an increasingly deeper water setting on a drowned shelf or ramp.

Rocks of the Chickamauga group exposed at Lay School display facies characteristic of increasingly shallower (or regressive) environments from the Benbolt Formation (Ecozone V) to the top of the Witten Formation (Ecozone VII) (Fig. 4-2).

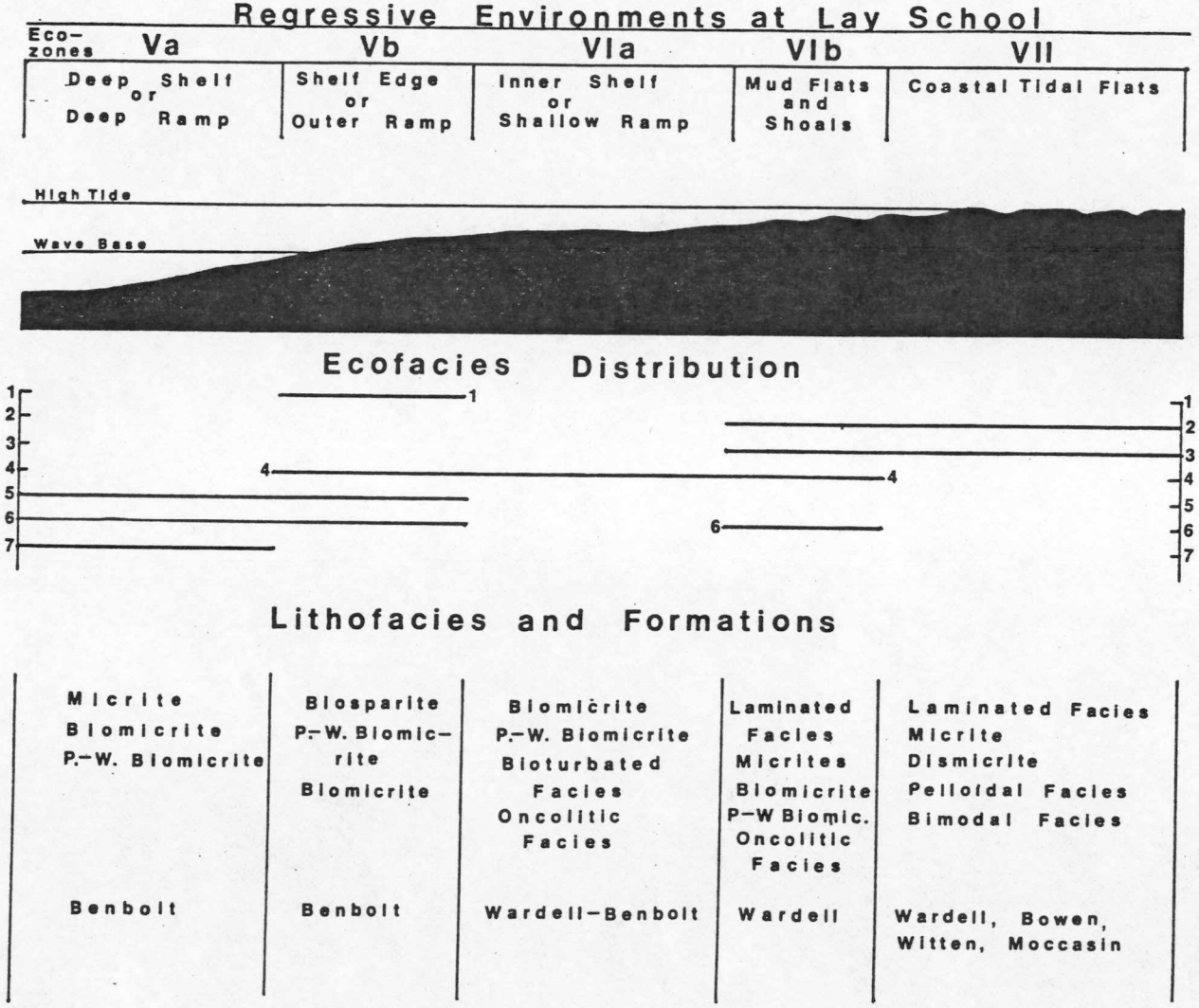


Figure 4-2. Ecofacies, lithofacies, and formations representing regressive environments of the Chickamauga Group at Lay School.

Deep Shelf or Drowned Ramp: Ecozone Va

Rocks of the lower to middle Benbolt Formation are primarily micrites and sparse biomicrites (wackestones) with occasional to common bioclastic layers of variably sparry packstones. Clay minerals are common and form abundant stylolitic layers. Algal diversity and abundance is low.

Ecofacies 6 is common in this zone in many of the bioclastic packstones. These are poorly-sorted skeletal layers with frequent 1-layer incrustations and whole, unabraded fossils. Many fossils have adhered and infilled micrite while micritic coatings (algal?) or envelopes are uncommon. Spar-filled burrows, often with fecal pellets, are the most frequent burrow feature. Shelter phenomena are characteristic of the facies, with both shelter pores and sheltered micrite present. Articulate brachiopods commonly occur, along with pelleted mud preserved under shelters. Horizontal fossils are present in some examples.

Another frequent facies found in poorly-washed skeletal layers in this zone is Ecofacies 5, which is less likely to have horizontal particles than Ecofacies 6. Shelter phenomena are also common, as are incrustations, adhered and infilled micrite, and intraclasts or micritic masses with irregular shape and ill-defined boundaries. A variety of other facies occur, often in mud-supported lithologies, including bioturbated rocks classed as Ecofacies 4 and those with pelmatozoan holdfasts classed in Ecofacies 7.

These ecofacies and frequent mud-supported lithologies suggest a setting below wave base that was quiet most of the time. Bioclastic

layers were of two origins: those reworked and redeposited after little transport, and those consisting of shallower sediments which occasionally moved downramp over muddy bottoms into quieter regimes.

Shelf-edge or Outer Ramp: Ecozone Vb

Sparry sediment layers increase up section and culminate in the medium to thick grainstone/sparry packstone beds at samples E54-57. The graded biosparite bed E56 is of Ecofacies 1 and has rounded and abraded grains, blackened particles, intraclasts, and horizontal fragments. Ecofacies 6, 5, and 4 also still occur. Algal diversity increases in this part of Zone V. These features indicate a shallowing up to wave base in this part of Ecozone V which could mark the Chickamauga shelf edge or effects of wave base on the outer ramp.

Inner Shelf or Shallow Ramp: Ecozone VIa

The uppermost part of the Benbolt Formation and the lower Wardell Formation lie in Ecozone VI, or the lower part of that ecozone. This sequence has thick and thin-bedded intervals, with the thick-bedded strata representing muddy, bioturbated inner shelf or shallow ramp sediments. These are fossil-rich rocks in which mud-supported facies are also common. Yet clay content is reduced from the previous ecozone, as shown by thicker carbonate beds. Ecofacies 4 rocks are most common in this zone. Characteristics of the facies, in addition to common burrow features, includes frequent coated (algal?) grains, increasing numbers of oncolites, poor sorting, whole and unabraded fossils, borings in fossils, and the richest algal flora in the upper half of the Chickamauga section.

This zone occupies a position similar to that of the thick-bedded, muddy and bioturbated Ecozone II in the transgressive, lower part of the section at Lay School. Both ecozones lie adjacent to shallow subtidal sediments with frequent sedimentary structures, oncolites, and well-sorted rocks (i.e., Ecozone Ic and Ecozones VIb and VII).

Subtidal Mudflats and Shoals: Ecozone VIb

The Wardell Formation begins with an oncolite-rich, thick-bedded interval with characteristics listed in VIa above. Just below that oncolite horizon and above it, are thin-bedded muddy shelly packstones, thin-bedded mudstones, and laminated calcareous siltstones. The laminated siltstones occur over erosive contacts with underlying mudstones or may grade upward into mudstones. These are included in Ecofacies 2. Shelly packstone layers (Ecofacies 6) often have horizontal and convex-up shells in a mud-rich matrix. Some Ecofacies 3 packstones are more sparry, and may have a silt-sized smaller particle fraction in addition to larger fossils. The thin-bedded zones lack Girvanella or grain coatings (algal?), as well as other algae. Biotic diversity also falls in these subzones.

Since these subzones are interbedded with oncolitic layers, yet lack subaerial exposure features (e.g., fenestral mudstones), a very shallow subtidal setting is suggested, in the range of 0-3 m in depth.

Coastal Tidal Flats: Ecozone VII

The upper half of the Wardell Formation have thin to medium beds with sharp, planar bedding surfaces and discrete shale beds separate

from carbonate layers. In the previous two ecozones, even thickly-bedded "pure" carbonate beds had, wavy stylolitic clay-rich seams which gave bedding planes a lumpy character. Upon weathering, these stylolitic carbonates became loose cobbles, nodules, or lumpy slabs.

The well-bedded carbonates and shales include calcareous mud and siltstones, laminated calcareous mud and siltstones, fenestral mudstones, and shales. Silt-sized dolomite rhombs and detrital quartz grains occur. Pelloids, or small, well-sorted micritic allochems are also present. Ecofacies common to this ecozone include Ecofacies 2 (laminated and cross-laminated rocks, fenestral mudstones) and Ecofacies 3 (packstone layers with a well-sorted matrix and horizontal fossils). Several types of cross- or ripple-lamination occur in Ecofacies 2 rocks. Biotic diversity of most of the strata is low, and occasional layers with abundant fossils of a single taxon occur (e.g., ostracodes). Calcareous algae does not commonly occur.

This zone also includes the Bowen Formation, a thin unit of reddish laminated mudstone above the Wardell Formation, and the Witten Formation. The Witten is similar to the well-bedded carbonates and shales of the upper Wardell Formation. Overlying the Witten Formation is a covered interval of reddish soil interpreted as the Moccasin Formation, which is not within the scope of investigations of this study (see, however, Simonson, 1985). All of the units in this ecozone represent a suit of subenvironments present in a coastal tidal flat setting. Subtidal, intertidal, and supratidal features are present.

This ecozone displays the shallowest water characteristics of the regressive or shallowing-up sequence of formations and ecozones of the Chickamauga Group section at Lay School.

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APPENDICES

APPENDIX A

STRATIGRAPHIC DESCRIPTION OF THE LAY SCHOOL SECTION

Measurement Conventions

Bed Thickness

Massively bedded .....greater than .5 m

Thick bedded .....3-.5 m

Medium bedded .....1-.3 m

Thin-bedded .....01-.1 m

Laminated ..... less than .01 m

Grain-size

Coarse grained ..... grains visible to unaided eye and readily identifiable (usually greater than 1 mm)

Medium grained ..... grains visible to unaided eye but unidentifiable (approximately .25-1 mm)

Fine grained ..... grains visible with hand lens (approximately 0.1-0.25 mm)

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

LAY SCHOOL SECTION

The Lay School section is located in Hogskin Valley (Grainger County) near the intersection of the Hogskin Valley Road and the road which lead south to Potato Valley (Powder Springs Quad, 154 SW), Lat. 83°39'24", Long. 36°18'16". The old Lay School is near this

intersection which lies near the center of the top of the southeast quarter of the quad. The Middle Ordovician section is about 450 m thick and is bounded by the Knox/ Chickamauga contact to the northwest and by the Moccasin Formation to the southeast. The Lay School stratigraphic section is a composite section consisting of five component field sections or Parts, named A-E, which are those selected by Carnes and Bergstrom for Carnes' 1975 study with the exception of Part A. Part A, the basal portion, was chosen for its contiguity with Part B. The sequence is described here in ascending order from oldest to youngest, with selected samples listed with measured thicknesses, both from the base of each Part, and cumulatively from the base of the section.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
			KNOX GROUP
			Unconformity
	18	18	CHICKAMAUGA GROUP

Part A begins approximately 20 m above the presumed contact of the Knox Group and Chickamauga Group strata. The contact is not exposed at this locality but can be estimated from the position of the last exposed Knox Group rocks northeast of the creek (and farm road) and the first pink biosparites and reddish shale exposed southwest of the road. The farm road and creek trend NW-SE at this location (Fig. 1-2, p. 4) and cut across the strike of the strata, which dip to the southeast at about 35°, strike N68°E.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
A1-A4	18-19.85	19.85	Blackford Formation. West side of farm road and creek. Reddish

Sample #	Cumul. Thk(m)	Cumul. Thk(m)	Part Section
			medium to coarse grainstone, thin-medium bedded. Red shale and laminated fine grained lithologies. Light gray, thin-medium bedded fenestral dismicrite.
	19.85-21.2	21.2	COVERED INTERVAL
A7-A8	21.2-22.4	22.4	Blackford Formation. Thick to massive beds, light gray, well-sorted grainstone with cross laminae.
	22.4-26.5	26.5	Poorly-exposed interval with small outcrops of dark gray, cherty, thin-bedded limestone.
A9-11	26.5-27.1	27.1	Dark brownish gray, cherty, thin-bedded to laminated limestone.
	27.1-30.7	30.7	COVERED INTERVAL
A12-13	30.7-31.1	31.1	Yellow shale underlying reddish shale and interlaminated red and yellow shale and calcareous siltstone.
			East side of creek and farm road.
	31.1-37	37	COVERED INTERVAL
A14-15	37-39	39	Thick-bedded, light gray or cream colored medium grainstone (A14) which grades upward to a well-sorted fine-grained grainstone with planar lamination.
	40.1-42.4	42.4	COVERED INTERVAL
A18	42.4-42.7	42.7	Yellowish brown shale and calcareous siltstone.
	42.7-57.4	57.4	COVERED INTERVAL
			Blackford Formation is 57.4 m thick.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
A19-24	57.4-60.6	60.6	ELWAY MEMBER. Beginning of section in small woods. Thick to massively-bedded gray wackestones, packstones, and grainstones with frequent wavy, stylolitic surfaces. Weathers cobbly. Oncolitic and fossiliferous.
	60.6-62.8	62.8	COVERED INTERVAL
A25-30	62.8-65.5	65.5	Thick to massively bedded gray wackestones and packstones, oncolitic, fossiliferous.
	65.5-69.2	69.2	COVERED INTERVAL
A32-38	69.2-74.4	74.4	Gray wackestones, thick-bedded, wavy stylolitic surfaces, frequent chert nodules (A32-35). A36-38 medium, fine grainstones with planar and festoon cross-lamination.
A39-43	74.4-78.7	78.7	Thin-bedded to laminated calcareous silt and mudstone, gray to yellowish-brown.
A44	78.7-78.8	78.8	Light gray laminated mudstone bed with 1 cm diameter vertical burrows.
A45	78.8-79.2	79.2	Medium bed of gray mudstone containing common small (less than 3 cm) Maclurites gastropods.
A46-50	79.2-82.2	82.2	Thin-bedded calcareous silt and shale, yellow-brown.
A51-52	82.2-82.7	82.7	Light gray dismicrite interbedded with yellow-brown shale and laminated lithologies.
A53-56	82.7-85.3	85.3	Poorly exposed interval. Bryozoan boundstone float specimens (A<56, A<59) with bryozoans in yellow-brown argillaceous and silty matrix.

Sample #	Cumul. Thk(m)	Cumul. Thk(m)	Part Section
			Thin-beds of coarse grainstone (A53, A56). A56 is last in situ sample in Part A. A60-A60-1, float samples about 5 m (horizontal distance) up hill from A56; contain large oncolites and diverse algal growths. Scattered, poorly-exposed outcrops of thin-bedded to laminated, brownish shales and siltstones up to thrust fault 26-27 m up hill from A56 (horizontal distance).
			Elway Member is 27.9 m thick.

Part B field section. This section is equivalent to Leg II of Carnes' 1975 study. It begins in the bottom of the creek which bisected the two parts of Part A field section. This creek runs parallel to strike (i.e., NE-SW) for a short distance at the northern end of the Part B hill before turning and cutting across strike (i.e., a NW-SE direction).

B1	.6	.6	Elway Member. Laminated calcareous silt with thin chert layers. Beds dip 45°SE, strike N65E.
	.9-5.3	86.2-90.6	COVERED INTERVAL
B2-B3	5.3-6.5	91.8	Laminated calcareous siltstone and mudstone.
B4	7	92.3	Light colored, medium bedded dismicrite.
B6-B5	7.5-7.8	93.1	Thin-bedded, dark gray-brown argillaceous micrite with chert. Interbedded with medium to fine grained, dark limestone.
B7	7.8-11	96.3	Medium-thin bedded, cherty wackestones, packstones.
B8-B9	11-13.8	99.1	Massively bedded mudstones, wackestones, wackestones, packstones. Lower part of massive bed has stained micritic hardground or stained surface (B8). Cherty.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
B10	13.8-15.5	100.8	Thin-medium beds, medium grained packstone with wavy bedding (cobbly weathering).
B11-B17	15.5-26	111.3	Thick-massive beds of cobbly weathering light gray, medium grained packstones-grainstones. Wavy bedding. Cherty near base (B11). Occasional pink fossil grains.
B17-19	26-32	117.3	Cobbly-weathering exposures, bedding possibly thinner (i.e., thin-thick bedded), cherty packstones. Grades into laminated siltstone with vertical and horizontal burrows (B19).
	32-39.5	124.8	COVERED INTERVAL
B20	39.5-41.5	126.8	Thin-bedded calcareous silt and yellow-brown shale. Beds just above covered interval have small folds.
	41.5-44.5	129.8	COVERED INTERVAL
B21-23	44.5-45.5	130.8	Thin-medium bedded sequence of yellowish calcareous siltstone (B21) and intradismicrite (B23).
B24-B25	47-505	135.8	Thin-bedded sequence of light or cream colored grainstone (B24) and oolite (B25).
			Elway Member (B-Part) is 50.5 m thick.
	50.5-60.5	145.8	COVERED INTERVAL containing chips and small float slabs of yellowish-brown shale.
B26-27	60.5-60.6	145.9	Yellowish-brown calcareous silt and gray, dolomitic silt.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
B28-38	60.6-65.5	150.8	Hogskin Member. Stromatoporoid biostrome with cavities filled with endocerid cephalopods, pelmatozoan holdfasts, multiple erosion surfaces (B28-33). Bryozoan boundstone (B34) in places overlies biostrome. Algal-bryozoan boundstone (B35). Encrinite grainstones/packstones (B36-38) which fine upward, have cross-lamination.
	65.5-68.0	153.3	COVERED INTERVAL
B42-64	68.0-77.5	162.8	Thin bedded sequence with occasional medium bed. Becomes poorly exposed near top (B49-50). Coarsely fossiliferous slabs of packstone; oncolitic; large Solenopora and other algal grains present; varied fauna includes brachiopods, bryozoans, Receptaculites.
	77.5-83	168.3	COVERED INTERVAL Hogskin Member is 32.5 m thick.
B66-74	83-85.8	171.1	Upper Lincolnshire Formation. Thick bedded gray cherty wackestones, fine packstones.
B75-78	85.8-100.5	185.8	Top part of Part B field section. Consists of small ledges (at 92.3, 96.6, 98.1, 99.5 m) of gray, cherty biomicrite separated by covered intervals.

Part C field section begins with exposures on the south side of Hogskin Valley Creek, along strike to the southwest of the last exposures on Part B.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
C1-C4	0.0-5.8	191.6	Wooded part of Part C field section. Massively bedded dark gray wackestone, with black chert nodules, dipping 46°SE, striking N55E.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
	5.8-14	199.8	COVERED INTERVAL
C5-C8	14-21.5	207.3	Massively bedded wackestones with black chert nodules.
	21.5-29.5	215.3	COVERED INTERVAL
C9-15	29.5-37.7	223.5	Massively bedded, dark gray wackestone with chert.
			Upper Lincolnshire Formation is 55.2 m thick.
			Rockdell Formation.
C15-16	37.7-43.0	228.8	Thick-bedded, light colored coarse grained biosparites which become increasingly thinner bedded up section. End of wooded portion.
C16-C18	43-44	229.8	Outcrops in field of high grass. Thin bedded, light colored grainstones, sparry packstones, coarse grained (C16). Bifoliate bryozoan wackestone (C18).
C19-22	44-48	233.8	Medium-thick beds of bryozoan-pelmatozoan wackestone/algal boundstones with cement-filled cavities. Interbedded with thin beds of packstone (bryozoan-pelmatozoan).
C22-35	48-64	249.8	Variably-bedded interval of slabby grainstones/packstones and thick to massive beds and boulders of wackestone/packstone, all coarse grained.
C35-38	64-66.5	252.3	Outcrops under a stand of cedars bordering field. Thickly-bedded packstones that weather to slabs.
	66.5-70	255.8	COVERED INTERVAL
C39-51	70-78.5	264.3	Beginning of outcrops by roadcut bordering small gravel parking

Sample #	Cumul. Thk(m)	Part Section Cumul. Thk(m)	
			area. Thin-bedded interval with occasional medium bed. Packstones. B39 is Receptaculites specimen. Wavy bedding planes, slabby weathering, occasional shale partings.
C51-52	78-79.5	265.3	Two thick packstone beds.
C52-58	79.5-82	267.8	Thin-medium bedded with shales interbedded. Packstones, occasional grainstone. Receptaculites specimens C53, C57 in float.
C58-60	82-84.5	270.3	Medium-bedded interval, packstones.
C60-62	84.5-86	271.8	Medium-massive beds. C60 just below massive grainstone/sparry packstone bed (Carnes No. 106). Other beds grainstones/packstones.
C62-63	86-87.5	273.3	Massive, fining-up grainstone bed.
C64-67	87.5-90	275.8	Thin-bedded, increase in wackestones, mudstones. Shaly in places.
C68-70	90-92	277.8	C68 massive mudstone/wackestone bed. Otherwise, thin-bedded, mudstones.
			Rockdell Formation 54.3 m thick.

Part D. The lower part of Part D lies opposite upper Part C on the east side of Hogskin Valley Road in the driveway to an unoccupied farm house and the hillside beside and behind the house.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
			Benbolt Formation.
D1-8	0-4.5	282.3	Beds in lower portion of Part D apparently dip much less than

Sample #	Part Section Cumul. Thk(m)	Section Cumul. Thk(m)	
			previous section's beds--measured dips range from 6°-10°, S-SW, although poor exposures limit readings. Cobbly weathering mudstones-wackestones. Massively-bedded with numerous stylolitic seams.
D9-D10	4.5-5.7	283.5	Massively bedded mudstones-wackestones with chert nodules.
D10-D14	5.7-8.5	286.3	Thin-beds, cobbly weathered zone. Mudstones-wackestones.
D15-17	8.5-11	288.8	Massive bed or ledge. Packstone-grainstone. D17 (10.5 m) is dasycladacean sparry packstone. Dips steepen, beds dipping 35°SE, strike N45-50°E.
D17-21	11-15	292.8	Massive packstone ledges, with frequent stylolitic seams. Cobbly-weathering. D21, 22 are Receptaculites float fragments.
	15-22.5	300.3	COVERED INTERVAL
D27-28	22.5-24.3	302.1	Last ledge in hillside field. Massive beds, cobbly weathering wackestones and packstones.

Part E outcrops begin in roadcut along east side of Hogskin Valley Road. Upper half of Part E is south of intersection with road leading to Potato Valley and also lies on the eastern side of that road (Fig. 1-2, p. 4). Part E begins with outcrops in roadcut almost adjacent to the Lay residence and continues beyond the old Lay School.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
			Benbolt Formation.
E1-19	0-13	315.1	Cobbly-weathering yellowish-brown mudstones and wackestones with

Part Section

Sample #	Cumul. Thk(m)	Cumul. Thk(m)	
			occasional packstone slabs and nodules. Abundant stylocumulate layers between layers and lenses give shaly appearance. Fossils and fossiliferous slabs present in float. Beds dip 30°-45°SE, strike N65-85°E.
	13-16	318.1	COVERED INTERVAL. Interval covered by loose float, bedding obscured. Assume dip of 45°.
E20-27	16-18.3	320.4	Cobbly-weathering shaly mudstone/ wackestone, as before, with occasional packstone. Possible fault, with beds immediately below E27 apparently dipping more steeply than those above. E27 dips less than underlying strata.
E27	18.3-18.6	320.7	Thick bedded grainstone, graded with blackened particles at base.
E28-35	18.6-23.6	325.7	Cobbly-weathering mudstones/ wackestones with occasional packstone layers. Beds dipping near 45°SE.
	23.6-26.5	328.6	COVERED INTERVAL
E36-49	26.5-34.0	336.1	Beginning of more slabby zone, possibly less argillaceous than below. Ripple-marked slab at E45 (33.5 m). Slabs of packstone.
E49-50	34.0-34.6	336.7	Thick bed of packstone/grainstone.
E50-53	34.6-36.25	338.35	Shaly, cobbly limestone.
E53-54	36.25-36.5	338.65	Thick bed of grainstone/packstone.
E54-58	36.5-38.2	340.4	Thinning-up interval of packstones and grainstones (E56) at base to thin beds of wackestone at top. E56 (37 m) is graded bed with blackened particles at base.

Sample #	Part Cumul. Thk(m)	Section Cumul. Thk(m)	
E58-66	38.2-41.1	343.3	Thin-bedded with occasional medium bed of wackestone, packstone.
E66-83	41.1-47.6	349.8	Thick-massively bedded zone of wackestone. Fossiliferous; sponges, gastropods, tabulate corals, brachiopods visible in outcrop.
E83-94	47.6-49.6	351.8	Thinning upward bedding sequence, ending in thin-bedded slabs. E94 (49.3 m) slab with lithistid sponge.
E96-103	49.6-55.4	357.6	Thick-bedded to massive zone with occasional thin-bedded intervals. Wackestones.
E103-113	55.4-68.7	370.9	Thin-bedded interval with many weathered float slabs. Wackestones, packstones.
			Benbolt Formation is 93 m thick.
			Wardell Formation.
E113-121	68.7-72.9	375.1	Thick-massive bedded zone. Oncolites frequent. E113 (68.7 m) grainstone/packstone with oncolites. Muddy oncolite packstones, and packstones that grade up to mudstones or wackestones.
E121-142	72.9-77.6	379.8	Thin-bedded interval. Shell beds common. Some laminated calcareous siltstones, also mudstones.
E142-152	77.6-90.8	393.0	Thick-massively bedded, oncolitic packstones, wackestones with common blackened particles and oncolites. Ending in mudstones (E152). Occasional thin-bedded or more deeply weathered intervals.
E152-159	90.8-111.6	413.8	Zone of medium-thin beds with sharp, flat bedding plane surfaces. Discrete shale beds interbedded

Sample #	Cumul. Thk(m)	Cumul. Thk(m)	Part Section
			with carbonate layers. Mostly mudstones or calcareous siltstones with occasional packstone layers (e.g., E154, 93.8 m, packstone slab with ripple-marked top).
			Wardell Formation is 42.9 m thick.
			Bowen Formation.
E159	111.6-113.4	415.6	Cream-colored shale zone with reddish mudstone beds. Bowen Formation is 1.8 m thick.
E159-165	113.4-153.6	455.8	Witten Formation. Thin-medium bedded calcareous mudstones with occasional bioclastic packstone layers. Bluish-gray colored which weathers to buff. Occasional beds with undulatory bases and flat tops. Shale interbeds. E163 is fenestral dismicrite. Above E163 is apparent burrow mottling.
			Witten Formation is 40.2 m thick.
E165-			Beginning of zone of reddish soil with common float slabs. Moccasin Formation.

APPENDIX B

CLASSIFICATION AND GLOSSARY OF FEATURES USED IN MICROFACIES ANALYSIS

Part 1

Classification of Features Used in Microfacies Analysis

Fossiliferous carbonate deposits possess several characteristics which make it likely that record of postmortem environmental processes operating on the constituent particles will be preserved. First, carbonate sediment particles are often skeletal remains which have a far greater variety of shapes and sizes than do particles in siliciclastic sediments. Thus, distinctive textures and fabrics may result from the response of these unusually-shaped particles to hydrodynamic events. Conceivably, these might provide specific environmental or taphonomic signatures. Carbonate particles are also relatively soft and therefore would be more likely to record the effects of transportation from nearby or contiguous carbonate subenvironments than siliceous particles. Furthermore, various activities of carbonate-secreting organisms to adapt to environmental conditions, such as the trapping and binding of sediment incrustation, may prevent postmortem transport or destruction of particles by diagenetic processes and thus allow preservation of organic responses to specific environments. An effort was made in this study, therefore, to approach the carbonate rocks at Lay School as fossil accumulations with the purpose of extracting environmental information about the depositional and postmortem (taphonomic) processes and events which produced the present assemblage.

Features of fossil assemblages relevant to their postmortem histories were gathered from many paleontological, paleoecological, and sedimentological studies. Among the important taphonomic studies are the works of R. G. Johnson, especially his study on the investigation of the mode of formation of a fossil assemblage (1960). By examining mainly shelly accumulations in the modern siliciclastic environment of Tomales Bay, California, Johnson was able to divide fossil particle and assemblage characteristics into two categories. One category of features reflects the taphonomic process of grain transport due to water turbulence. The other category of features reflects several other processes which operate on skeletal particles exposed at the sediment-water-interface. By looking for these features in a fossil assemblage, a postmortem history of its particles can be formed which is useful in assessing the extent to which the assemblage represents an in situ community. This study uses many of these features to reconstruct environmental processes.

The most important environmental factors involved in skeletal and nonskeletal sediment accumulation in the siliciclastic setting of Tomales Bay are water turbulence and sediment supply (Johnson, 1960). The interplay of processes influencing these two factors resulted in the various kinds of skeletal accumulations. Studies of modern carbonate depositional regimes, however, reveal that a more complex interplay of processes are responsible for sediment accumulation. Even the roles of

water turbulence and sediment supply can be different from those in siliciclastic settings. The following is a brief description of important factors of carbonate sedimentology and taphonomic features possibly related to those factors. The fossil particle and assemblage features form the variables or parameters used in microfacies examination of the Lay School samples. Some features may yield information about several processes or factors and, therefore, are listed under several categories. Some of the features listed under each environmental or ecologic category can result from other processes, such as the good sorting of fossil particles in some instances can be attributed to biogenic production of similarly sized particles (e.g., pelmatozoan columnals) rather than modification by water currents. Thus, valid environmental interpretations regarding a sample or group of samples should be based on the multiple occurrence of features (or suites of features, Benedict and Walker, 1978) rather than any single feature. Also, since it is possible to conceive alternate processes or modes of formation for some assemblages, Johnson suggested that it is best to use compound evidence in determining environments or modes of formation of fossil assemblages. A possible inherent weakness of such an approach is the assumption that multiple lines of evidence contribute equally to the strength of a hypothesis (Johnson, 1960). A description of each feature, its use in previous studies, and the location of an example (if any) in this study is presented as a glossary following this classification.

I. Water Turbulence

This study follows the distinction made by Dunham (1962) between water turbulence functioning as currents of grain transport and as currents of removal. Turbulence may cause a similar taphonomic response (e.g., skeletal particle movement) in some areas of modern carbonate deposition as it does in many siliciclastic settings. Shelf-edge carbonate sand shoals of skeletal particles or ooids can exhibit similar grain features, sediment textures, and structures as offshore siliciclastic sands (Ball, 1967). In these areas, water turbulence functions as currents of transport and depositional textures or structures may reflect the strength and nature of the currents responsible. Skeletal particles and assemblages in such depositional regimes may exhibit such features described by Johnson (1960) as reflecting a collection of totally transported fossils--particle abrasion and fragmentation, excellent sorting, frequent sedimentary structures (cross bedding), etc.

In other parts of carbonate depositional settings, such as protected inner shelf environments, skeletons of organisms are deposited at or very near their living sites (Swinchatt, 1965; Laporte, 1969). Because these areas are protected from open sea swells, waves, and often, longshore currents, they are considerably less turbulent most of the time than exposed shelf edges and consequently serve as areas of micrite accumulation (Enos and Perkins, 1977). Taphonomic characteristics of skeletal

accumulations in this setting may approach those listed by Johnson (1960) as indicative of an in situ fossil assemblage or community. Such features include whole fossils with delicate parts preserved, poor sorting, articulated bivalved fossils, etc.

Protected, near shore areas on carbonate platforms or shelves are nevertheless intermittently turbulent due to storms or migration of turbulent subenvironments (e.g., tidal channels) through the area. In these cases, water turbulence functions as currents of removal of already deposited grains, and the amount of micrite remaining in the sediment matrix is a means of judging the nature of the currents (Dunham, 1962). The wide range of shapes of carbonate skeletal particles and their intraparticle porosities act to retain some early-deposited micrite from winnowing and "poorly-washed" textures often result. Such features as sheltered micrite and adhered micrite on particles may indicate such reworking or winnowing events.

A. Features Related to Water Turbulence (Functioning as Currents of Transport)
   1. Presence of only spar in sediment matrix
   2. Good sorting
   3. Planar layering or lamination
   4. Horizontal or preferred particle orientation
   5. Cross bedding or lamination
   6. Convex-up shells
   7. Ooids
   8. Graded bedding
   9. Inverse or reverse grading
   10. Fragmented fossils
   11. Abraded fossils
   12. Imbrication of fossils
   13. Bimodal or polymodal particle size distribution
   14. Oncolites (onkoids)

B. Features Related to Water Turbulence (Functioning as Currents of Removal or Reworking
   1. Presence of both micrite and spar in sediment matrix
   2. Adhered micrite on fossil particles
   3. Intraclasts
   4. Pelloids
   5. Sheltered micrite
   6. Matrix channel pores
   7. Interstitial spar increases upward in sediment

C. Features Related to Lack of Water Turbulence
   1. Presence of only micrite in sediment matrix
   2. Poor sorting
   3. Whole fossils
   4. Delicate features on fossils preserved
   5. Articulated bivalved fossils
   6. Interstitial micrite increases upward in sediment
   7. Micritic infilling of pores in fossils (may, however, indicate cementation)

II. Sediment Supply

An important factor of siliciclastic sedimentation mentioned by Johnson (1960), this refers to the amount of sediment furnished to a basin or depocenter from an emergent land area. This factor is important in carbonate deposition only in the negative sense, that is, carbonate sediment production is inhibited by terrigenous clastic influx (Walker et al., 1983). Carbonate production and deposition is essentially intrabasinal in nature and does not depend on terrestrial drainage systems for sediment supply (Laporte, 1969). Within carbonate regimes, skeletal sediment supply is controlled by ecologic factors such as warm temperatures and normal salinities, which stimulate the growth of benthic organisms (Wilson, 1975). Accordingly, no features specifically related to this factor are used in the microfacies descriptions in this study. However, in some parts of the Lay School section fine grained terrigenous clastic sediments (quartz silt and clay minerals) are significant constituents of the sediments. This is primarily true for the basal (Blackford Formation) and upper portions (upper Wardell, Bowen, Witten, and Moccasin Formations) and is noted in the environmental discussions of those intervals.

III. Biological Processes Influencing Sediment Accumulation

Carbonate depositional regimes are characterized not only by organic production of sediment but also by organo-sedimentary interactions which cause carbonate accumulation in addition to purely sedimentary or hydrodynamic processes. Some of these interactions include: trapping and binding of sediment particles by sticky algal mats (yielding stromatolites), incrustation and binding of substrates by colonial organisms (yielding boundstones), and the construction of massive stony colonies (yielding reefs or framestone) (Logan et al., 1964; Dunham, 1962; Embry and Klovan, 1971). Other organo-sedimentary interactions in addition to trapping and binding or incrusting have the effect of preserving or retaining fine-grained carbonate particles which otherwise might be removed by renewed turbulence. Baffling, for instance, describes the deposition and protection of fines by the action of elongate, erect sessile marine organisms in lowering local water turbulence. Similarly, the process of trapping and preserving fines under shelly skeletons ("sheltering") is also due to specialized organic shapes which inhibit or modify normal hydrodynamic processes. By restricting grain movement, all of these interactions contribute to the autochthonous nature of many carbonate deposits and significantly alter the postmortem histories of organic remains.

A. Features Related to Organo-Sedimentary Processes of Accumulation

1. Trapping and binding features

a. Layered algal stromatolites, oncolites, and some coated grains

b. Lamellar bryozoan boundstone; bryozoan/algal boundstone
c. Incrusting and binding pelmatozoan holdfast systems

2. Baffling features: bafflestone
3. Sheltering features: sheltered micrite in poorly-washed biomicrites or packstones
4. Massive stony colonies: framestone

IV. Early Diagenetic Processes (Excluding Cementation)

Early diagenetic processes or agents occur at or near the sediment-water-interface in marine siliciclastic as well as carbonate settings. Because more particles in carbonate sediments are composed of biologically degradable minerals and organic materials, the effects of these destructive or modifying agents may be more pervasive than in siliciclastic sediments. Organisms and plants responsible for predation, scavenging, and particle degradation are an important category of what Johnson called "exposure" features or agents which act upon an organism's remains after death (Johnson, 1960). Ginsburg (1957) emphasized the importance of biologically destructive agents in the early diagenesis of carbonate sediments. If it is true that skeletal remains exposed at the sediment-water interface for a long period of time after death have more of such exposure features than those which are quickly buried, then these features have implications for judging the rate of burial (or sediment accumulation) of carbonates.

A. Features Suggesting Early Diagenetic Processes (sensu Ginsburg, 1957)

1. Features related to biological diagenesis that can occur in epifaunal or infaunal situations
   a. Borings in skeletal particles
   b. Fragmentation of skeletal particles
2. Features related to biological diagenesis which are infaunal
   a. Mud-filled burrows-horizontal, vertical, or random orientation
   b. Spar-filled burrows-horizontal, vertical, or random orientation
   c. Concentrically arranged particles or churned or swirled particles
   d. Fecal pellets--pelleted mud
3. Epifaunal biogenic diagenetic features
   a. Incrustations on particles--bryozoan, worm tubes; bryozoan/algal incrustations; single and multiple layers
   b. Oncolites
   c. Coated grains (cortoids)
   d. Loose or unattached lamellar bryozoan sheets (presumably incrusted particles epifaunally)
4. Early chemical diagenetic features--epifaunal or infaunal
   a. Pyritization or blackening of grains

V. Early Lithification Processes

Other early diagenetic processes which are relevant to environmental and taphonomic studies are those involved in early carbonate cementation or lithification. Submarine cementation of carbonate sediment has been observed in a number of modern settings, such as in shelf-edge reefal build-ups. In these deposits, cementation causes the skeletal masses to be more resistant to postmortem erosion. Early submarine cementation in more particulate skeletal sediment bodies, such as shelf-edge sand, also promotes preservation of primary depositional facies by inhibiting postdepositional reworking.

Carbonate sediment experiences cementation when even briefly exposed to freshwater in phreatic or vadose zones (Longman, 1980). Thus hardgrounds and crusts which are seldom present in most siliciclastic sediment may form at low stands of sea level. Peritidal carbonates often develop distinctive fabrics related to early lithification due to subaerial exposure, such as fenestral pore systems, which are useful in environmental studies. Early lithification is another factor which removes carbonate particles from cycles of reworking and diagenetic degradation and contributes to the autochthonous nature of some deposits. Additionally, early cementation and lithification form hard substrates suitable for colonization by many benthic organisms.

A. Features Related to Early-Lithification and Cementation

1. Radiaxial cement
2. Sediment surfaces incrusted by sessile, benthic marine plants or animals
3. Sediment surfaces stained by finely-dispersed pyrite or organic stains
4. Sediment surfaces which truncate underlying particles
5. Borings in rock
6. Intraclasts
7. Pelloids (nonpellet)
8. Moldic porosity (cement-filled)
9. Fenestral porosity (cement-filled)
10. Matrix vug porosity (cement-filled)

VI. Carbonate Pore Systems (Cement-Filled in Lay School Rocks)

Most carbonate primary porosity is fabric selective, that is, a dependent relation can be observed between fabric elements and porosity (Choquette and Pray, 1970). Fabric selectivity is useful in determining the time of origin of the pores in relation to other events in the rock's diagenetic history. Pore systems serve as loci for cementation and thus indirectly influence early lithification and preservation of primary depositional fabrics. Since some pore systems are specific to some settings, such as fenestral fabrics in peritidal rocks, significant environmental information can be obtained from them.

A. Carbonate Pore Systems (Cement-Filled)

1. Interparticle pores
2. Intraparticle pores
3. Moldic pores
4. Fenestral pores
5. Shelter pores
6. Matrix channel pores
7. Matrix vug pores

Part 2

Glossary of Features

Abraded Fossils-Delicate Features (Fossil Abrasion). Abrasion of fossils is a feature of fossil assemblages noted by Johnson (1960) which may suggest fossil transport by water turbulence. Johnson noted that abrasion may be manifest in fossil assemblages in two ways, the morphological composition of an assemblage and the surface condition of the fossils. Abrasion can cause the elimination of delicate fossil parts, ornaments, or shapes, resulting in an assemblage containing only the most durable parts and shapes. For example, in the Hogskin Member of the Lincolnshire Formation there are cavities in a stromatoporoid biostrome that contain endocerid cephalopod fossils. Often, only the more durable thick-walled siphuncles are present, the thinner septal and outer shell walls having been destroyed prior to deposition. Driscoll (1967, 1973) found that mollusk shells with greater surface areas per unit weight are most rapidly abraded. Thus, fossils or fossils part with compact shapes should dominate highly-transported and abraded accumulations. This does not mean that all assemblages of similarly-shaped, compact particles are necessarily highly-transported and abraded. Some such accumulation may result from biogenic production of similarly-sized and shaped particles (e.g., pelmatozoan columnals). In those cases, other features of the assemblage should reveal the true nature of the mode of formation.

The other aspect of abrasion noted by Johnson (1960) and used in subjective estimates of abrasion in this study was the surface condition of the fossil. This aspect may in some instances be evaluated in thin-section (Walker, 1972). Aspects of the surface condition of fossil parts which might suggest abrasion often involve a subjective estimate of several criteria or relations which are often unstated and lumped under the general terms "abraded" or "worn." Such criteria or features might include irregular surface topography which truncates shell microstructural elements (such as the shell laminae of brachiopod shells which parallel the outer shell wall) and rounding or smoothing of anular portions of fossil parts, although this may be difficult to determine in two-dimensions (i.e., in a thin-section). This study suffers from a vague or imprecise definition of surface abrasion as well as the above problems in recognition of abrasion in thin-section. Thus abrasion was only roughly quantified into two states: low-moderate abrasion (Delicate Part or Features) and moderate-high abrasion (Abraded Fossils).

Additionally, this study may have mistaken grain abrasion for organic grain degradation (e.g., Fig. 3-13a, p. 128) in some instances. Driscoll (1967, 1973) estimated that physical grain abrasion was important in skeletal particle size reduction only in littoral environments. In sublittoral settings, grain size reduction is probably

accomplished by primarily organic agents (see also, Ginsburg, 1957). The stratigraphic plot of ecofacies features arranged into groups of maximum association by R-mode cluster analysis (Fig. 3-3a,b, p. 64), show that grain abrasion and associated features occur most frequently in the well-sorted, sparry facies present in the lower part of the section (Ecozones IA and IB, Blackford Formation, Elway and Hogskin Members). Apparent abrasion was also noted, however, in the micritic and heavily bioturbated Ecozone II (Upper Lincolnshire Formation), where organic grain degradation may have been a major process in size reduction. In support of this conclusion, micritic envelopes or coated grains and associated features (Group 2 in Fig. 3-3a) occur most often in the Upper Lincolnshire Formation in the lower part of the section. Formation of micrite envelopes is probably a result of micritization, which is complexly related to organic grain degradation by algae and fungi and the precipitation of micrite cements (Bathurst, 1975). Thus, the effects of physical abrasion may have been over emphasized in micritic parts of the section which also lack multiple features suggesting water turbulence or grain transport.

Adhered Micrite. This feature describes the presence of micrite or carbonate mud on a fossil particle that is clearly different from the surrounding matrix. Kreisa (1981) noted its presence on apparently reworked or exhumed fossil particles. Practical petrographic identification of this feature is made more difficult by the common occurrence of micrite coatings or envelopes on particles (presumably related to "micritization" processes). A general identification rule used in this study was that if the micrite present on a fossil allochem was irregularly distributed and did not form a coating over the whole grain, it was considered Adhered Micrite. On the other hand, if the micrite on a particle was present over the boundary of the entire grain, or was layered, clotted, or spongiostrome, it was considered a Coated Grain or an Oncolite. Adhered Micrite was most commonly associated with the features Infilled Micrite, Coated Grains, Intraclasts, and Blackened Grains (see dendrogram, Appendix C). The close association of Adhered Micrite and Coated Grains in overall occurrence may well reflect the common operation of both processes (Reworking and Micritization) in the paleoenvironments present at Lay School. This makes the distinction between the already similar products of the processes that much more difficult.

Articulated Fossils. Johnson (1960) expected that an in situ fossil assemblage would have a much higher proportion of articulated bivalved fossils (e.g., pelecypods, brachiopods) than a transported assemblage. Thus, articulated bivalved fossils should indicate a lack of grain transport due to water turbulence. Reliability of this feature as a criterion for nontransport is somewhat limited by the common occurrence of some bivalved fossils in an articulated state regardless of the nature of the surrounding facies (e.g., rhynchonellid brachiopods). Also, predation and scavenging can cause in situ disarticulation. Articulated Fossils is associated in overall distribution with

shelter phenomena, which include Shelter Pores (cement-filled), Sheltered Micrite, Perched Sediment, and Unattached Bryozoan or other crustose sheets. Articulated Fossils is most closely associated with Fecal Pellets, which also occur with shelter phenomena. This relation is a result of the selective preservation of fecal pellets under shelters, of which articulated fossils are a type. For example, fecal pellets are preserved in the articulated brachiopod in Fig. 3-17e, p. 162.

Bimodal Size Distribution. Some facies present at Lay School consist of a well-sorted fine-grained matrix fraction of silt or sand-sized particles including fossil and nonfossil (e.g., pelloids or small, equant micritic grains) allochems and a larger fraction of fossils or oncolites. These facies are best developed in sparry lithologies. An overall subjective impression from the samples was that the larger fraction of fossils was less fragmented and abraded than the matrix fraction. Because the matrix fraction exhibited good-sorting which could suggest modification by hydrodynamic processes, this feature was initially included in the features related to water turbulence or grain transport. The sample cluster analysis found that this feature most frequently occurs in Ecofacies (1 and 3) which also contain other features related to grain transport (e.g., sparry facies, good-sorting, fragmentation and abrasion, oriented or horizontal particles, convex-up shells, graded bedding, etc.). This suggests that bimodally sorted facies also may be related to common water turbulence. In those cases where the larger-sized fossils appear to be less fragmented and abraded than a sparry matrix fraction, these could represent a fauna indigenous to a frequently turbulent environment (e.g., trilobites are sometimes the largest and best preserved fossils in some biosparites). In other instances, especially in muddier samples, the fine-grained matrix may represent sediment transported from turbulent areas into quiet water setting. Bimodal facies are associated in overall distribution with oncolites, borings in fossils, and 2 and 3-layer concentric encrustations (see R-mode or feature dendrogram, Appendix C, Part 2). Oncolites and multiple encrustations form due to grain agitation or transport and borings result from postmortem subtidal epifaunal exposure which can accompany grain transport, and are, therefore, features which can reasonably be associated with water turbulence.

Bimodally-sorted facies have been described in a number of studies, often associated with shelf margin littoral settings. Bimodal facies were associated with oncolites, ooids, low angle asymmetrical cross-lamination, and ripple marks in the Calcare Massiccio of Umbria Marche in north-central Italy (Colacicchi et al., 1975). Algal-coated and oncolitic packstone facies that are bimodally sorted occur in the Stuart City Trend, Lower Cretaceous, South Texas. Up to 70% of grains have algal coats and larger grains have thick coats. Geopetals and borings in grains also occur. A shelf-margin stabilized grain flat was the suggested depositional environment (Debout et al., 1979). A rudist grainstone facies in this trend was also bimodally sorted and

consisted of coarsening and fining up sequences with parallel lamination. This facies was interpreted to represent beaches, off-shore bars, spits, and tidal channels. Wilson (1975) illustrates bimodal facies in the Winnowed Shelf edge sands of Facies Belt 6. These occur in Standard Microfacies 12.

Blackened Grains. A common microfeature of some samples at Lay School is the presence of pyritized fossil infillings or coatings which appear black in transmitted light or brassy in reflected light. Pyrite is also present in laminae of oncolites and coated grains. Presence of pyrite in marine sediments has been used as an indicator of both epifaunal and shallow infaunal chemical diagenesis. Hallam (1969) regarded pyritized sediment surfaces to be the result of submarine exposure. Iron sulfides are also deposited in carbonate muds at the interface between the zone of oxidation processes and that of reduction processes, i.e., the redox potential discontinuity (RPD) (Levinton, 1982). H_2S is generated below the RPD by bacterial action and is a common constituent of carbonate muds on the Florida inner shelf (Ginsburg, 1957) along with pyrite (Berner, 1966). The depth of the RDP below the sediment-water interface is related to the zone of biogenic reworking which transfers oxygen-rich water into the sediment and which usually extends to a few centimeters depth (Rhoads, 1974). Thus, pyrite deposition on skeletal particles is also a near-surface or shallow infaunal process in carbonate muds. The association of Blackened Grains with such "micritic" features as Intraclasts, Coated Grains, Adhered Micrite, and Infilled Micrite in the Lay School samples (dendrogram, Appendix C) suggests an analogous genetic relationship between pyrite diagenesis and the occurrence of micrite or carbonate mud.

Borings in Fossils. Johnson (1960) noted that borings by predators and scavengers occur in skeletal particles that are exposed at the sediment-water interface. Because there were no boring predators (e.g., naticid gastropods) or scavengers (e.g., decapods) in the Middle Ordovician, however, borings in this case must have been domiciles. This feature was among those suggested as a means of estimating the pre-burial time spent by a fossil assemblage at the sediment-water interface. Epifaunal exposure features, therefore, are related to the rates of burial of fossil particles. Borings are a common features of particles in the Lay School sediments (e.g., Fig. 3-9f, p. 93). Swirled patterns of small particles in some borings suggest that they were the result of infaunal, rather than epifaunal activity. Borings are related in overall occurrence, however, to 2- and 3-layer incrustations which are indicators of prolonged epifaunal exposure (dendrogram, Appendix C).

Bored Lithologies. This is a destructive diagenetic feature commonly found in lithified or hard substrates in modern carbonate environments, such as the rocky intertidal and shallow subtidal zones in the

Florida Keys. Agents are generally boring pholad clams (Perkins, 1977). A boring in a lithology was defined as a sharp-walled hole, and would be an indicator of lithification or hard substrate. Occurrence were confined to crusts in the mud-pod facies in Ecozone III and occasional intraclasts elsewhere. Bored Lithologies was associated with Radiaxial Cement in the R-mode cluster analysis (Appendix C) because of their co-occurrence in the mud-pod facies.

Burrow Features. This category of infaunal biogenic diagenesis includes three features: Mud-filled Burrows, Spar-filled Burrows, and Swirled or concentric Particles. Mud-filled burrows are manifest as round, micrite-filled areas that are coarser particle-poor in surrounding sediment that is coarser particle-rich. The round mud area may or may not have concentrically disposed fragments surrounding it. Examples of mud-filled burrows are shown in Fig. 3-12g, p. 114.

Spar-filled Burrows occur in both micritic and sparry lithologies. In micritic sediments, spar-filled burrows have sharp to diffuse walls and contain blocky cements. Fig. 3-12e is an example. In sparry, or laminated sediments, spar-filled burrows may be mud-lines, as in Fig. 3-7e (p. 76) or 3-8d and 3-8e (p. 87).

Swirled or Concentric Particles refer to those that often surround a burrow or present a churned appearance. This feature is often what is meant by a bioturbated sample. Examples can be seen in Fig. 3-12g.

The characteristics of a burrow in soft substrata vary with the water content or fluidity of the mud. Burrows in muds with 60-70% water content will be diffuse and lack distinct borders or walls (Rhoads, 1970). Those in sediments with much less than 50% water content, on the other hand, may have more distinct walls and be surrounded by shear deformation haloes (Rhoads, 1970). Thus, diffuse, mud-filled burrows, which leave little trace other than concentrically arranged particles (Enos, 1977) may indicate either shallower burrowing in the fluidized biogenically reworked zone or early burrowing before the compaction and hardening of the mud (Rhoads, 1970). Spar-filled burrows occurred in muds sufficiently coherent to remain open after the passage of the deposit-feeding animal. They, and those with distinct deformation haloes, may indicate burrowing which occurred deeper in the substrata or later in the diagenetic history of the mud, when water content is reduced by compaction (Rhoads, 1970). In this regard, the presence in Ecozone V of more spar-filled than mud-filled burrows could indicate a substrate which hardened (or lost water through compaction) earlier than muds in other heavily bioturbated zones with more equal proportions of burrow types (e.g., Ecozone II or VI).

Coated Grains and Oncolites. Coated Grains were defined for this study as skeletal particles with micritic coatings or concentric laminae less than the minimum apparent diameter of the central particle. The coating or laminae may contain Girvanella tubules, as in Fig. 3-13a (p. 128) or may not. Oncolites were defined as skeletal particles with

micritic coatings or concentric laminae greater than the minimum apparent diameter of the central particle. Since oncolites and some coated grains form in a layer by layer manner, those with many laminae probably were exposed at the sediment-water interface longer than those with few laminae. Thus, a comparison of the distribution of Coated Grains with that of Oncolites should reveal different associated features and facies. This proves to be true. Coated Grains are associated in overall distribution with the other "micritic" features: Intraclasts, 1-layer incrustations, Adhered Micrite and Infilled Micrite (dendrogram, Appendix C). Oncolites, on the other hand, have a distribution related to Bimodal Size Distribution, Borings in Fossils, and 2- and 3-layer incrustations. These features suggest epifaunal exposure. Coated Grains and Oncolites also appear in different ecofacies. Coated Grains occur in significant amounts in all but one ecofacies (No. 2). Oncolites are present primarily in Ecofacies 1, 4, and 5 (Table 2-1, p. 55).

Convex-up Shells. Disarticulated concave-convex shells of bivalved animals become oriented in a convex-up attitude when exposed to current action under certain conditions (Menard and Boucot, 1951; Johnson, 1957). Thus a high proportion of convex-up shells in a sediment may be an indicator of water turbulence and perhaps grain transport. There are, however, factors which restrict the use of this feature as a diagnostic indicator of turbulence. The shells must be in an uncrowded condition (Menard and Boucot, 1951). Also, the nature of the underlying substrate is important (Brenchley and Newall, 1970). Shells may move long distances in a concave position when exposed to currents on a sand substrate. Burial by scouring is common on sand substrates, resulting in shell burial at all orientations. On firm mud substrates exposed to currents, shell transport is minimal and burial by scouring does not occur. In this situation, shells quickly assume the stable convex-up attitude (Brenchley and Newall, 1970).

In the Lay School samples, Convex-up Shells are most closely associated in distribution with Graded Bedding and Mud Increases Up (dendrogram, Appendix C). These features occur together most frequently in Ecozones V, VI, and VII. In zones V and VI, especially, these three features occur in thin bioclastic layers. Zone V layers are often sparry facies developed on mud, have frequent shelter features, and quickly grade into mud. Convex-up shells in Ecozone VI occur in thin-bedded intervals characterized by muddy facies (Fig. 3-20f, p. 185; Fig. 3-21d, p. 194), laminated sands and silts overlying mud surfaces (E127), and bioclastic layers which grade up to muds (Figs. 3-21c,e).

Cross-lamination. Inclined sediment laminae with respect to horizontal bedding. Indicates sediment grain transport by a combination of three processes: (a) sedimentation, or settling of particles from suspension; (b) accretion, or deposition from a moving bed load due to a change in capacity or competence; and (c) enroachment, or deposition in the lee

of an obstacle, including the lee side of a ripple, dune, or delta (Blatt, Middleton, Murray, 1972). Examples in the Lay School section are found at the bottom of the section (Ecozone I, Fig. 3-8c, p. 87; 3-12f, p. 114) and the top (Ecozone VII, Fig. 3-22e,f, p. 205).

Crystal Silt. Fine-grained, frequently graded detrital sediment found in vug pores (Fig. 3-14a, p. 139), matrix channel pores, and some fenestral pores.

Fenestral Pores. These pores (cement-filled) are identical to those described by Read (1973) as laminoid fenestral pores. They are large compared to the interparticle pores of the surrounding sediments and often parallel any lamination present in the sediment (Fig. 3-7a,b, p. 76; Fig. 3-23c, p. 214). This fabric results from the desiccation of algal-laminated sediment in the intertidal and supratidal zones of tidal flats (Shinn, 1968; Hardie et al., 1977). Fenestral fabrics are present in the lower formations at Lay School (Blackford Formation, Ecozone I) and in the uppermost ones (Witten Formation, Ecozone VII).

Fragmentation: Whole Fossils-Fragmented Fossils. In his analysis of transported fossil assemblages, Johnson (1960) noted that a feature of transported assemblages was the high proportion of skeletal remains that were fragments. Consequently, this study attempted a gross estimate of the fragmentation of fossil particles in a sample. Careful tabulation of what constituted a whole fossil (or fossil part) in all the phyla or smaller, recognizable fossil groups was not attempted. Nor was a record made of the degree of fragmentation of each fossil group present in a sample. Instead, fossil particles were listed as fragmented when the grain was identifiable to a gross taxonomic level (by shape and microstructure) and appeared to represent only a portion of a whole fossil or fossil part (e.g., only part of a brachiopod shell). Also such particle condition features as abrupt and/or jagged termination of whole fossils or fossil parts was used in recognition of fragmentation. Fragmentation so defined ignores the problems of comparison of fragmentation between solitary and colonial organisms and between single and multiple-part fossils (e.g., echinoderms). Thus, in many cases whole parts of multiple-part organisms were treated as whole fossils (e.g., single brachiopod valves). Similarly, estimates of fragmentation are probably closer to estimates of fragmentation in fossil groups where fragmentation is more easily recognized, such as some solitary organisms (e.g., mollusks, brachiopods, ostracodes). Some colonial organisms erect structures that are more resistant to breakage (stromatoporoids, tabulate corals, mound-like bryozoans) or which are so shaped that it is impossible to tell from the view presented in thin-section whether the fossil is a fragment or a whole colony (e.g., arborescent bryozoans). This study shares these biases with all carbonate environmental studies that do not specify what constitutes fragmentation in the encountered fossil groups and the proportions the fossil groups contribute to the total amount of fragments.

Grading: Graded Bedding and Inverse Grading. Graded Bedding refers to the progressive decrease in particle size from the bottom to the top of a sediment layer (Fig. 3-17h, p. 162; Fig. 3-18a, p. 166). This results from sedimentation from water currents or turbulence that decreases progressively in strength. Inverse Grading or Reverse Grading refers to a progressive increase in particle size from the bottom to the top of a sediment layer (Fig. 3-9b, p. 93). It results from sedimentation from currents or turbulence that progressively increases. Graded laminae occur in peritidal portions of the lower section (Ecozone I). Graded beds (<1 cm thick) occur in the Benbolt Formation (Ecozone V). Inversely graded bedding occurs in sand portions of Elway Formation cycles in Ecozone I.

Holdfasts. Holdfasts are the anchoring portion of the pelmatozoan echinoderm animal (Figs. 3-9e; 3-11a,b,c, p. 109; 3-14d, p. 139; 3-15c, p. 142). These often bind and incrust the substrate's sediment particles and are therefore agents in an organo-sedimentary process of sediment accumulation like incrusting bryozoans or algal mats. Holdfasts occur in several environmental settings. They are present in bryozoan boundstones, sands, and on stromatoporoid biostromes in a very near shore, subtidal setting (Elway, Hogskin Formations, Ecozone I). The mud-pod facies in the lower Rockdell (Ecozone III) has extensive holdfast systems, and the lower Benbolt Formation (Ecozone V) contains a few.

Horizontal or oriented fossils. Horizontal fossils were noted by Johnson (1960) to be associated with well-sorted sediments of sand-size or smaller where the density of fossils was not too great. Horizontal fossils have been interpreted in some depositional studies to be the result of currents or water turbulence (e.g., horizontal Lingula shells in the delta-front facies of the Floyd Shale, Broadhead, 1976). Oriented fossils, i.e., those with parallel long axes, were also noted by Johnson to occur in transported fossil accumulations and have also been interpreted to be the response of the particles to currents or turbulence in depositional studies (Ball, 1971). As with other features in this study, these should not be used alone to infer environmental conditions but should be used when other features also point to a similar inference. Thus, horizontal fossils are more likely to reflect water turbulence when associated with other features, such as a sparry matrix, good sorting, abrasion and fragmentation, etc. Examples of this phenomenon are relatively common at Lay School, such as Figs. 3-13b, p. 128; 3-17c; 3-20a,f, p. 185; 3-21c,d,e, p. 194). Horizontal particles seem to display an antithetic relationship to oncolitic facies, i.e., horizontal particles are uncommon in most facies which contain oncolites (stratigraphic distribution of features, Figs. 3-3a,b, p. 64; Table 2-1, p. 55).

Imbrication. This feature is defined as particles which are inclined to the plane of bedding and partially overlap each other (e.g., Fig. 3-17g). Imbrication is a common sediment response to currents in

terrigenous alluvial environments but is uncommon in the Lay School samples.

Incrustations. Single or multiple incrustations of particles by incrusting organisms is common in some facies at Lay School (see facies summaries, Table 2-1, p. 55). Multiple incrustations probably require greater pre-burial exposure time for formation than do single-layer incrustations. This is suggested by the overall association of single-layer incrustations with features different from those associated with multiple incrustations. This could indicate different particle histories (dendrogram, Appendix C). Examples include Fig. 3-7e, p. 76; Fig. 3-9g, p. 93.

Lamination or planar layering. Layering parallel to bedding which is observable in thin-section. Sediment layers less than 1 cm are referred to as laminae (A.G.I. Dictionary of Geological Terms). Non-lacustrine lamination of sands and silts result from the traction phase of sediment transport in siliclastic environments (Blatt, Middleton, and Murray, 1972). Lamination on a millimeter scale is characteristic of some areas on carbonate tidal flats (Hardie et al., 1977). Examples from Lay School can be seen in Figs. 3-7b; 3-8c,d,e,f, p. 87; 3-10a,b,d, p. 105, 3-12e, p. 114; 3-15f, p. 142.

Unattached Crusts or sheet-like colonies. Apparently unattached sheet-like colonies of incrusting bryozoans are a common feature in the Lay School sediments. There are also a few instances of unattached Girvanella crusts. Bryozoan sheets often form shelters in bioclastic sediments and were therefore clustered with shelter features in the R-mode (or feature) cluster analysis (Appendix C).

Matrix Channel Pores. This term is modified from the pore type described by Choquette and Pray (1970) as a channel pore, i.e., a pore elongate in one or two directions relative to a third and which cuts across elements of a rock fabric. A matrix channel pore is elongate in one or two directions, is interparticle in nature, extends beyond possible overlying shelters, and has smooth, sometimes graded sediment on its floor. It is confined to the matrix and is, therefore, fabric selective. Examples occur in Figs. 3-12a; 3-13b,c, p. 128; 3-22c,d, p. 205. Matrix channel pores seem to be a winnowed or washed texture as is suggested by the smooth, graded floors and different overall association from that of shelter pores (Appendix C).

Micrite Infilled Fossils. This refers to the presence of micrite infilling of intrafossil porosity and was suggested by Kreisa (1981) as a criterion for reworked or exhumed fossils. It is associated with other "micritic" features, such as Adhered Micrite and Intraclasts, in overall distribution (Appendix C).

Moldic Porosity. Spar-filled pores which retain the outline of fossils whose original material has been removed by solution (Fig. 3-23e, p. 214). Mollusk fragments are found in this condition due to selective solution or original aragonitic material. Moldic porosity is a common feature in very shallow subtidal rocks at Lay School, especially in sparry facies (Ecozone I, VI, and VII; Fig. 3-3a,b, p. 64). For this reason its overall distribution is related to that of 2- and 3-layer incrustation, which occur in similar facies (Appendix C). Moldic pores also occur frequently in the mud-pod zone (Ecozone III) and thus the cluster analysis of features also related it distribution to holdfasts and vug pores, common features in that zone.

Mud Increases Upward. This term was used to describe the situation where micrite comformably overlies a sparry skeletal layer and yet the size decrease upwards is too rapid to be described as true graded bedding (Fig. 3-19f, p. 175; 3-21a,b,c, p. 194). Like graded bedding, this feature presumably results from sedimentation of fines in a quiet water setting following a more turbulent period. Associated in overall distribution with Graded Bedding, this features is found primarily in Ecozones V and VI, Benbolt and Wardell Formations (Appendix C; Fig. 3-3b).

Ooids. Originally aragonitic carbonate allochem of radial or concentric structure formed in an accretionary manner in an agitated subtidal environment. Present in the lower parts of the Lay School section (Ecozone I) usually as a minor constituent, ooids form a major portion of B25 (Fig. 3-10f,g, p. 105).

Pellets. Fecal pellets resulting from the activities of infaunal, deposit-feeding organisms. These are usually oval or football-shaped and up to .5 mm long (Figs. 3-17e, p. 162; 3-19b; 3-23h). Since individual fecal pellets are commonly preserved in shelter pores their overall occurrence is related to shelter pores, articulated fossils (which frequently act as shelters) and sheltered mud (Appendix C).

Pelleted Mud is a related term used to describe the presence of numerous pellets, whose total outlines may be obscured by compaction. This was distinguished from individual pellets or occurrences of only a few pellets in order to better define areas of intense infaunal activity (or preservation of such activity). Pelleted Mud mainly occurs in Ecozone V (Fig. 3-3b) and is associated in this zone with the feature Mud Increases Up (Appendix C). An example is Fig. 3-12d, p. 114.

Pelloids. Micritic, nonskeletal allochems that are equant, small (<.2 mm) and often well-sorted. Sometimes they are stained a dark color (Fig. 3-23f). These may be well-sorted, small intraclasts, and are probably not pelloids as defined in modern environmental studies that are fecal pellets, the end result of micritization, or other origins

(Wilson, 1975). Pelloids are associated with Good Sorting, Fragmented Fossils, and Abraded Fossils (Appendix C).

Radiaxial Cement. This type of cement has been recognized as an early-deposited cement in ancient carbonates, perhaps being a recrystallized early marine fibrous aragonitic cement (Bathurst, 1959, 1975). Radiaxial cement has dusty brown color and undulose extinction under crossed nicols which sweeps across the long axis of the crystals. These crystals may be elongate normal to the cavity wall and isopachous in nature, that is, the majority of the crystals extend the same length into the cavity. Radiaxial cement is primarily present in the mud-pod facies of Ecozone III (Fig. 3-13e, p. 128).

Shelter Effects. Shelter effects are primary depositional features that indicate grain-support in a rock's texture (Dunham, 1962). This study recognizes three related features, Shelter Pores (or voids in Dunham, 1962), Perched Sediment, and Sheltered Mud. Shelter effects form a group of associated features in the R-mode or feature cluster analysis (Feature Group No. 5 in Fig. 3-3a,b, p. 64) which may be used to outline parts of the section that retain primary depositional features. Ecozone II, for example, is characterized by postdepositional bioturbation which has destroyed all primary features, including those of the shelter group (Fig. 3-3a).

Shelter Pores. Shelter pores are cement-filled voids which form underneath overlying larger particles (shelters) that prevent a complete infiltering of finer clastic particles into all interparticle spaces. This effect includes the conspicuous geopetal features that are useful in determining the up direction in bioclastic slabs. Examples are present in Figs. 3-17e, p. 162; 3-19b, p. 175; 3-23f,h, p. 214.

Sheltered Mud. Mud or micrite under a larger particle that has an overlying sparry facies. Presumably, sheltered micrite was co-deposited with the overlying shelter which later prevented the micrite from being reworked by the renewed turbulence responsible for the sparry facies. This feature was used by Specht and Brenner (1979) as a criterion for winnowing. Since this phenomenon traps fine sediments through organic means (i.e., the organic production of sheltering fossils), it deserves to be included with other organo-sedimentary processes of sediment accumulation such as the trapping and binding of sediment by algal mats or crustose benthic organisms (e.g., bryozoans). It is included (as Sheltering) with other organo-sedimentary accumulation processes in the stratigraphic distribution of features at Lay School arranged by environmental category in Fig. 3-6a,b, p. 73. The close association of Sheltered Micrite and Shelter Pores in overall distribution (Appendix C; Fig. 3-3a,b) could indicate that much of shelter porosity results from in situ winnowing or transportation of sheltering fossils mainly within areas of original accumulation.

Perched Sediment. Apparently infiltrated sediment which rests upon larger, sheltering fossils. Kreisa (1981) suggested that much of

perched sediment in shell accumulations in the Martinsburg Formation resulted from infiltration of storm-winnowed fines after reworking, rather than resulting from original depositional episodes. Proof of the infiltration origin of perched sediment in any particular instance is found when there is a progressive decrease in the amount of perched sediment downward in a fossil accumulation (Kreisa, 1981). This effect was termed "screening" by Kreisa and is identical to experimental features obtained by Dunham (1962) and seen in Fig. 3-23f, p. 214.

Sorting. Johnson (1960) noted that sorting characteristics of transported fossil assemblages would be different from those of in situ accumulations. Transported assemblages should exhibit better sorting than in situ accumulations. The reliability of this factor depends on the nature of the organisms present. Some organisms furnish well-sorted segments or parts upon disarticulation after death, such as pelmatozoan echinoderms or some modern Codiacean algae (i.e., Halimeda). This study made a gross estimate of the sorting of the sample because the sorting of a fossil accumulation or its surrounding sediments may give environmental information when it is determined that it does not result from the above mentioned structural nature of the organisms present. Since sorting values of fossil particle accumulations is difficult to estimate easily, this study described sorting conditions as either poor to moderately-sorted (Poorly-sorted) or moderately to well-sorted (Well-sorted) using subjective evaluation. Well-sorted sediments, using this gross estimate, were related in distribution to Fragmented and Abraded Fossils, and Pelloids (Appendix C). Poorly-sorted sediments, on the other hand, were associated with Whole Fossils, Fossils with delicate parts, and 1-layer incrustations.

Spar Increases Up. This phrase describes the occasional decrease in interparticle micrite upward in a slide, or the upward increase in spar-filled interparticle porosity. The feature could be a plausible result of incomplete winnowing.

Surface Incrusted. Early cementation and lithification of carbonate sediments resulting from subaerial or submarine exposure is a distinctive aspect of carbonate sedimentation. Recognition of early-lithified or partially-lithified substrates (e.g., hardgrounds) yields environmentally relevant information in carbonate depositional studies. A sharp surface which is incrusted by sessile marine plants or animals and which separates two lithologies may be an indication of the hardness or lithification of the underlying lithology when used with other criteria (Read and Grover, 1977). An example occurs in the cavity fill in the stromatoporoid biostrome in Ecozone I (B-section).

Surface Stained. This describes the condition of a sharp surface between two lithologies which is stained by organic agents or by pyrite. Such staining has been interpreted as evidence for a hardground (Prokopovitch, 1955; Hallam, 1969; Ruppel, 1981). Sample B8

in Ecozone I (B-section), Elway Formation is the best example at Lay School of this feature (Fig. 3-10c, p. 105).

Surface which truncates. This is another surface description or feature which suggests the lithified or hardened condition of the lithology underlying the surface. If a surface truncates an underlying particle, it is implied that the underlying lithology was sufficiently cemented or lithified to hold the grain during erosion or truncation rather than allowing it to be plucked from the matrix. An example of this feature occurs in B33(1), Ecozone I (B-section), Hogskin Formation (Fig. 3-11d, p. 109).

Vug Porosity. A cement-filled pore that is larger than interparticle pores and shows little orientation with respect to bedding. In fenestral dismicrites, this corresponds to the irregular fenestrae of Read (1973) and Grover and Read (1977) which have equant to irregular shapes and may grade into or be bounded by laminoid pores (Fig. 3-7a, p. 76). In the mud-pod zone (Ecozone III), vugs also have irregular shapes and may have irregular or smooth floors, sometimes composed of graded sediment (Figs. 3-13e, p. 128; 3-14a, p. 139).

APPENDIX C

NATURE OF DATA, NUMERICAL DATA AND FEATURE DENDROGRAM

Part 1

Environmental Data and Cluster Analysis

The environmental features listed in the previous chapter were recorded in the presence/absence or two-state format. This approach sacrifices extracting quantitative volumetric data on a few features in order to record a large number of parameters from many thin sections. One hundred and twenty-one thin sections were point-counted to establish general limits of the constituents that are routinely used in carbonate petrology (see Appendix D for the results). The attributes chosen as relevant to this environmental analysis are of a compound nature, however, giving rise to several problems concerning qualitative definition, data coding, and data comparison.

Nature of Data

The parameters or features can be divided into those of a two-state or presence/absence nature and those of a multistate character, where the data measured are values in a range of possible values. An example of a two-state feature in this study is cross-lamination, which is either present or absent in a sample. Multistate data can be of a quantitative or qualitative nature, with the former being used in this study. Multistate parameters of a qualitative nature are those which are ordered along a scale but not on a numerical basis, for example, the ecological stages in a plant community succession scheme (Sokal and Sneath, 1963). No parameters of this type were used in this study.

Coding Multistate Discrete Values into Two-State Format

Quantitative multistate data are characterized by two kinds of values--discrete and continuous. Multistate characteristics which yield discrete values have inherent gaps between successive observable values (Remington and Schork, 1970). An example of this kind of variable from this study is the number of layers of incrustations found on an allochem. There may be one, two, or three successive layers of incrustations but there cannot be 1½ or 2.63. There are unobservable values or gaps between the observed values in the parameter. This study coded the discrete multistate values of incrustation sequences into a two-state format by assigning a parameter to each layer in a sequence and scoring each parameter additively for each slide. Thus, 1, 2, 3, and 4-layers of incrustation become four two-state (presence/

absence) parameters, all of which are marked as present when a slide has grains showing four layers of incrustation.

Coding Multistate Continuous Values into Two-State Format

Quantitative multistate parameters which yield continuous values have the property that between any two observed values lies at least another potentially observable value (Remington and Schork, 1970). Length and weight are two such variables. There are several such attributes in this study which are continuous variables, such as sorting, fragmentation, abrasion, percentage of fossils with infilled micrite, etc.

One characteristic of a continuous variable is that it never can be measured exactly, that is, there must always be some measurement error. The recorded value for a continuous variable only approximates the true value, the recorded value reflecting the precision of the measurement. Thus, a continuous variable is always recorded in discrete form, the size of gap between recordable values being determined by the precision of measurement. This principle illuminates a possible approach to a problem common to several of the continuous parameters used in this study (i.e., a precise scheme of measurement does not exist or cannot be rapidly used). Sorting of particles is a good example of such an attribute. It would be easy to code a range of continuous values into a two-state format for particle sorting if it were possible to quickly measure sorting in carbonates. This could be done by assigning a parameter to each of a number of classes encompassing a fixed range of values, similar to that which is done for the length coordinate in a length-frequency histogram. The investigator would then mark the appropriate sorting value class which corresponded to the sorting of the slide. Unfortunately, application of sorting charts developed for terrigenous clastic sediments to carbonate sediments is impossible due to the wide range of particle shapes in carbonates. Another method would be to measure the longest apparent length of each particle encountered when point-counting the slide for constituent allochems, and then construct a size-frequency diagram for each slide. This would be too time consuming to apply to very many samples.

Instead, this study used a completely subjective visual estimate of sorting, but the lack of precision in measurement is indicated by dividing the range of variation into just two parts. A slide was judged to be either poorly-sorted (i.e., poorly to moderately sorted) or well-sorted (i.e., moderately to well sorted). This approach undoubtedly involves a large information loss per slide, but allows for examination of many slides.

A similar coding approach was used for several other continuous, multistate parameters whose measurement seemed impractical or too time consuming. Fragmentation, for example, was divided into two

variables--whole fossils and fragmented fossils. Abrasion was similarly recorded.

Multivariate Cluster Analysis Used to Evaluate Data

This investigation examined 302 thin-sections for 51 features or variables. It became apparent during the tabulation of the data that it would be difficult to interpret by "eye" the distribution of so many variables over so many samples. Some method of classifying samples and variables into groups of similar character became necessary. This problem resolved itself into two parts: (1) how to measure similarity between samples and variables, and (2) how to display the results of such measurements for easy interpretation. The use of cluster analysis as a technique to analyze multivariate data from large numbers of samples was suggested to the investigator by Brower (1982). From examining these references, the writer concluded that cluster analysis might be a useful tool in the interpretation of the considerable amount of data collected in the present study.

Measurements of Similarity

There are several different ways of measuring similarity between objects or parameters of investigation but only the method used in the available computer program, the Euclidean distance function, will be treated in any detail in this discussion. First, however, two common types of measures of similarity should be mentioned. The correlation coefficient is a measure of the adequacy of fit of a straight line to plots of data in one dimension and is a means of explaining the variability of the dependent "Y" variable. If all of the variability of "Y" values is explained, because all of the sample points fall on the fitted straight line, then the equation for the line summarizes accurately the relationship between the two variables (Koch and Link, 1970). Values range from +1 (indicating perfect co-occurrence of dependent and independent variables) to -1, which means a perfect inverse relationship.

For environmental studies, this measure of similarity or dependence is usually not applicable. This is because the correlation coefficient is best applied if variables have continuously measured quantitative "values which can be expected to exhibit linear, proportionate relationships denoting some simple underlying control" (Park, 1974, p. 335). Most environmental data do not satisfy those requirements.

Another group of similarity or association coefficients has been developed for primarily biological data which is expressed in binary or two-state form. An example of such a measure is the Dice Coefficient (Sokal and Sneath, 1963) used in two recent papers on quantification of assemblage zones (Brower et al., 1978; Millendorf et al., 1978).

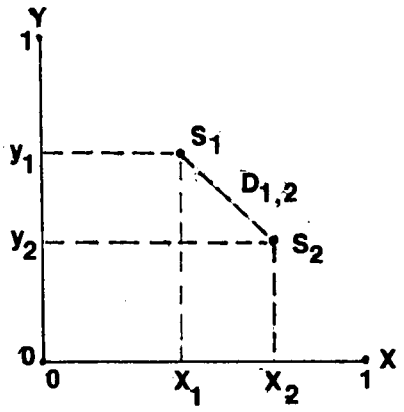
$$\text{Dice Coefficient} = \frac{2C}{N_1 + N_2}$$

where

C = Number of taxa or characters present in both units compared.
N_1 = Total taxa or characters present in first unit or sample.
N_2^1 = Total taxa or characters present in second unit or sample.

There are many other measures of similarity which use binary or two-state data and which differently weigh presences and absences. For a detailed discussion of these, see Cheetham and Hazel, 1969.

The computer program used in the present study incorporates a function known as "Euclidean metric" or distance as a measure of similarity. The following explanation of this measure is adapted from the discussion in Sokal and Sneath (1963). Assume that we have two samples for which n parameters have been measured. The states for each parameter have been assigned values along a scale ranged for this discussion from zero to unity. A pair of rectangular coordinates are drawn in which the abscissa represents parameter X and the ordinate parameter Y. Next, we plot the position of the two samples (S_1, S_2) with respect to these coordinate axes.



Then, the distance, $D_{1,2}$ between the two samples becomes (according to the Pythagorean relation):

$$D_{1,2}^2 = (X_1 - X_2)^2 + (Y_1 - Y_2)^2.$$

If the two samples are identical with respect to the two parameters under discussion, their positions will coincide and the distance between them will be zero. The greater the distance between the two positions, the greater will be their difference. The maximum distance possible between the two samples will be $\sqrt{2}$, when the samples occupy the tips of the two coordinate axes and each axis is of unity length. This is the case where the two samples have nothing in common.

If we wish to measure the distance between two samples with respect to three parameters, a third coordinate (Z) must be added to the diagram. The distance between the two samples becomes:

$$D^2_{1,2} = (X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2.$$

The maximum distance between the two positions with respect to the three axes becomes $\sqrt{3}$.

Although one cannot visualize the geometry of adding a fourth and other parameters, and one cannot graphically depict such axes, a multidimensional space is postulated for multivariate analysis. Further, it is demonstrated algebraically that most of the geometric theorems of conventional three dimensional space can be extended to n-dimensions in what is called Euclidean hyperspace. In hyperspace one may postulate n-dimensions for n-parameters, and can calculate the distance between the two samples. The maximum distance between the samples will be $\sqrt{n}$ in an n-dimension hyperspace. The distance between the two samples j, k becomes:

$$Djk = \sqrt{\sum_{i=1}^{n} (X_{ij} - Xik)^2}$$

This is known as the Euclidean distance, or metric, which can be squared and becomes:

$$D^2_{jk} = \sum_{i=1}^{n} (Xij - Xik)^2.$$

Since D^2_{jk} increases with the number of parameters used in the comparison, and average distance can be computed by dividing D^2_{jk} by n:

$$d_{jk} = \sqrt{\frac{D^2_{jk}}{n}} \qquad \text{or} \qquad d^2_{jk} = \frac{D^2_{jk}}{n}.$$

The square root form of average distance was used by Parks (1969) in his paper on cluster analysis applied to multivariate geological problems.

Cluster Techniques

The type of clustering produced by the available computer program is hierarchical, that is, classes are formed at different levels on the bases of shared similarity. The process is also agglomerative, in that it successively fuses n samples into groups, as opposed to divisive clustering methods which partition the complete set of n samples into successively finer partitions. The method used in the present study was developed by Johnson (1967), who called it the minimum method. This is also known as the nearest neighbor or single link method of clustering (Anderberg, 1973; Everitt, 1974). It begins by examining the matrix of similarity or, in this case, distance measures calculated between all possible combinations of samples. Initially, each individual sample is considered a group or cluster. The two closest (most similar) single-sample clusters are fused or joined to form the first multisample group. The program then calculates the closest remaining single-sample cluster to the new two-sample cluster and adds it to form a three-sample cluster. This process continues until all the samples are fused into one large group. Thus, in the dendrograms constructed by the investigator from the computer cluster map in the following chapters, the bottom scale begins with the number of samples or variables to be clustered and ends at one. This is the last clustering which adds the most different sample to the n-1 samples already clustered.

The results of clustering are usually depicted graphically in a two-dimensional diagram illustrating the fusions which have been made at successively higher levels. The diagram may take the form of a cluster map (Appendix C, Part 2) as devised by Johnson (1967) and produced by the available program. This diagram resembles a histogram, with the vertical axis related to Euclidean distance (cluster number) and the horizontal axis being dimensionless. Since the cluster map devised by Johnson is not as familiar as the dendrogram, dendrograms were constructed by hand from the cluster maps.

The dendrogram displays on the abscissa or horizontal axis the distance values at which the group fusions or clusterings occur. In the case of the sample dendrogram and the variable dendrogram constructed for this study, the horizontal axis uses number of clusters (samples or variables) remaining after each fusion rather than the distance. This is because the cluster number was used to construct the dendrogram and is a convenient unit of equal magnitude, whereas the distances between clusters is variable and the number of samples or variables with similar distances becomes fewer as the clustering process proceeds. Thus, lines denoting distance become confusingly

close together at the terminal or right side of the dendrogram. In any case, the exact distance at which a particular clustering occurs is listed alongside the cluster number in the printout included as Appendix C, Part 2. The vertical axis, on the other hand, is dimensionless and the samples or variables are listed along it. The order in which the samples are listed is determined by the clustering process.

The computer program which did the cluster analysis for this study is the Cluster Procedure in the Statistical Analysis System (SAS) Language, developed by the SAS Institute Inc., Box 8000, Cary, N.C. 27511. The procedure is described in the SAS User's Guide, 1979 Edition. Due to the large number of calculations involved, the program suggests limiting the number of samples to be clustered to around 250. Accordingly, over 50 slides and/or lithologies were deleted from the data set on the basis that they closely resembled facies already present. Maximum diversity of facies and features was the goal, following the strategy of Parks (1966), rather than using samples "representative" of a general population, or "randomized" samples. The Digital Equipment Corp. VAX 11/780 computer available for the analysis had no difficulty in processing the remaining 250 sample in the data set.

Both samples and variables (features) were clustered in this study. Classifying techniques which partition a large number of samples or objects upon which multiple observations have been made into homogeneous subgroups on the basis of some similarity are said to be operating in the Q-mode. The similarity between samples in a group is that between their attributes, parameters, or variables. Techniques which compare the distribution of the variables or attributes are said to operate in the R-mode (McCammon, 1968). This study then, may interchangeably use the term Q-mode cluster for sample cluster or R-mode cluster for variable or feature cluster.

Choice of Variables for Cluster Analysis

There are other factors, in addition to those related to the specific study area, which should guide the selection of variables or parameters for a multivariate cluster analysis. The selection of variables (characters) in numerical taxonomy, for instance, is guided by biological as well as purely statistical rules or hypotheses. As a result of several purely biological assumptions or reasons, Sokal and Sneath (1963) argued that there are no a priori grounds for favoring one character over another in taxonomic classifications and that all categories of characters are of equal taxonomic importance. As a result of this and a tendency to err on the side of comprehensiveness, numerical taxonomic studies using cluster analysis involve large numbers of variables. For a complete discussion of character or variable choice, see Chapter 5 of Sokal and Sneath (1963).

Investigators in other disciplines, such as statisticians, social scientists, and engineers generally recommend parsimony in selection of variables. Since the selection of variables will have the single largest effect on the cluster analysis, it is important to consider the consequences that a variable will have on the results (Anderberg, 1975). A meaningful choice of variables must balance relevance and discriminating power. Variables which are relevant to a discipline or general study area may vary little between samples or stations in any particular case. A variable which is generally invariant for all the data units (samples) has little discriminating power and may cause clusters (the groups of similar samples or features) to merge into large, confusing groups. Those parameters that vary from data subgroup to another can discriminate clear distinctions in the resultant clusters. On the other hand, variables which are strong discriminators but only indirectly relevant can cause well-defined, apparently easily interpreted clusters which completely mask the true relations being investigated (Anderberg, 1975). Consequently, several features in this study were considered in the environmental analysis but were deleted from the cluster analysis because of their ubiquitous occurrence (invariant nature). Cement-filled interparticle and intraparticle pores are examples of such features. On the other hand, vertical burrows and framestone were deleted from the cluster analysis because they occurred too rarely. In retrospect, several other rare variables might have been excluded from the clustering, such as stained sediment surfaces, fenestral porosity, sediment surfaces which truncate underlying grains, incrusted sediment surface, and imbrication of particles.

Problems with Qualitative or Subjective Estimation

Several relevant parameters for taphonomic studies are not easily quantified, as mentioned earlier in this chapter. Most of these parameters were defined by dividing their range of possible values into two and assigning a binary parameter to each half. This was the case for fossil fragmentation and abrasion. Thus fragmentation in a sample has only two possible values: low to moderate (called Whole Fossils), or moderate to high (called Fragmented). The difficulty with such low-information parameters, or those defined too loosely, is their lack of discriminating power. Judging from the data gathered, such loose definitions cause the variable to be recorded too frequently and they approach becoming invariably present. There are several possible strategies for remedying this problem. One way would be to multiply the number of parameters used to describe the range of possible values. Instead of using two parameters, for instance, in describing fragmentation, four parameters could be used. Using subjective verbal definitions, the four possible values of fragmentation could be: Rare fossils fragmented, Occasional fossils fragmented, Common fossils fragmented, and Frequent fossils fragmented. The accuracy of such a

scheme could be augmented by visual estimation charts, such as those used for estimating percentages of microconstituents (e.g., Terry and Chilingar, 1955). This would greatly increase the discriminating power and information retrieval capabilities of the general feature "Fragmentation." It would do so, however, at the expense of using two more parameters which could be used for other features.

Another possible solution would be to simply ignore less relevant parts of the range of values for a variable. For instance an investigator may decide that only Frequent fragmentation or Frequent whole fossils has much environmental significance. These two subjectively restricted parameters would then have much greater discriminatory power and would help yield more compact and more easily interpreted clusters. A variation of this strategy was used in restricting application of the feature" Articulation" to brachiopods and bivalves. If the parameter were also applied to the frequently-articulated ostracodes, the parameter would approach being invariably present. This is to be avoided when choosing or defining variables (Sokal and Sneath, 1963; Anderberg, 1975).

Part 2

Cluster Analysis Numerical Data and Feature Dendrogram

Part I.

A. Numerical data printout for Variable (Feature) Cluster Analysis. For each step or fusion, the program (S.A.S. Language, 1979 Ed.) prints out:

1. The number of clusters present (in this case, with each feature being a cluster, there are 51 clusters present before clustering).

2. The maximum distance between two observations in a cluster, called the maximum diameter of a cluster.

3. The number of distances within clusters (these are all less than the maximum diameter).

4. The total number of distances less than the maximum diameter.

5. The ratio of 3 and 4.

B. Cluster map printout of Variable (Feature) Cluster Analysis. Clustered variables (called Observations) are connected by a line. Variable name is listed by its number in Appendix A, the consecutive listing of samples and features for 302 thin-sections (samples) with respect to 51 variables.

C. Dendrogram of Variable (Feature) Cluster Analysis. Constructed from cluster map (Part B, above), the dendrogram depicts similarities in distribution of the environmental features. Abbreviation key is on the following page.

Part II.

A. Numerical summary of Sample Cluster Analysis. Displays the same relations and calculations as explained in Part 1a above, except that observations are samples. Samples clustered are 255 samples listed by subcluster in Appendix B. Cluster map from which sample cluster analysis dendrogram was constructed (Fig. 2-1, p. 27) was not included due to its great length (41 pages).

Table C-1. Numerical Summary of Variable (Feature) Cluster Analysis [Part I(A)].

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
51	0.0000	0	0	0.000
50	7.0000	1	1	1.000
49	9.0000	3	4	0.750
48	11.0000	6	13	0.462
47	11.0000	7	13	0.538
46	12.0000	8	17	0.471
45	14.0000	12	27	0.444
44	15.0000	17	39	0.436
43	16.0000	23	49	0.469
42	17.0000	24	57	0.421
41	18.0000	31	69	0.449
40	18.0000	32	69	0.464
39	20.0000	33	85	0.388
38	20.0000	34	85	0.400
37	23.0000	50	120	0.417
36	24.0000	60	127	0.472
35	24.0000	62	127	0.488
34	26.0000	84	138	0.609
33	29.0000	86	160	0.538
32	31.0000	89	181	0.492
31	31.0000	90	181	0.497
30	32.0000	91	189	0.481
29	39.0000	117	240	0.488
28	41.0000	118	254	0.465
27	42.0000	122	264	0.462
26	44.0000	125	274	0.456
25	45.0000	127	276	0.460
24	51.0000	202	306	0.660
23	51.0000	203	306	0.663
22	57.0000	283	342	0.827
21	59.0000	284	358	0.793
20	65.0000	285	421	0.677
19	72.0000	287	463	0.620
18	74.0000	311	483	0.644
17	74.0000	312	483	0.646
16	75.0000	314	494	0.636
15	76.0000	320	499	0.641
14	80.0000	370	528	0.701
13	81.0000	373	535	0.697
12	82.0000	375	541	0.693
11	86.0000	376	581	0.647
10	88.0000	379	599	0.633
9	98.0000	384	649	0.592
8	102.0000	388	669	0.580
7	107.0000	392	685	0.572
6	108.0000	554	691	0.802
5	114.0000	620	729	0.850
4	134.0000	640	922	0.694
3	152.0000	652	1134	0.575
2	191.0000	715	1240	0.577
1	229.0000	1275	1275	1.000

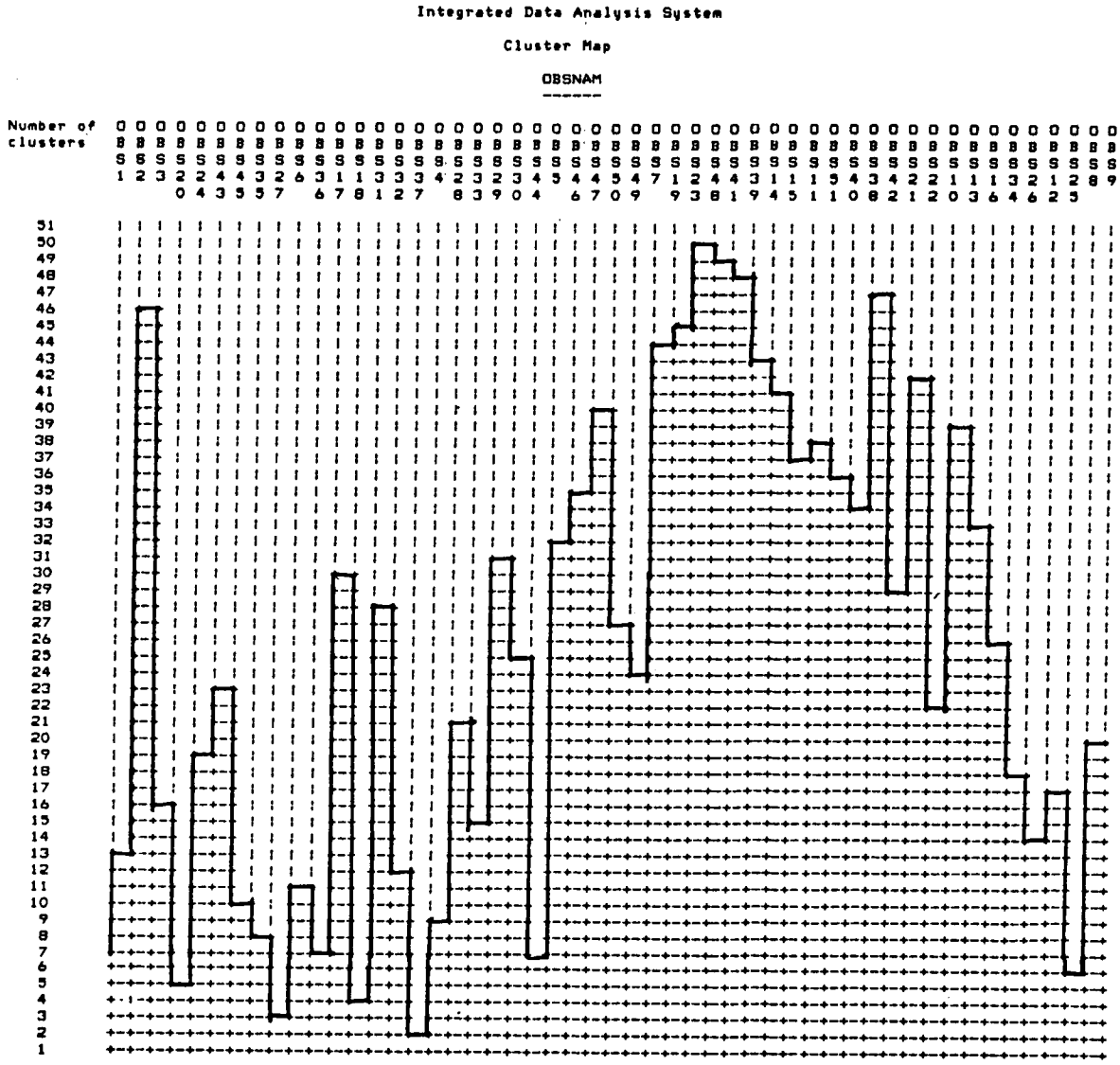


Figure C-1. Cluster map of variable cluster analysis [Part I(B)].

Figure C-2. Feature cluster analysis dendrogram [Part I(C)]. Constructed from the S.A.S. Program Cluster Map Printout (Fig. C-1). Depicts similarities in distribution of features used in sample descriptions. Outlined and numbered clusters are groups of features with maximum association which form the order of feature listing in Appendix B, and sample cluster (Ecofacies) descriptions in Chapter 4.

Abbreviation Key

PS = Poorly Sorted
WF = Whole Fossils
DEL = Delicate Parts
1L = 1-Layer Incrustations
CG = Coated Grain
MI = Micrite Infilled
AM = Adhered Micrite
INT = Intraclasts
BG = Blackened Grains
WS = Well Sorted
PEL = Pelloids
FR = Fragmented Fossils
AB = Abraded Fossils
MB = Mud-filled Burrow
SP = Swirled Particles
SB = Spar-filled Burrow
LC = Loose Crustose Sheet
ART = Articulated
FEC = Fecal Pellets
SHP = Shelter Porosity (Cement-filled)
PSD = Perched Sediment
SHM = Sheltered Mud
CHL = Matrix Channel Porosity (Cement-filled)
XL = Crystal Silt
VUG = Vug Porosity (Cement-filled)
HLD = Holdfasts
MLD = Moldic Porosity (Cement-filled)
2L = Two-Layer Incrustations
3L = Three-Layer Incrustations
FEN = Fenestral Porosity
4L = Four-Layer Incrustations
STR = Surface which truncates grains
SIN = Surface incrusted
IMB = Imbricate Particles
XLM = Cross-Lamination
INV = Inverse Grading
SUP = Spar Increases Up
OID = Ooids
HEM = Hemispheroidal Oncolites
SSN = Surface Stained
BL = Bored Lithology
RAD = Radiaxial Cement
CU = Coarsens Up
GR = Graded Bed
MU = Mud Increases Up
PM = Pelleted Mud
BR = Borings in Fossils
BI = Bimodal Size Distribution
ONC = Oncolites
PLA = Planar Layering or Lamination
HOR = Horizontal or Preferred Particle Orientation

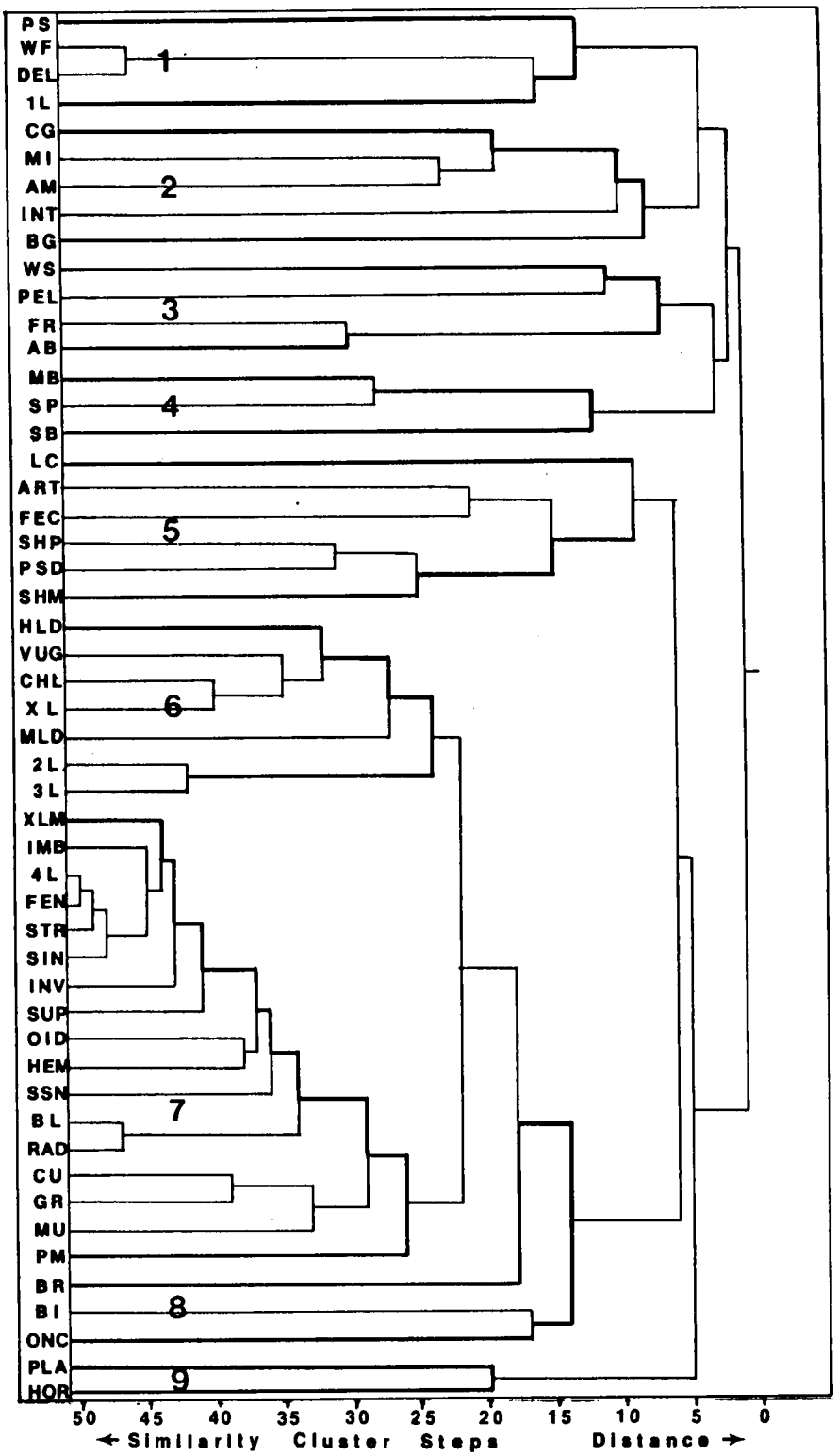

PS
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ART
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PSD
SHM
HLD
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XLM
IMB
4L
FEN
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HOR
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7
8
9
50 45 40 35 30 25 20 15 10 5 0
← Similarity Cluster Steps Distance →

Figure C-2.

Table C-2. Numerical Summary of Sample Cluster Analysis (Part IIA).

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
255	0.0000	0	3	0.000
254	0.0000	1	3	0.333
253	0.0000	2	3	0.667
252	0.0000	3	3	1.000
251	1.0000	5	34	0.147
250	1.0000	6	34	0.176
249	1.0000	7	34	0.206
248	1.0000	8	34	0.235
247	1.0000	9	34	0.265
246	1.0000	11	34	0.324
245	1.0000	12	34	0.353
244	1.0000	13	34	0.382
243	1.0000	14	34	0.412
242	1.0000	15	34	0.441
241	1.0000	16	34	0.471
240	1.0000	17	34	0.500
239	2.0000	18	109	0.165
238	2.0000	21	109	0.193
237	2.0000	23	109	0.211
236	2.0000	25	109	0.229
235	2.0000	27	109	0.248
234	2.0000	28	109	0.257
233	2.0000	31	109	0.284
232	2.0000	32	109	0.294
231	2.0000	33	109	0.303
230	2.0000	35	109	0.321
229	2.0000	37	109	0.339
228	2.0000	38	109	0.349
227	2.0000	39	109	0.358
226	2.0000	40	109	0.367
225	2.0000	41	109	0.376
224	3.0000	42	282	0.149
223	3.0000	43	282	0.152
222	3.0000	51	282	0.181
221	3.0000	52	282	0.184
220	3.0000	55	282	0.195
219	3.0000	56	282	0.199
218	3.0000	57	282	0.202
217	3.0000	65	282	0.230
216	3.0000	66	282	0.234
215	3.0000	72	282	0.255
214	3.0000	74	282	0.262
213	3.0000	76	282	0.270
212	3.0000	77	282	0.273
211	3.0000	79	282	0.280
210	3.0000	80	282	0.284
209	3.0000	81	282	0.287
208	3.0000	82	282	0.291
207	3.0000	83	282	0.294
206	3.0000	84	282	0.298

Table C-2 (continued).

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
205	3.0000	85	282	0.301
204	3.0000	86	282	0.305
203	3.0000	87	282	0.309
202	3.0000	88	282	0.312
201	4.0000	90	571	0.158
200	4.0000	92	571	0.161
199	4.0000	98	571	0.172
198	4.0000	102	571	0.179
197	4.0000	105	571	0.184
196	4.0000	106	571	0.186
195	4.0000	107	571	0.187
194	4.0000	108	571	0.189
193	4.0000	109	571	0.191
192	4.0000	110	571	0.193
191	4.0000	111	571	0.194
190	4.0000	112	571	0.196
189	4.0000	127	571	0.222
188	4.0000	128	571	0.224
187	4.0000	130	571	0.228
186	4.0000	131	571	0.229
185	4.0000	132	571	0.231
184	4.0000	133	571	0.233
183	4.0000	135	571	0.236
182	4.0000	136	571	0.238
181	4.0000	137	571	0.240
180	4.0000	138	571	0.242
179	4.0000	139	571	0.243
178	5.0000	145	1005	0.144
177	5.0000	166	1005	0.165
176	5.0000	168	1005	0.167
175	5.0000	173	1005	0.172
174	5.0000	179	1005	0.178
173	5.0000	181	1005	0.180
172	5.0000	183	1005	0.182
171	5.0000	184	1005	0.183
170	5.0000	185	1005	0.184
169	5.0000	191	1005	0.190
168	5.0000	192	1005	0.191
167	5.0000	193	1005	0.192
166	5.0000	195	1005	0.194
165	5.0000	201	1005	0.200
164	5.0000	202	1005	0.201
163	5.0000	203	1005	0.202
162	5.0000	204	1005	0.203
161	5.0000	205	1005	0.204
160	5.0000	206	1005	0.205
159	5.0000	207	1005	0.206
158	5.0000	208	1005	0.207
157	6.0000	216	1681	0.128
156	6.0000	217	1681	0.129
155	6.0000	221	1681	0.131
154	6.0000	222	1681	0.132

Table C-2 (continued).

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
153	6.0000	226	1681	0.134
152	6.0000	227	1681	0.135
151	6.0000	229	1681	0.136
150	6.0000	230	1681	0.137
149	6.0000	232	1681	0.138
148	6.0000	235	1681	0.140
147	6.0000	236	1681	0.140
146	6.0000	237	1681	0.141
145	6.0000	243	1681	0.145
144	6.0000	267	1681	0.159
143	6.0000	271	1681	0.161
142	6.0000	273	1681	0.162
141	6.0000	275	1681	0.164
140	6.0000	277	1681	0.165
139	6.0000	279	1681	0.166
138	6.0000	280	1681	0.167
137	6.0000	281	1681	0.167
136	6.0000	285	1681	0.170
135	6.0000	286	1681	0.170
134	7.0000	296	2669	0.111
133	7.0000	326	2669	0.122
132	7.0000	327	2669	0.123
131	7.0000	331	2669	0.124
130	7.0000	373	2669	0.140
129	7.0000	376	2669	0.141
128	7.0000	386	2669	0.145
127	7.0000	387	2669	0.145
126	7.0000	391	2669	0.146
125	7.0000	392	2669	0.147
124	7.0000	394	2669	0.148
123	7.0000	395	2669	0.148
122	7.0000	396	2669	0.148
121	7.0000	397	2669	0.149
120	7.0000	400	2669	0.150
119	7.0000	455	2669	0.170
118	7.0000	459	2669	0.172
117	7.0000	465	2669	0.174
116	7.0000	466	2669	0.175
115	7.0000	467	2669	0.175
114	7.0000	468	2669	0.175
113	8.0000	494	3857	0.128
112	8.0000	497	3857	0.129
111	8.0000	536	3857	0.139
110	8.0000	545	3857	0.141
109	8.0000	547	3857	0.142
108	8.0000	575	3857	0.149
107	8.0000	577	3857	0.150
106	8.0000	581	3857	0.151
105	8.0000	583	3857	0.151
104	8.0000	584	3857	0.151
103	8.0000	586	3857	0.152
102	8.0000	592	3857	0.153

Table C-2 (continued).

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
101	8.0000	597	3857	0.155
100	8.0000	601	3857	0.156
99	8.0000	604	3857	0.157
98	8.0000	606	3857	0.157
97	8.0000	607	3857	0.157
96	8.0000	609	3857	0.158
95	8.0000	611	3857	0.158
94	8.0000	612	3857	0.159
93	8.0000	613	3857	0.159
92	8.0000	614	3857	0.159
91	9.0000	621	5381	0.115
90	9.0000	636	5381	0.118
89	9.0000	640	5381	0.119
88	9.0000	644	5381	0.120
87	9.0000	646	5381	0.120
86	9.0000	650	5381	0.121
85	9.0000	654	5381	0.122
84	9.0000	656	5381	0.122
83	9.0000	662	5381	0.123
82	9.0000	663	5381	0.123
81	9.0000	664	5381	0.123
80	9.0000	666	5381	0.124
79	10.0000	690	7253	0.095
78	10.0000	802	7253	0.111
77	10.0000	806	7253	0.111
76	10.0000	810	7253	0.112
75	10.0000	812	7253	0.112
74	10.0000	856	7253	0.118
73	10.0000	861	7253	0.119
72	10.0000	862	7253	0.119
71	10.0000	864	7253	0.119
70	10.0000	865	7253	0.119
69	10.0000	869	7253	0.120
68	10.0000	877	7253	0.121
67	10.0000	925	7253	0.128
66	11.0000	971	9415	0.103
65	11.0000	974	9415	0.103
64	11.0000	989	9415	0.105
63	11.0000	992	9415	0.105
62	11.0000	1004	9415	0.107
61	11.0000	1007	9415	0.107
60	11.0000	1025	9415	0.109
59	11.0000	1027	9415	0.109
58	11.0000	1029	9415	0.109
57	11.0000	1031	9415	0.110
56	11.0000	1037	9415	0.110
55	11.0000	1039	9415	0.110
54	12.0000	1089	11878	0.092
53	12.0000	1164	11878	0.098
52	12.0000	1170	11878	0.099
51	12.0000	1182	11878	0.100
50	12.0000	1191	11878	0.100

Table C-2 (continued).

Number of clusters	Maximum distance within a cluster	Number of within distances <= maximum	Total number of distances <= maximum	Ratio
49	12.0000	1203	11878	0.101
48	12.0000	1205	11878	0.101
47	12.0000	1209	11878	0.102
46	12.0000	1342	11878	0.113
45	12.0000	1344	11878	0.113
44	12.0000	1362	11878	0.115
43	12.0000	1370	11878	0.115
42	12.0000	1372	11878	0.116
41	13.0000	1416	14483	0.078
40	13.0000	1436	14483	0.099
39	13.0000	1441	14483	0.099
38	13.0000	1451	14483	0.100
37	14.0000	1476	17228	0.086
36	14.0000	1484	17228	0.086
35	14.0000	2004	17228	0.116
34	14.0000	2028	17228	0.118
33	14.0000	2052	17228	0.119
32	14.0000	2088	17228	0.121
31	14.0000	2114	17228	0.123
30	15.0000	2546	19903	0.128
29	15.0000	2761	19903	0.139
28	15.0000	2779	19903	0.140
27	15.0000	2807	19903	0.141
26	15.0000	2810	19903	0.141
25	16.0000	2915	22421	0.130
24	16.0000	2948	22421	0.131
23	16.0000	2966	22421	0.132
22	16.0000	2972	22421	0.133
21	17.0000	3478	24548	0.142
20	17.0000	3508	24548	0.143
19	17.0000	3571	24548	0.145
18	18.0000	3681	26521	0.139
17	18.0000	3693	26521	0.139
16	18.0000	3701	26521	0.140
15	19.0000	3827	28189	0.136
14	19.0000	4037	28189	0.143
13	19.0000	4213	28189	0.149
12	20.0000	4384	29525	0.148
11	21.0000	5440	30461	0.179
10	21.0000	7180	30461	0.236
9	21.0000	7279	30461	0.239
8	22.0000	7327	31223	0.235
7	22.0000	7462	31223	0.239
6	24.0000	7840	32065	0.245
5	25.0000	8050	32217	0.250
4	25.0000	8690	32217	0.270
3	27.0000	11683	32356	0.361
2	28.0000	21829	32376	0.674
1	30.0000	32385	32385	1.000

APPENDIX D

TABLES

Table D-1. Consecutive Listing of Samples and Contained Features.

Sample	Feature																																																	
	PS 1	WHL 2	DEL 3	LC 4	HLD 5	WS 6	XLM 7	PLA 8	HOR 9	CU 10	OOID 11	BI 12	GR 13	INV 14	SUP 15	MU 16	FR 17	AB 18	IMB 19	1L 20	2L 21	3L 22	4L 23	CG 24	ONC 25	BR 26	BG 27	ART 28	SHP 29	PS 30	MB 31	SP 32	FEC 33	PM 34	INT 35	PEL 36	SB 37	BL 38	SIN 39	SSN 40	STR 41	RAD 42	MI 43	SHM 44	AM 45	VUG 46	CHNL 47	FEN 48	MLD 49	XL 50	HEM 51
LS-A1					X			X								X	X													X				X	X	X															
LS-A2					X			X		X						X	X													X				X	X	X								X						
LS-A3					X			X			X					X	X							X											X	X							X		X						
LS-A4					X												X	X												X	X			X	X														X		X			
LS-A6					X		X	X								X	X														X				X																	
LS-A7					X	X		X								X	X																X	X							X		X						
LS-A9					X			X								X	X																	X															
LS-A11	X	X	X			X			X			X					X	X																	X															
LS-A12					X		X	X								X	X												X	X			X	X															
LS-A14	X	X	X			X			X			X					X	X		X				X													X							X		X				X		
LS-A15					X												X	X																	X															
LS-A16	X	X	X			X						X					X	X						X							X	X			X	X							X		X	X	X		X		
LS-A17	X	X	X													X	X		X				X							X	X			X									X				X		
LS-A18					X												X	X																															
LS-A19					X												X	X		X				X							X				X	X							X		X						
LS-A20	X																	X	X		X	X	X		X	X						X	X			X	X	X								X						
LS-A22	X					X						X					X	X							X		X				X	X				X								X		X						
LS-A23	X	X	X	X					X								X			X			X					X								X	X									X						
LS-A24			X	X		X			X								X	X		X	X		X	X									X	X							X		X						X
LS-A25	X		X	X		X			X						X			X	X											X						X	X							X		X				X		
LS-A26	X	X	X	X		X							X					X	X		X	X	X	X	X	X				X	X	X	X			X	X								X	X				X		
LS-A27	X	X	X	X		X							X					X	X		X	X	X		X			X		X	X	X	X				X	X								X	X				X		
LS-A28	X					X					X	X					X	X						X	X		X				X	X			X								X		X				X		
LS-A29	X																	X	X		X				X	X						X	X			X		X								X						
LS-A30	X	X	X	X													X	X		X				X	X	X	X	X			X	X			X		X								X		X	X			X		X
LS-A31	X																	X	X		X	X	X		X	X	X	X				X	X	X		X	X	X							X		X						
LS-A32	X	X	X	X		X			X			X					X	X		X												X	X																			
LS-A34	X	X	X			X						X					X	X													X	X				X	X															
LS-A35	X		X			X			X							X	X	X													X	X			X	X	X							X	X	X					
LS-A36					X	X	X	X								X	X											X			X			X	X	X								X				X		
LS-A37					X		X									X	X													X				X										X						
LS-A39					X		X	X								X	X													X	X				X	X															
LS-A40					X		X	X								X	X													X	X																				
LS-A41					X		X	X								X	X													X	X				X	X															
LS-A42					X		X	X								X	X									X				X	X				X									X	X							
LS-A43					X		X	X					X	X		X	X																X										X	X				
LS-A44					X		X					X			X	X													X	X				X	X															
LS-A47					X			X								X	X																	X										X					
LS-A48					X		X									X	X													X	X				X	X															
LS-A49					X		X									X	X																	X															
LS-A50					X		X									X	X														X				X															
LS-A51					X												X	X													X	X		X		X												X	X		X	X	
LS-A52					X												X	X													X	X		X		X												X	X	X	X		
LS-A53	X	X	X	X		X		X	X				X		X			X	X		X													X	X						X										X							
LS-A54		X	X	X		X										X	X													X	X													X		X		X			
LS-A<56	X	X	X	X		X						X					X	X		X						X					X	X				X	X															
LS-A56		X	X	X		X								X			X												X	X	X				X	X							X		X						
LS-A57	X	X	X																											X	X	X			X		X								X	X						
LS-A<59		X	X	X	X															X	X	X	X	X		X					X	X					X														
LS-A59	X	X	X	X																X							X	X	X				X										X	X	X					
LS-A60(1)	X	X			X						X						X	X		X	X	X	X	X	X	X	X				X	X			X	X	X			X			X		X						X
LS-A62	X	X	X														X	X		X	X			X							X	X													X						
LS-A64	X	X	X								X						X			X	X			X	X			X	X	X			X	X	X	X								X	X					
LS-B1					X		X									X	X														X				X															
LS-B2					X		X	X					X				X	X													X					X															
LS-B3					X			X								X	X	X								X	X							X	X												
LS-B4					X												X	X													X	X				X	X											X					

Table D-1 (continued).

Sample	Feature																																																		
	PS 1	WHL 2	DEL 3	LC 4	HLD 5	WS 6	XLM 7	PLA 8	HOR 9	CU 10	OOID 11	BI 12	GR 13	INV 14	SUP 15	HU 16	FR 17	AB 18	IMB 19	1L 20	2L 21	3L 22	4L 23	CG 24	ONC 25	BR 26	BG 27	ART 28	SHP 29	PS 30	MB 31	SP 32	FEC 33	PM 34	INT 35	PEL 36	SB 37	BL 38	SIN 39	SSN 40	STR 41	RAD 42	MI 43	SHM 44	AM 45	VUG 46	CHNL 47	FEN 48	MLD 49	XL 50	HEM 51
LS-B5				X		X			X				X				X	X														X			X	X															
LS-B6	X	X	X	X		X		X	X	X							X	X											X		X	X			X	X															
LS-B7						X											X	X		X															X	X							X		X						
LS-B8	X					X											X	X						X							X	X			X	X	X	X	X	X											
LS-B10						X						X					X	X						X								X				X									X						
LS-B11						X											X	X						X			X					X																			
LS-B12						X						X					X	X						X	X										X	X															
LS-B15						X			X			X					X	X						X					X	X			X		X	X							X	X	X						
LS-B16	X	X	X	X							X						X	X		X				X					X	X					X	X							X	X	X						
LS-B19						X		X	X								X	X													X	X	X		X	X	X	X													
LS-B20						X		X	X								X	X													X	X				X															
LS-B22						X											X	X																X	X	X										X					
LS-B23	X			X													X	X																	X											X	X		X		
LS-B24	X	X	X	X					X					X		X	X	X						X				X	X	X												X		X							
LS-B25	X	X	X	X							X						X	X		X				X				X							X								X								X
LS-B26						X	X	X									X	X																	X	X															
LS-B27						X											X	X																			X														
LS-B33(1)	X	X	X	X	X												X	X		X	X			X		X									X				X		X					X			X	X	
LS-B33(2)		X	X																															X								X							X	X	
LS-B34		X	X	X													X	X		X																															
LS-B35	X	X	X		X						X						X	X		X	X			X		X		X	X		X	X														X	X		X	X	
LS-B36		X	X		X	X			X									X		X									X						X								X	X	X	X	X			X	
LS-B37		X	X		X	X			X								X	X	X	X									X	X	X				X		X						X	X	X	X	X		X	X	
LS-B38						X					X						X	X								X		X							X								X		X						
LS-B39	X	X	X			X			X			X					X	X		X					X				X	X						X															
LS-B40	X	X	X	X		X			X			X					X	X									X		X	X		X			X	X							X	X	X				X		
LS-B44						X	X	X	X								X	X								X	X		X							X							X		X						
LS-B45	X				X						X						X	X		X	X			X	X						X				X								X	X							
LS-B48	X					X						X					X	X		X				X	X		X				X	X			X	X	X						X								
LS-B49	X	X	X	X						X							X	X		X				X		X	X	X					X		X								X	X	X		X				
LS-B50	X	X	X	X		X			X			X					X	X		X						X	X		X		X	X	X		X	X	X						X	X	X						
LS-B52	X	X	X			X						X					X	X													X	X	X			X	X														
LS-B57	X	X	X	X		X						X					X	X		X							X		X				X		X	X	X						X						X		
LS-B58	X	X	X	X	X						X						X	X		X	X			X	X			X							X		X			X			X		X						
LS-B59	X	X	X						X								X															X	X				X						X								
LS-B60	X	X	X			X			X			X					X	X	X						X				X	X					X	X							X	X	X		X		X		
LS-B62	X					X					X						X	X						X			X				X	X			X		X						X		X						
LS-B64	X																X	X						X	X		X				X	X			X								X		X						
LS-B65	X										X						X	X		X				X		X	X								X	X			X	X			X		X						X
LS-B67	X																X	X						X	X	X					X	X			X		X						X		X						
LS-B70	X																X	X						X							X	X			X	X	X						X		X						
LS-B71	X																X	X		X				X	X		X				X	X			X	X	X						X		X						
LS-B72	X																X	X								X					X	X				X							X		X						
LS-B77	X																X	X						X	X						X	X			X		X						X		X						
LS-B78	X																X	X		X				X		X	X				X	X			X	X	X						X		X						
LS-C1	X																X	X						X							X	X			X		X						X		X						
LS-C4						X											X	X						X							X	X				X	X						X		X						
LS-C6	X	X	X														X	X						X	X						X	X			X		X						X		X						
LS-C7	X	X	X			X						X					X	X						X	X		X				X	X					X						X		X						
LS-C8	X																X	X						X	X						X	X					X						X								
LS-C9	X	X	X			X						X					X	X		X				X	X	X	X				X	X			X	X	X						X		X						
LS-C10	X																X	X						X	X						X	X													X						
LS-C12	X	X	X						X								X	X		X				X			X		X	X			X		X	X							X	X	X						
LS-C13	X	X	X	X	X												X	X		X				X	X		X		X	X			X		X	X							X		X						
LS-C14	X																X	X						X					X	X					X	X							X		X				X		
LS-C15	X	X	X	X	X				X											X				X		X			X	X					X								X	X	X		X		X	X	
LS-C17	X	X	X	X	X												X			X				X					X				X	X		X							X		X						

Table D-1 (continued).

Sample	Feature																																																		
	PS 1	WHL 2	DEL 3	LC 4	HLD 5	WS 6	XLM 7	PLA 8	HOR 9	CU 10	OOID 11	BI 12	GR 13	INV 14	SUP 15	MU 16	FR 17	AB 18	IMB 19	1L 20	2L 21	3L 22	4L 23	CG 24	ONC 25	BR 26	BG 27	ART 28	SHP 29	PS 30	MB 31	SP 32	FEC 33	PM 34	INT 35	PEL 36	SB 37	BL 38	SIN 39	SSN 40	STR 41	RAD 42	MI 43	SHM 44	AM 45	VUG 46	CHNL 47	FEN 48	MLD 49	XL 50	HEM 51
LS-C18	X	X	X		X															X											X						X									X					
LS-C21(2)	X	X	X	X	X															X											X	X			X		X	X				X				X	X		X	X	
LS-C22	X	X	X	X	X	X			X						X					X				X	X		X	X	X	X			X	X									X	X	X	X	X		X		
LS-C23	X	X	X	X	X															X											X						X	X				X			X	X	X		X	X	
LS-C27		X	X		X	X														X				X		X									X			X				X	X	X	X	X			X		
LS-C30		X	X	X	X	X			X															X																		X	X	X	X		X		X		
LS-C31	X	X	X	X	X															X				X	X						X						X	X				X	X		X	X			X	X	
LS-C32	X			X	X															X	X	X		X							X						X	X	X			X	X		X				X	X	
LS-C34	X			X	X															X				X							X						X	X	X			X			X	X			X	X	
LS-C35	X	X	X	X	X															X				X							X						X		X			X	X		X	X			X	X	
LS-C36		X	X	X	X	X			X											X	X			X		X			X				X	X									X		X	X	X		X	X	
LS-C37	X	X	X		X				X								X	X		X					X	X			X	X			X		X	X							X	X	X						
LS-C41	X	X	X		X															X	X			X	X		X	X	X				X	X	X								X			X					
LS-C42	X	X	X	X													X	X		X	X	X		X	X											X	X						X		X						
LS-C44	X																X	X						X	X		X				X	X	X	X	X								X		X						
LS-C46	X					X		X	X								X	X						X	X		X		X	X					X	X							X	X	X						
LS-C49	X	X	X			X									X		X	X						X	X		X	X	X	X			X		X	X							X	X	X						
LS-C50	X					X						X					X	X						X	X		X								X	X							X		X						
LS-C52						X											X	X						X			X				X	X			X		X						X		X						
LS-C54	X	X	X														X	X		X	X			X			X				X	X	X		X		X						X		X						
LS-C56	X	X	X			X						X					X	X		X				X	X		X	X	X	X			X		X								X	X	X						
LS-C58	X	X	X														X	X		X				X				X		X			X				X						X	X	X				X		
LS-C60	X	X	X			X						X					X	X						X			X		X	X	X	X	X		X	X	X						X	X	X						
LS-C62		X	X			X		X	X					X			X	X		X										X					X								X	X	X						
LS-C63	X			X		X						X					X	X						X							X	X				X	X						X		X				X		
LS-C64	X		X	X													X	X		X				X			X				X	X			X		X						X		X						
LS-C65	X			X													X	X		X				X			X				X	X				X	X						X		X						
LS-C66		X	X	X		X			X						X		X	X											X	X	X	X	X		X	X	X								X						
LS-C68	X	X	X														X	X									X				X	X					X	X					X		X						
LS-C70	X																X	X									X				X	X				X	X														
LS-D1	X																X	X						X			X				X	X	X		X		X						X		X						
LS-D5		X	X			X											X	X									X	X			X	X	X				X														
LS-D8	X	X	X													X	X	X						X			X				X	X			X	X	X						X	X	X				X		
LS-D9						X											X	X						X			X				X	X			X		X						X		X						
LS-D13			X			X						X					X	X						X		X	X				X	X					X														
LS-D16	X	X	X			X						X					X	X		X				X	X	X	X				X	X			X								X		X						
LS-D17	X	X	X			X						X					X	X							X		X		X	X		X	X		X					X			X	X							
LS-D19	X			X		X			X			X					X	X						X					X	X													X		X						
LS-D20	X																X	X						X			X				X	X			X								X		X						
LS-D27	X																X	X						X			X				X	X			X	X	X						X		X						
LS-E1	X	X	X		X												X			X						X	X		X				X	X		X							X		X		X				
LS-E2	X	X	X																									X																							
LS-E4	X	X	X	X																X								X									X						X								
LS-E5	X	X	X	X												X	X			X								X			X		X	X			X						X		X						
LS-E7			X														X	X													X	X					X														
LS-E8(2)	X	X	X	X	X				X							X	X		X	X							X	X	X	X			X				X						X		X						
LS-E9	X	X	X													X										X	X	X	X	X	X		X	X	X		X						X	X	X						
LS-E10	X																X			X	X										X	X					X						X		X						
LS-E11	X	X	X	X													X	X						X				X	X		X	X					X						X		X						
LS-E13	X	X	X						X											X						X	X	X	X				X	X		X	X						X		X						
LS-E16(2)	X	X	X						X	X													X					X	X	X			X	X	X		X						X	X	X						
LS-E18	X	X	X	X														X		X				X					X	X			X		X								X	X	X						
LS-E19(2)	X	X	X	X					X	X							X			X				X			X	X	X	X			X	X			X						X	X	X						
LS-E20(2)	X	X	X	X													X			X				X					X	X		X	X	X			X						X								
LS-E21	X	X	X	X													X			X								X	X						X	X							X		X						
LS-E22(2)	X	X	X						X							X				X						X		X	X	X			X	X	X		X							X	X	X				X	
LS-E23	X	X	X		X															X											X	X	X				X								X						

Table D-1 (continued).

Sample	Feature																																																	
	PS 1	WHL 2	DEL 3	LC 4	HLD 5	WS 6	XLM 7	PLA 8	HOR 9	CU 10	OOID 11	BI 12	CR 13	INV 14	SUP 15	MU 16	FR 17	AB 18	IMB 19	1L 20	2L 21	3L 22	4L 23	CG 24	ONC 25	BR 26	BG 27	ART 28	SHP 29	PS 30	MB 31	SP 32	FEC 33	PM 34	INT 35	PEL 36	SB 37	BL 38	SIN 39	SSN 40	STR 41	RAD 42	MI 43	SHM 44	AM 45	VUG 46	CHNL 47	FEN 48	MLO 49	XL 50	HEM 51
LS-E24(a,b)		X	X	X																X								X	X	X	X		X	X	X		X									X				X	
LS-E25																															X	X					X														
LS-E27			X						X				X				X	X						X			X		X						X				X	X			X		X						
LS-E28	X																X	X		X				X			X								X								X		X						
LS-E29	X			X													X	X		X				X			X		X	X			X	X	X								X								
LS-E30	X	X	X			X			X			X					X			X								X	X	X			X	X	X								X	X	X						
LS-E32	X	X	X	X													X	X		X								X	X	X			X		X		X						X	X	X						
LS-E33	X	X	X	X													X			X				X					X			X					X						X								
LS-E34	X	X	X	X					X			X					X	X						X				X	X	X		X			X	X	X						X	X	X						
LS-E35(b)	X	X	X													X	X	X		X				X	X	X	X	X	X				X	X	X	X	X	X		X			X	X	X						
LS-E36	X	X	X	X													X			X							X	X	X	X				X	X	X	X						X	X	X						
LS-E37	X	X	X													X	X			X									X	X			X		X		X						X	X	X						
LS-E38	X	X	X			X						X		X			X	X		X							X	X	X	X					X	X	X						X	X	X						
LS-E40	X	X	X	X													X			X	X	X		X							X	X			X	X	X								X						
LS-E42	X	X	X	X													X	X		X	X			X	X		X		X	X	X	X	X		X	X	X						X	X	X						
LS-E43	X	X	X	X													X			X				X		X	X				X	X			X		X								X						
LS-E48	X	X	X	X		X						X								X								X	X	X			X		X	X	X							X							
LS-E49	X					X						X					X	X						X			X				X	X			X	X	X	X		X			X		X						X
LS-E50	X	X	X									X					X	X	X	X				X			X	X	X	X	X		X	X	X	X	X	X					X	X	X						
LS-E52	X	X	X	X	X										X		X			X						X		X	X	X	X		X		X	X	X							X	X						
LS-E53	X	X	X	X											X		X							X			X	X			X				X		X			X			X		X						
LS-E54		X	X			X											X	X		X				X			X		X	X			X		X								X	X	X						
LS-E55	X	X	X			X											X	X									X					X	X	X	X		X			X			X		X						
LS-E56						X			X				X				X	X						X			X								X	X							X		X						
LS-E57	X					X						X					X	X						X			X		X		X	X			X	X	X						X								
LS-E60	X	X	X	X												X	X	X		X				X		X	X		X	X	X	X			X	X	X			X	X			X	X						
LS-E62						X		X									X	X									X									X															
LS-E63	X	X	X														X			X				X			X				X	X	X				X			X			X								
LS-E64	X	X	X	X																X				X		X					X						X						X								
LS-E69	X	X	X	X													X	X		X				X		X	X	X			X	X	X		X	X	X						X		X						
LS-E74	X	X	X														X			X								X									X						X								
LS-E80	X	X	X												X	X	X	X						X	X	X			X	X	X	X			X	X							X		X						
LS-E83	X			X													X	X		X				X		X					X	X				X							X								
LS-E86	X			X													X	X									X				X	X				X							X		X						
LS-E87			X	X								X				X	X	X						X		X	X		X		X	X				X	X				X			X	X						
LS-E88	X																X	X		X				X		X	X				X	X			X	X	X						X		X						X
LS-E93	X	X	X	X													X							X			X				X	X											X		X						
LS-E97						X											X	X		X				X		X	X				X	X			X	X	X						X		X						X
LS-E98	X	X															X	X		X				X			X				X	X				X							X								
LS-E100	X	X	X			X			X							X	X	X						X			X				X	X			X	X	X						X		X						
LS-E102	X																X	X						X	X	X	X	X			X	X				X	X						X		X						X
LS-E105	X	X	X	X													X														X	X	X				X														
LS-E106	X	X	X			X				X		X				X	X	X		X				X		X	X		X	X	X	X			X	X	X						X	X	X						
LS-E107	X	X	X			X			X	X		X					X	X	X	X				X		X			X		X	X	X	X		X	X							X	X						
LS-E108	X	X	X	X					X			X								X	X					X					X	X				X	X														
LS-E109	X	X	X			X			X	X							X			X									X		X	X	X				X														
LS-E111(b)	X																X	X		X				X	X										X	X	X						X		X						
LS-E111(T)	X																X	X						X		X	X				X	X			X		X						X		X						
LS-E113	X	X	X						X								X	X		X				X			X		X	X					X	X				X			X	X	X						X
LS-E114	X																X	X		X	X			X	X	X	X				X	X			X	X							X		X						X
LS-E117	X			X												X	X	X		X				X	X	X	X				X	X			X	X	X						X		X						
LS-E118	X					X							X			X	X	X						X	X	X	X				X	X			X	X	X						X		X				X		
LS-E120	X			X		X			X				X			X	X	X						X		X					X	X			X	X	X						X		X						
LS-E121						X											X	X														X				X	X														
LS-E124	X	X	X						X	X						X	X	X		X									X		X	X				X	X						X	X	X						
LS-E125						X											X	X													X	X	X				X														
LS-E126	X	X	X	X					X	X						X	X			X						X			X	X	X	X	X	X		X	X						X	X	X				X		

Table D-1 (continued).

Sample	PS 1	WHL 2	DEL 3	LC 4	HLD 5	WS 6	XLM 7	PLA 8	HOR 9	CU 10	OOID 11	BI 12	GR 13	INV 14	SUP 15	MU 16	FR 17	AB 18	IMB 19	1L 20	2L 21	3L 22	4L 23	CC 24	ONC 25	BR 26
LS-E127	X	X	X			X		X	X	X		X	X				X	X	X							
LS-E130	X	X	X			X						X					X	X		X						X
LS-E131	X	X	X						X	X																
LS-E135	X	X	X	X		X		X	X	X		X	X			X	X	X		X						
LS-E137						X		X	X							X	X	X								
LS-E140						X		X	X						X	X	X	X								
LS-E142(c)	X					X		X	X			X	X				X	X		X				X	X	X
LS-E144	X	X	X	X		X			X	X		X				X	X	X		X				X	X	X
LS-E145	X														X		X	X		X				X	X	
LS-E146	X																			X	X	X		X		X
LS-E147	X																X	X						X	X	X
LS-E148	X																X	X		X	X			X	X	
LS-E149	X	X															X	X		X	X	X		X	X	X
LS-E152		X	X			X											X	X								
LS-E153		X	X			X	X	X	X	X							X	X								
LS-E154	X	X	X		X							X	X			X	X			X						
LS-E155			X			X	X	X	X								X	X								
LS-E156						X	X	X	X								X	X								
LS-E157						X	X	X																		
LS-E158(c)	X	X	X			X		X	X			X					X	X		X	X					
LS-E159	X							X									X	X								
LS-E160	X	X	X													X	X									
LS-E161	X	X	X			X			X			X	X			X	X			X	X					X
LS-E162						X		X									X	X								
LS-E163						X		X									X	X								
LS-E164	X	X	X														X									
LS-E165(c)	X	X	X			X			X	X		X	X			X	X	X	X	X						X

Sample	BG 27	ART 28	SHP 29	PS 30	MB 31	SP 32	FEC 33	PM 34	INT 35	PEL 36	SB 37	BL 38	SIN 39	SSN 40	STR 41	RAD 42	MI 43	SHM 44	AM 45	VUG 46	CHNL 47	FEN 48	MLD 49	XL 50	HEM 51
LS-E127			X		X	X	X				X						X	X	X						
LS-E130										X															
LS-E131		X			X		X	X		X							X								
LS-E135		X			X	X				X	X														
LS-E137					X	X				X	X														
LS-E140					X	X	X	X	X	X	X				X										
LS-E142(c)	X				X	X	X		X	X					X		X		X						
LS-E144	X		X	X	X		X		X	X	X							X	X						
LS-E145	X				X	X			X	X							X		X						X
LS-E146	X			X	X	X			X	X	X								X						
LS-E147	X	X			X	X			X	X	X						X		X						X
LS-E148	X				X	X					X														
LS-E149		X			X	X			X		X			X				X	X				X		
LS-E152					X	X	X				X														
LS-E153			X							X															
LS-E154	X		X	X						X	X	X		X					X	X	X		X	X	
LS-E155	X		X			X				X															
LS-E156	X				X					X	X														
LS-E157										X	X														
LS-E158(c)	X		X							X							X			X			X		
LS-E159									X																
LS-E160					X	X			X	X										X					
LS-E161	X		X	X					X	X				X					X	X	X		X	X	
LS-E162										X															
LS-E163									X	X										X		X			
LS-E164		X			X		X				X														
LS-E165(c)		X	X		X	X	X		X	X	X							X			X		X	X	

Table D-2. List of Samples and Contained Features Arranged by Sample Cluster Analysis (Q-Mode).

	Feature																																																	
Samples	PS	W/D	1L	CG	MI	AM	INT	BG	WS	PEL	FR	AB	MB	SP	SB	LC	ART	FEC	SHP	PS	SHM	CHNL	XL	VUG	HLD	MLD	2L	3L	FEN	4L	STR	SIN	IMB	XLM	INV	SUP	OOID	HEM	SSN	BL	RAD	CU	GR	MU	PM	BR	BI	ONC	PLA	HOR
1a	subcluster																																																	
A1							X		X	X	X	X	X		X																																		X	
A2							X		X	X	X	X	X		X																						X												X	
A3				X	X	X	X		X	X	X	X																																		X			X	
A7					X	X	X		X	X	X	X																						X															X	
E56				X	X	X	X	X	X	X	X	X																														X							X	
A19			X	X	X	X	X		X	X	X	X	X																																					
B7			X		X	X	X		X	X	X	X																																						
B38					X	X	X		X		X	X					X																				X								X					
B10				X		X			X	X	X	X		X																																X				
B11				X				X			X	X		X																																				
B12				X			X		X	X	X	X																																		X	X			
1b	subcluster																																																	
B15				X	X	X	X		X	X	X	X						X	X	X	X																									X			X	
C46	X			X	X	X	X	X	X	X	X	X									X																										X	X	X	
D19	X			X	X	X			X		X	X				X			X	X																										X			X	
E27		X		X	X	X	X	X			X	X							X													X							X			X							X	
1C	subcluster																																																	
A22	X				X	X		X	X	X	X	X	X	X																																X	X			
C50	X			X	X	X	X	X	X	X	X	X																																		X	X			
A28	X			X	X	X	X	X	X		X	X	X	X																							X									X	X			
C7	X	X		X	X	X		X	X	X	X	X	X	X																																X	X			
C9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																														X	X	X			
D16	X	X	X	X	X	X	X	X	X		X	X	X	X																															X	X	X			
E142	X		X	X	X	X	X	X	X	X	X	X	X	X				X													X											X			X	X	X	X	X	
2a	subcluster																																																	
A4							X		X	X	X	X	X	X										X					X																					
E163							X		X	X	X	X												X					X																			X		
B22							X		X	X	X	X												X																				X						
A6									X	X	X	X		X																																		X	X	
A50									X	X	X	X		X																																		X		
B1									X	X	X	X		X																																		X		
A37						X			X	X	X	X		X																																		X		
A49									X	X	X	X																																				X		
A62								X	X	X	X	X																																				X		
B26							X		X	X	X	X																						X														X		
A9									X	X	X	X																																					X	
A15									X	X	X	X																																						
A47									X	X	X	X																																					X	
B3							X	X	X	X	X	X																															X		X				X	
B5							X		X	X	X	X		X		X																										X							X	
A43									X	X	X	X										X		X											X	X												X	X	
2b	subcluster																																																	
A12							X		X	X	X	X	X	X																																		X	X	
B20									X	X	X	X	X	X																																		X	X	
A40									X		X	X	X	X																																		X	X	
B2									X	X	X	X	X																													X						X	X	
E137									X	X	X	X	X	X	X																												X					X	X	
A42						X		X	X	X	X	X	X	X							X																											X	X	
E156								X	X	X	X	X	X		X																			X														X	X	
B19							X		X	X	X	X	X	X	X			X																						X								X	X	
E140							X		X	X	X	X	X	X	X			X													X					X							X	X				X	X	
2c	subcluster																																																	
A51									X	X	X	X	X	X								X	X	X		X																		X						
A52									X	X	X	X	X	X								X		X		X			X															X						
2d	subcluster																																																	
A18									X		X	X																																						
B27									X		X	X			X																																			
E162									X	X	X	X																																				X		

Table D-2 (continued).

Samples	Feature																																																	
	PS	W/D	1L	CG	MI	AM	INT	BG	WS	PEL	FR	AB	MB	SP	SB	LC	ART	FEC	SHP	PS	SHM	CHNL	XL	VUG	HLD	MLD	2L	3L	FEN	4L	STR	SIN	IMB	XLM	INV	SUP	OOID	HEM	SSN	BL	RAD	CU	GR	MU	PM	BR	BI	ONC	PLA	HOR
2e	subcluster																																																	
E125									X		X	X	X	X	X			X																																
E7											X	X	X	X	X	X																																		
E25													X	X	X																																			
A39									X	X	X	X	X	X	X																																	X	X	
A41									X	X	X	X	X	X	X																																	X	X	
A48									X	X	X	X	X	X	X																																	X		
A44									X	X	X	X	X	X	X																				X													X		
B4									X	X	X	X	X	X	X									X																										
E121									X	X	X	X		X	X																																			
C70	X							X		X	X	X	X	X	X																																			
E152		X							X		X	X	X	X	X			X																																
D13		X		X				X	X		X	X	X	X	X																														X	X				
D5		X						X	X		X	X	X	X	X		X	X																																
2f	subcluster																																															X	X	
A36						X	X		X	X	X	X		X	X				X							X								X											X			X	X	
B44					X	X		X	X	X	X	X							X															X							X							X	X	
E153		X							X	X	X	X							X															X														X	X	
E155		X						X	X	X	X	X		X					X															X														X		
E157									X	X					X																			X																
2g	subcluster																																								X			X	X	X			X	
E107	X	X	X	X		X			X	X	X	X	X	X	X			X	X		X												X								X	X				X		X	X	
E127	X	X			X	X			X		X	X	X	X	X			X	X		X												X								X	X	X		X	X			X	
E165	X	X	X				X		X	X	X	X	X	X	X		X	X	X		X	X	X			X							X																	
3a	subcluster																																													X			X	
A11	X	X							X	X	X	X																																	X	X				
E130	X	X	X						X	X	X	X																																		X	X		X	
B39	X	X	X						X	X	X	X							X	X																										X		X	X	
A53	X	X	X						X		X	X				X																			X											X		X	X	
E158	X	X	X		X			X	X	X	X	X							X					X		X	X																							
3b	subcluster																																													X			X	
A32	X	X	X						X		X	X	X	X		X																													X	X				
A056	X	X	X						X	X	X	X	X	X	X	X																														X				
A34	X	X							X	X	X	X	X	X	X																															X				
B52	X	X							X	X	X	X	X	X	X			X																							X	X	X			X		X	X	
E135	X	X	X						X	X	X	X	X	X	X	X	X																																	
3c	subcluster																																																X	
A23	X	X	X	X		X	X			X	X					X			X																															
E21	X	X	X		X	X	X			X	X					X	X		X																														X	
A25	X	X			X	X	X		X	X	X	X				X			X							X									X												X		X	
A24		X	X	X	X	X	X		X	X	X	X				X											X																							
A54		X			X	X			X		X	X				X			X	X		X																												
A56		X			X	X	X		X	X	X					X	X		X	X															X													X	X	
C52		X	X		X	X	X		X		X	X								X	X														X						X							X	X	
B6	X	X					X		X	X	X	X	X	X		X			X																														X	
C66		X				X	X		X	X	X	X	X	X	X	X		X	X	X																X									X	X			X	
B50	X	X	X					X	X	X	X	X	X	X	X	X		X	X																											X				
B57	X	X	X		X		X	X	X	X	X	X			X	X		X	X							X																								
3d	subcluster																																													X	X			
A26	X	X	X	X		X	X		X	X	X	X	X	X		X			X	X	X					X	X	X		X																X				
A27	X	X	X	X		X		X	X	X	X	X	X	X	X	X			X	X	X					X	X	X																			X			
E42	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X	X						X																			X				
C60	X	X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X																				X		X		X	X				
E106	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X																				X		X		X	X	X		X	
E144	X	X	X	X		X	X	X	X	X	X	X	X		X	X		X	X	X	X																													
3e	subcluster																																													X			X	
A14	X	X	X	X	X	X	X		X		X	X														X																				X				
A16	X	X		X	X	X	X		X	X	X	X	X	X								X		X		X																				X			X	
B40	X	X			X	X	X	X	X	X	X	X		X		X			X	X	X					X																				X	X		X	
B60	X	X			X	X	X		X	X	X	X							X	X	X	X				X							X																	

Table D-2 (continued).

Samples	PS	W/D	1L	CG	MI	AM	INT	BG	WS	PEL	FR	AB	MB	SP	SB	LC	ART	FEC	SHP	PS	SHM	CHNL	XL	VUG	HLD	MLD	2L	3L
3f	subcluster																											
B36		X	X		X	X	X		X			X							X		X	X	X	X	X			
B37		X			X	X	X		X		X	X	X		X				X	X	X	X	X	X	X	X		
E154	X	X	X			X		X	X	X	X				X				X	X		X	X	X		X		
E161	X	X	X			X	X	X	X	X	X								X	X		X	X	X		X	X	
3g	subcluster																											
B23	X						X				X	X				X						X		X		X		
E159	X						X				X	X																
E29	X		X	X	X		X	X			X	X				X		X	X	X								
B24	X	X		X							X	X				X	X		X	X	X							
B331	X	X	X	X			X				X	X				X							X	X	X	X	X	
B35	X	X	X	X							X	X		X				X	X	X		X	X	X	X	X	X	
4a	subcluster																											
A17	X	X	X	X		X	X				X	X	X	X												X		
A62	X	X	X	X		X					X	X	X	X													X	
E40	X	X	X	X		X	X			X	X		X	X	X	X											X	X
E43	X	X	X	X		X	X	X			X		X	X	X	X												
E160	X	X					X			X	X		X	X										X				
A35	X	X			X	X	X		X	X	X	X	X	X	X						X							
E100	X	X		X	X	X	X	X	X	X	X	X	X	X	X													
D8	X	X		X	X	X	X	X		X	X	X	X	X	X						X					X		
E80	X	X		X	X	X	X			X	X	X	X	X					X	X								
E60	X	X	X	X		X	X	X		X	X	X	X	X	X	X			X	X	X							
E87		X		X		X		X		X	X	X	X	X	X	X			X		X							
4b	subcluster																											
A20	X		X	X		X	X			X	X	X	X	X	X												X	X
A29	X		X	X		X	X				X	X	X	X	X													
E148	X		X	X				X			X	X	X	X	X												X	
E10	X		X		X	X					X		X	X	X												X	
E146	X		X	X		X	X	X		X			X	X	X					X							X	X
4c	subcluster																											
A31	X		X	X	X	X	X	X		X	X	X	X	X	X			X									X	X
E117	X		X	X	X	X	X	X		X	X	X	X	X	X	X												
4d	subcluster																											
B48	X		X	X	X		X	X	X	X	X	X	X	X	X													
B71	X		X	X	X	X	X	X		X	X	X	X	X	X													
B78	X		X	X	X	X	X	X		X	X	X	X	X	X													
E88	X		X	X	X	X	X	X		X	X	X	X	X	X													
E97			X	X	X	X	X	X	X	X	X	X	X	X	X													
4e	subcluster																											
E102	X			X	X	X		X		X	X	X	X	X	X		X											
E147	X			X	X	X	X	X		X	X	X	X	X	X		X											
E114	X		X	X	X	X	X	X		X	X	X	X	X													X	
E145	X		X	X	X	X	X	X		X	X	X	X	X														
4f	subcluster																											
B72	X				X	X				X	X	X	X	X														
E86	X				X	X		X		X	X	X	X	X		X												
E83	X		X	X	X					X	X	X	X	X		X												
E98	X	X	X	X	X			X		X	X	X	X	X														
4g	subcluster																											
B8	X			X			X		X	X	X	X	X	X	X													
E49	X			X	X	X	X	X	X	X	X	X	X	X	X													
E57	X			X	X		X	X	X	X	X	X	X	X	X				X									
C4				X	X	X			X	X	X	X	X	X	X													
C63	X			X	X	X			X	X	X	X	X	X	X	X										X		
E118	X			X	X	X	X	X	X	X	X	X	X	X	X											X		
E120	X			X	X	X	X		X	X	X	X	X	X	X	X												
4h	subcluster																											
B62	X			X	X	X	X	X	X		X	X	X	X	X													
C52				X	X	X	X	X	X		X	X	X	X	X													

Samples	FEN	4L	STR	SIN	IMB	XLM	INV	SUP	DOID	HEM	SSN	BL	RAD	CU	GR	MU	PM	BR	BI	ONC	PLA	HOR
3f																					X	
B36																					X	
B37					X						X	X		X	X			X				
E154											X			X	X		X	X			X	
E161																						
3g																						
B23																				X		
E159																X						
E29													X		X						X	
B24							X										X					
B331			X	X					X								X					
B35																						
4a																						
A17																						
A62																						
E40																	X					
E43															X							
E160															X						X	
A35															X						X	
E100																						
D8								X							X		X		X			
E80								X			X				X		X					
E60			X												X		X	X				
E87			X																			
4b																			X			
A20																			X			
A29																			X			
E148																						
E10																	X					
E146																						
4c																	X		X			
A31															X		X		X			
E117																						
4d																		X	X			
B48																			X			
B71																	X					
B78										X							X					
E88										X							X					
E97																						
4e										X							X		X			
E102										X							X		X			
E147										X							X		X			
E114										X									X			
E145								X														
4f																	X					
B72																						
E86																	X					
E83																						
E98																						
4g											X	X										
B8				X						X	X	X						X				
E49																		X				
E57																						
C4																		X				
C63														X	X		X		X			
E118														X	X		X				X	
E120																						
4h									X													
B62																						
C52																						

Table D-2 (continued).

Samples	Feature																																																	
	PS	W/D	1L	CG	MI	AM	INT	BG	WS	PEL	FR	AB	MB	SP	SB	LC	ART	FEC	SHP	PS	SHM	CHNL	XL	VUG	HLD	MLD	2L	3L	FEN	4L	STR	SIN	IMB	XLM	INV	SUP	OOID	HEM	SSN	BL	RAD	CU	GR	MU	PM	BR	BI	ONC	PLA	HOR
D9				X	X	X	X	X	X		X	X	X	X	X																																			
D1	X			X	X	X	X	X			X	X	X	X	X			X																												X				
E111T	X			X	X	X	X	X			X	X	X	X	X																																			
B70	X			X	X	X	X			X	X	X	X	X	X																																			
C1	X			X	X	X	X				X	X	X	X	X																																			
D27	X			X	X	X	X	X		X	X	X	X	X	X																																	X		
B64	X			X	X	X	X	X			X	X	X	X																																				
D20	X			X	X	X	X	X			X	X	X	X																															X			X		
C44	X			X	X	X	X	X			X	X	X	X				X																												X		X		
B67	X			X	X	X	X				X	X	X	X	X																																	X		
B77	X			X	X	X	X				X	X	X	X	X																																	X		
C6	X	X		X	X	X	X				X	X	X	X	X																																	X		
C8	X			X	X						X	X	X	X	X																																	X		
C10	X			X		X					X	X	X	X																																				
4i	subcluster																																																	
C14	X			X	X	X	X			X	X	X							X	X						X																								
E28	X		X	X	X	X	X	X			X	X																																				X		
E1118	X		X	X			X			X	X	X			X																																			
5a	subcluster																																				X	X	X							X		X		
A601	X	X	X	X	X	X	X	X		X	X	X	X	X	X										X		X	X		X							X	X	X							X				
B65	X		X	X	X	X	X	X		X	X	X																				X					X											X		
B45	X		X	X	X		X				X	X	X								X				X		X																							
5b	subcluster																																					X								X		X		
A30	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X							X		X																				X				
E69	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X																					X											
E53	X	X		X	X	X	X	X			X		X		X	X	X																			X														
C64	X	X	X	X	X	X	X	X			X	X	X	X	X	X																																		
C65	X		X	X	X	X		X		X	X	X	X	X	X	X																								X										
C68	X	X			X	X		X			X	X	X	X	X																																			
E93	X	X		X	X	X		X			X		X	X		X																																		
E11	X	X		X	X	X					X	X	X	X	X	X	X		X																															
5c	subcluster																																				X	X												
B25	X	X	X	X	X		X				X	X				X	X																				X									X				
B49	X	X	X	X	X	X	X	X			X	X				X	X	X			X	X																												
C58	X	X	X	X	X	X					X	X			X		X	X		X	X					X											X											X		
B58	X	X	X	X	X	X	X				X	X			X	X	X								X		X																					X		
C42	X	X	X	X	X	X				X	X	X			X	X											X	X											X							X		X		
E149	X	X	X	X		X	X				X	X	X	X	X		X				X					X	X	X																						
5d	subcluster																																				X													
B16	X	X	X	X	X	X	X			X	X	X				X			X	X	X																													
E18	X	X	X	X	X	X	X					X				X		X	X	X	X																											X		
C13	X	X	X	X	X	X	X	X		X	X	X				X		X	X	X					X																									X
C12	X	X	X	X	X	X	X	X		X	X	X						X	X	X	X																	X	X											X
E113	X	X	X	X	X	X	X	X		X	X	X							X	X	X																									X		X		X
C37	X	X	X		X	X	X			X	X	X						X	X	X	X				X																						X			X
E34	X	X		X	X	X	X			X	X	X		X	X	X	X		X	X	X																								X					
E36	X	X	X		X	X	X	X		X	X				X	X	X		X	X	X																										X			
E38	X	X	X		X	X	X	X	X	X	X	X			X		X		X	X	X														X															
5e	subcluster																																															X		
C49	X	X		X	X	X	X	X	X	X	X	X					X	X	X	X	X															X											X	X		
C56	X	X	X	X	X	X	X	X	X		X	X					X	X	X	X	X																													
E54		X	X	X	X	X	X	X	X		X	X						X	X	X	X																		X								X	X		
D17	X	X			X		X	X	X		X	X		X				X	X	X	X																		X	X				X	X	X		X		
E35	X	X	X	X	X	X	X	X		X	X	X			X		X	X	X		X																			X					X		X			
E50	X	X		X	X	X	X	X		X	X	X	X		X		X	X	X	X	X												X																	
6a	subcluster																																																	
A57	X	X				X	X										X	X	X	X	X																													
A59	X	X	X		X	X	X									X	X		X	X	X																													
E32	X	X	X		X	X	X				X	X			X	X	X	X	X	X	X																							X						
E37	X	X	X		X	X	X				X				X			X	X	X	X																								X		X			X

Table D-2 (continued).

Samples	PS	W/D	1L	CG	MI	AM	INT	BG	WS	PEL	FR	AB	MB	SP	SB	LC	ART	FEC	SHP	PS	SHM
E30	X	X	X		X	X	X		X		X						X	X	X	X	X
A64	X	X	X	X		X	X			X	X						X	X	X	X	X
E48	X	X	X				X		X	X					X	X	X	X	X	X	X
E52	X	X	X			X	X			X	X		X		X	X	X	X	X	X	X
E9	X	X			X	X	X	X					X		X		X	X	X	X	X
E22	X	X	X			X	X								X		X	X	X	X	X
E24		X	X				X						X		X	X	X	X	X	X	
6b	subcluster																				
B59	X	X			X						X			X	X			X			
E105	X	X									X		X	X	X	X		X			
E164	X	X									X		X		X		X	X			
E109	X	X	X						X		X		X	X	X			X			
E202	X	X	X	X	X						X			X	X	X		X	X	X	
E33	X	X	X	X	X						X			X	X	X			X		
C54	X	X	X	X	X	X	X	X			X	X	X	X	X			X			
E63	X	X	X	X	X			X			X		X	X	X			X			
E55	X	X			X	X	X	X	X		X	X		X	X			X			
6c	subcluster																				
E5	X	X	X		X	X					X				X	X		X			
E8	X	X	X		X	X		X			X				X	X	X	X	X	X	
E13	X	X	X		X	X		X		X					X		X	X	X		
E16	X	X	X		X	X	X								X		X	X	X	X	X
E19	X	X	X	X	X	X		X			X				X	X	X	X	X	X	X
E124	X	X	X		X	X				X	X	X	X	X	X				X		X
E126	X	X	X		X	X				X	X		X	X	X	X		X	X	X	X
6d	subcluster																				
C15	X	X	X	X	X	X	X									X			X	X	X
C36		X	X	X	X	X			X							X		X	X		
C22	X	X	X	X	X	X		X								X	X	X	X	X	X
C27		X	X	X	X	X	X		X												X
C30		X		X	X	X										X					X
7a	subcluster																				
A<59		X	X	X									X	X	X	X					
E64	X	X	X	X	X								X		X	X					
E108	X	X	X							X			X	X	X	X					
7b	subcluster																				
C18	X	X	X										X		X						
E23	X	X	X			X							X	X	X			X			
C21	X	X	X				X						X	X	X	X					
C23	X	X	X			X							X		X	X					
7c	subcluster																				
C31	X	X	X	X	X	X							X		X	X					
C35	X	X	X	X	X	X							X		X	X					
C32	X		X	X	X	X							X		X	X					
C34	X		X	X		X							X		X	X					
7d	subcluster																				
B332		X																			
B34		X	X								X	X				X					
E2	X	X															X				
E4	X	X	X		X										X	X	X				
E74	X	X	X		X						X				X		X				
E131	X	X			X					X			X				X	X			
C17	X	X	X		X	X				X	X					X		X	X		
E1	X	X	X		X	X		X		X	X							X	X		
Ch1	X	X	X	X	X		X	X									X	X	X		

Samples	CHNL	XL	VUG	HLD	MLD	2L	3L	FEN	4L	STR	SIN	IMB	XLM	INV	SUP	OOID	HEM	SSN	BL	RAD	CU	GR	MU	PM	BR	BI	ONC	PLA	HOR
E30																X							X			X			
A64						X																			X				
E48																								X					
E52				X											X							X	X	X					
E9																						X	X	X				X	
E22		X	X																				X						
E24		X	X																										
6b																												X	
B59																													
E105																													
E164																				X								X	
E109																							X						
E202																													
E33																													
C54						X											X												
E63																							X						
E55																													
6c																						X	X						
E5																						X						X	
E8												X											X	X				X	
E13																				X			X					X	
E16						X	X		X											X			X					X	
E19																				X		X						X	
E124																				X		X	X	X				X	
E126					X																								
6d																								X				X	
C15	X	X		X	X																		X	X				X	
C36	X	X	X	X	X																		X			X		X	
C22	X		X	X	X										X			X	X					X					
C27			X	X	X														X									X	
C30	X			X																									
7a																								X					
A<59				X		X	X		X															X					
E64																								X	X			X	
E108						X																							
7b																													
C18			X	X																									
E23				X														X	X										
C21	X	X	X	X	X													X	X										
C23	X	X	X	X	X																								
7c																		X	X							X			
C31		X	X	X	X														X										
C35		X	X	X	X						X							X	X										
C32		X		X	X	X	X				X							X	X										
C34		X	X	X	X						X																		
7d																			X				X						
B332		X			X																								
B34																													
E2																													
E4																													
E74																				X			X					X	
E131																							X						
C17				X																			X	X					
E1	X			X																			X			X			
Ch1			X	X		X																							

Note: Order of features arranged by feature (R-mode) cluster analysis.

Table D-3. Features Present in the Sample Subclusters.

Subcluster	PS	W/D	1L	CC	HI	AM	INI	BC	WS	PEL	FR	AB	MB	SP	SB	LC	ARI	FEC	SHP	PS	SHM	CHNL	XL	VUG	HLD	MLD	2L	3L	FEN	4L	STR	SIN	IMB	XLN	INV	SUP	OOID	HEM	SSN	BL	RAD	CU	CR	MU	PM	BR	BI	ONC	PLA	HOR	(n)*
1a			2	6	6	7	9	2	11	9	11	11	3	2	2		1																	1			2						1			1	3	1		5	11
1b	2	1		4	4	4	3	2	3	2	4	4				1		1	3	2	2											1							1				1				2	1	1	4	4
1c	7	3	3	6	7	7	5	7	7	5	7	7	6	6	1			1								1					1						1						1			3	7	7	1	1	7
2a						1	6	2	16	16	16	16	1	6		1						1		4		1			2					1	1	1							1	1	1	1			9	6	16
2b						1	3	2	9	8	9	9	9	7	4			2			1										1			1		1				1			1	2	1				9	9	9
2c									2	2	2	2	2	2								2	1	2		2			1																2						2
2d									3	1	3	3			1																																		1		3
2e	1	3		1				3	10	7	12	12	12	13	13	1	1	3						1											1											1	1		4	2	13
2f		2			1	2	1	2	5	5	4	4		2	2				4							1								5								1				1			5	4	5
2h	3	3	2	1	1	2	1		3	2	3	3	3	3	3		1	3	3		3	1	1			1							3									3	2	1	1	2	3		1	3	3
3a	5	5	4		1			1	5	4	5	5				1			2	1				1		1	1								1											1	5	1	2	4	5
3b	5	5	3						5	4	5	5	5	5	4	3	1	1																								1	1	1		1	5		1	2	5
3c	6	11	6	2	7	8	9	2	9	9	11	8	3	3	3	10	2	3	9	4	1	1				2	1							3	1							1				1	2	1	2	7	11
3d	6	6	5	6	3	6	5	5	5	6	6	6	6	5	5	4		3	6	6	6					2	3	2		1												2		2		2	5	3		1	6
3e	4	4	1	2	4	4	4	1	4	3	4	4	1	2		1			2	2	2	2		1		4							1														4	1		3	4
3f	2	4	3		2	4	3	2	4	2	3	2	1		2				4	3	2	4	4	4	2	3	1						1						2	1			2	2		1	2			3	4
3g	6	3	3	4	1		4				6	6		1		4	1	2	3	3	1	2	2	3	2	3	2				1	1			1		1				1			1	1	2			1	1	6
4a	10	11	5	9	4	10	9	5	2	8	11	8	11	11	7	4			3	2	4			1		2	2	1			2					2			1					6		4	1	1		2	11
4b	5		5	4	1	4	3	2		2	4	3	5	5	5					1							4	2																		1		3			5
4c	2		2	2	2	2	2	2		2	2	2	2	2	2	1		1									1	1																1		2		2			2
4d	4		5	5	5	4	5	5	2	5	5	5	5	5	5																							2								3	1	2			5
4e	3		2	4	4	4	3	4		4	4	4	4	4	2		2										1									1		4								3		4			4
4f	4	1	2	2	4	2		2		4	4	4	4	4		2																														2					4
4g	6			7	6	5	5	3	7	7	7	7	7	7	7	2			1							2						1						1	2	2			2	2		2	3	1		1	7
4h	14	1		16	15	15	14	9	3	2	16	16	16	16	12			2																			1								1	2		7			16
4i	3		2	3	2	2	3	1		2	3	3			1				1	1						1																						1			3
5a	3	1	3	3	3	2	3	2		2	3	3	2	1	1						1				2		2	1		1		1					3	2	2							2		2			3
5b	8	7	4	7	8	8	4	7		2	8	6	8	7	7	7	4	1	1					1		1										1		1	1	1						2		1			8
5c	6	6	6	6	5	5	4	1		1	6	6	1	1	4	4	5	2		1	3	1			1	2	3	2									3	1	1							2		3			6
5d	9	9	8	6	9	9	9	5	1	8	8	8		1	3	5	3	4	9	9	8				2										1		1	1	1						1	1	2	2		4	9
5e	5	6	3	5	6	5	6	6	4	3	6	6	1	1	2		4	6	6	5	6												1			1			2	2				1	2	1	3	4			6
6a	10	11	9	1	5	9	11	1	2	3	5	1	3		7	5	10	10	11	11	10		2	2	1		1									1	1							3	5	3	2	1		2	11
6b	9	9	5	4	6	2	2	3	2		9	2	5	8	9	3	1	8	2	1							1												1			1			2					2	9
6c	7	7	7	1	7	7	1	3		3	5	1	2	2	7	4	4	6	6	4	4					1	1	1		1			1									4		4	5	2				6	7
6d	2	5	4	5	5	5	2	1	2							4	1	2	3	2	4	4	2	3	5	4										1				1	2				2	3		1		4	5
7a	2	3	3	2	1					1			3	2	3	3									1		2	1																		3	1			1	3
7b	4	4	4			2	1						4	2	4	2		1				2	2	3	4	2														2	2										4
7c	4	2	4	4	3	4							4		4	4							4	3	4	4	1	1				3								3	4							1			4
7d	7	9	6	1	6	2	1	2		3	4	1	1		2	3	5	4	3			1	1	1	3	1	1														1	1			5	1		1		1	9

*Number of slides.

Note: Order of features arranged by feature cluster analysis (R-mode).

Table D-4. Lithologic Composition (After Folk, 1974) of Samples Arranged by Sample Subclusters Established by Sample (Q-Mode) Cluster Analysis.

Sample Subclusters	Micrite Only	Micrite + Spar	Spar Only	Biolithite	Dismicrite	Laminite
1a	Subcluster					
A1			x			
A2			x			
A3			x			
A7			x			
E56			x			
A19			x			
B7		x				
B38			x			
B10	x	x				
B11		x	x			
B12	x	x				
1b	Subcluster					
B15			x			
C46			x			
D19			x			
E27			x			
1C	Subcluster					
A22	x	x				
C50	x		x			
A28			x			
C7	x					
C9	x	x				
D16	x					
E142	x	x	x			
2a	Subcluster					
A4					x	
E163					x	
B22					x	
2b	Subcluster					
A6						x
A50						x
B1		x	x			
A37			x			
A49						x
E62	x					
B26			x			
A9	x					
A15			x			
A47			x			
B3						x
B5	x					
A43						x
2c	Subcluster					
A12						x
B20						x
A40						x
B2						x
E137	x					
A42						x
E156						x
B19						x
E140						x
2d	Subcluster					
A51					x	
A52					x	
2e	Subcluster					
A18	x					
B27						x
E162						x
2f	Subcluster					
E125	x					
E7	x					
E25	x					
A39						x
A41						x
A48						x
A44						x
B4					x	
E121	x					
C70	x					
D5	x					
E152	x					
D13	x					
2g	Subcluster					
A36						*
B44						*
E153						*
E155						*
E157						*
2h	Subcluster					
E107						
E127						
E165						
3a	Subcluster					
A11	x					
E130	x	x				
B39			x			
A53			x			
E158	x		x			
3b	Subcluster					
A32	x					
A<56	x		x			
A34	x	x				
B52	x	x				
E135	x					
3c	Subcluster					
A23			x			
E21	x	x				
A25			x			
A24			x			
A54			x			
A56			x			
C62			x			
B6	x					
C66	x		x			
B50		x	x			
B57			x			
3d	Subcluster					
A26	x	x				
A27	x	x				
E42	x	x				
C60		x	x			
E106	x	x				
E144		x				
3e	Subcluster					
A14			x			
A16	x					
B40			x			
B60			x			
3f	Subcluster					
B36		x	x			
B37		x	x			
E154		x				
E161	x	x				
3a	Subcluster					
B23					x	
E159						x
E29	x	x				
B24		x	x			
B331	x					
B35	x					
4a	Subcluster					
A17	x					
A62	x					
E40	x	x				
E43	x					
E160	x					
A35			x			
E100	x					
D8	x	x				
E80	x	x				
E60	x	x	x			
E87	x	x				
4b	Subcluster					
A20	x	x				
A29	x					
E148	x					
E10	x					
E146	x					
4c	Subcluster					
A31		x	x			
E117	x					
4d	Subcluster					
B48	x	x				
B71	x	x				
B78	x					
E88	x					
E97	x					
4e	Subcluster					
E102	x					
E147	x					
E114	x					
E145	x					
4f	Subcluster					
B72	x					
E86	x					
E83	x					

Table D-4 (continued)

Sample Subclusters	Micrite Only	Micrite + Spar	Spar Only	Biolithite	Dismicrite	Laminite
E98	x					
4a	Subcluster					
B8	x	x				
E49		x	x			
E57	x					
C4	x					
C63	x	x				
E118	x	x				
E120	x	x	x			
4h	Subcluster					
B62	x					
C52	x					
D9	x					
D1	x	x				
E111T	x					
B70	x					
C1	x					
D27	x					
B64	x	x				
D20		x	x			
C44	x	x				
B67	x					
B77	x					
C6	x					
C8	x					
C10	x					
4i	Subcluster					
C14	x		x			
E28	x					
E111B			x			
5A	Subcluster					
A601	x					
B65	x	x	x			
B45			x			
5b	Subcluster					
A30	x					
E69	x					
E3	x					
C64	x					
C65	x					
C68	x					
E93	x					
E11	x	x				
5c	Subcluster					
B25			x			
B49	x	x				
C58		x	x			
B58	x					
C42	x					
E149	x					
5d	Subcluster					
B16			x			
E18			x			
C13	x	x				
C12		x	x			
E113		x	x			

Sample Subclusters	Micrite Only	Micrite + Spar	Spar Only	Biolithite	Dismicrite	Laminite
C37	x	x	x			
E34	x		x			
E36		x				
E38	x	x	x			
5e	Subcluster					
C49	x		x			
C56			x			
E54	x	x	x			
D17			x			
E35	x	x	x			
E50		x	x			
6a	Subcluster					
A57		x	x			
A59				x		
E32		x	x			
E37	x	x	x			
E30		x	x			
A64	x					
E48	x	x				
E52	x		x			
E9	x	x				
E22	x	x				
E24				x		
6b	Subcluster					
B59	x					
E105	x					
E109	x					
E20	x					
E33	x					
C54	x	x				
E63	x					
E55	x	x	x			
E164						
6c	Subcluster					
E5	x					
E8	x	x				
E13	x	x				
E16	x	x				
E19	x	x				
E124	x	x				
E126	x	x				
6d	Subcluster					
C15		x	x			
C36		x				
C22	x	x	x			
C27	x					
C30		x	x			
7a	Subcluster					
A<59				x		
E64	x					
E108	x					
7b	Subcluster					
C18	x					
E23	x					
C21	x					
C23	x					

Sample Subclusters	Micrite Only	Micrite + Spar	Spar Only	Biolithite	Dismicrite	Laminite
7c	Subcluster					
C31	x	x				
C35	x					
C32	x					
C34	x					
7d	Subcluster					
B332				x		
B34				x		
E2	x					
E4	x					
E74	x					
E131	x					
C17	x	x				
E1	x	x				
C41	x					

Table D-5. Petrographic Fossil Diversity Table.

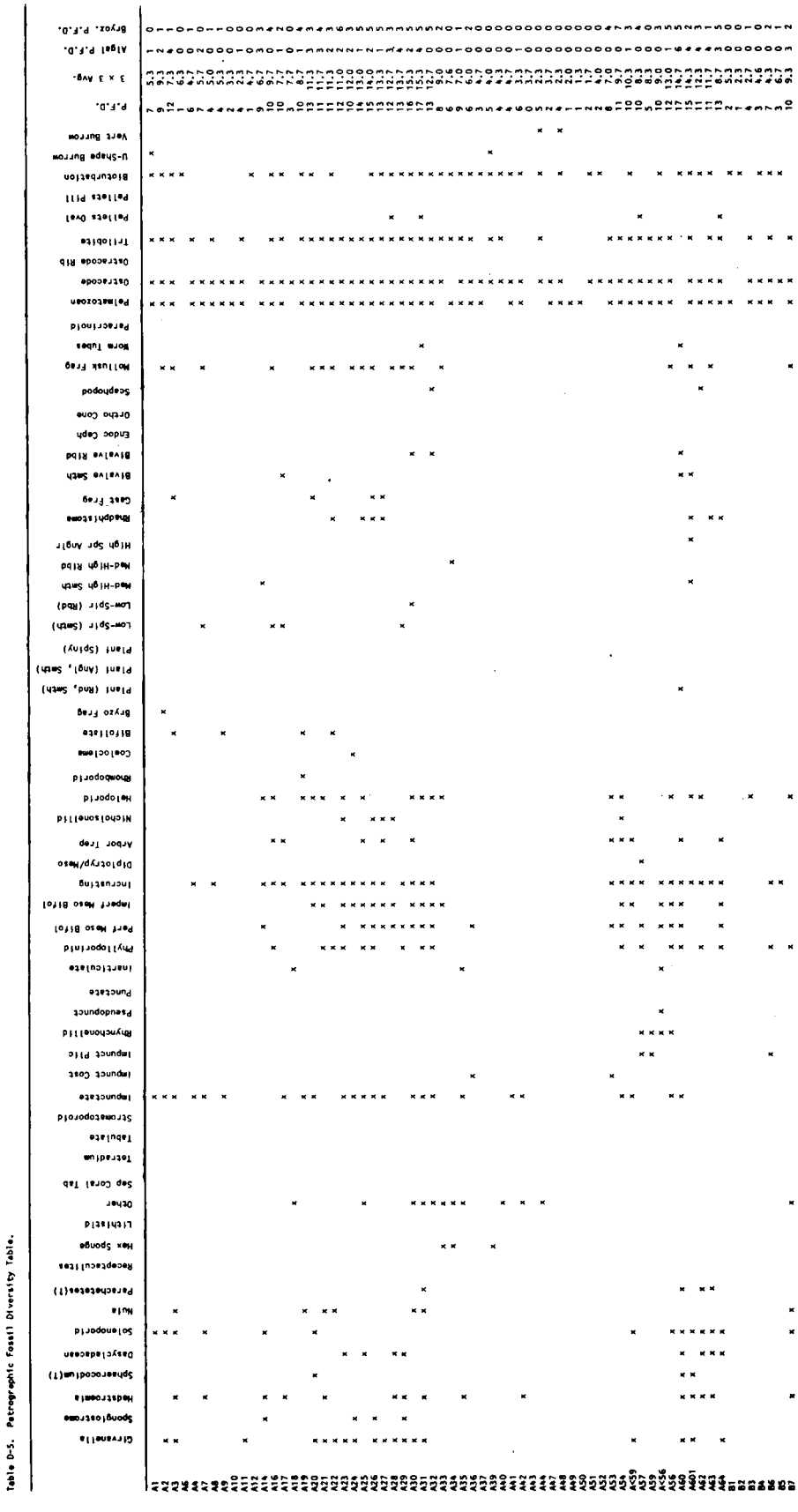


Table D-5 (continued).

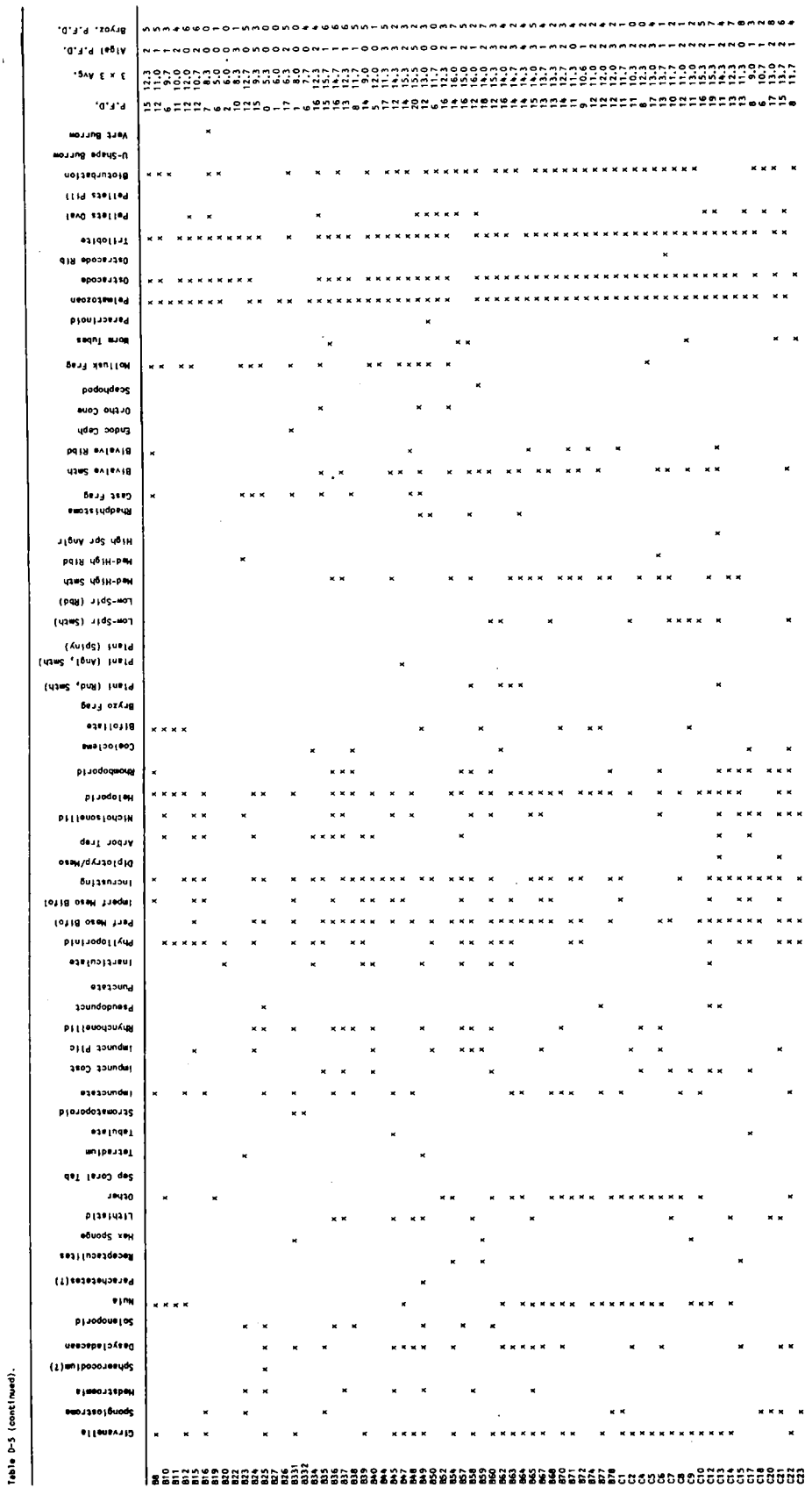


Table D-5 (continued).

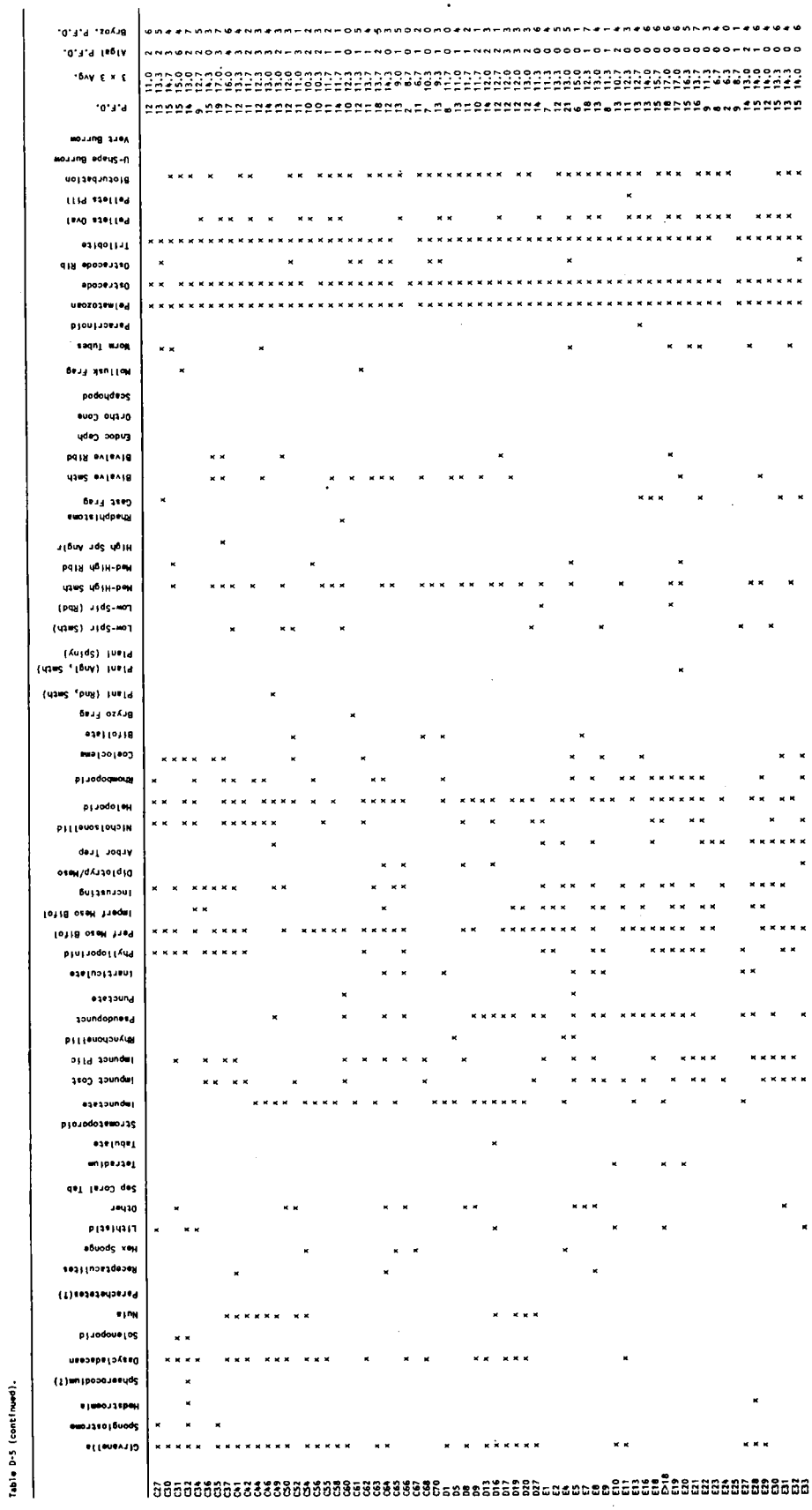


Table D-5 (continued).

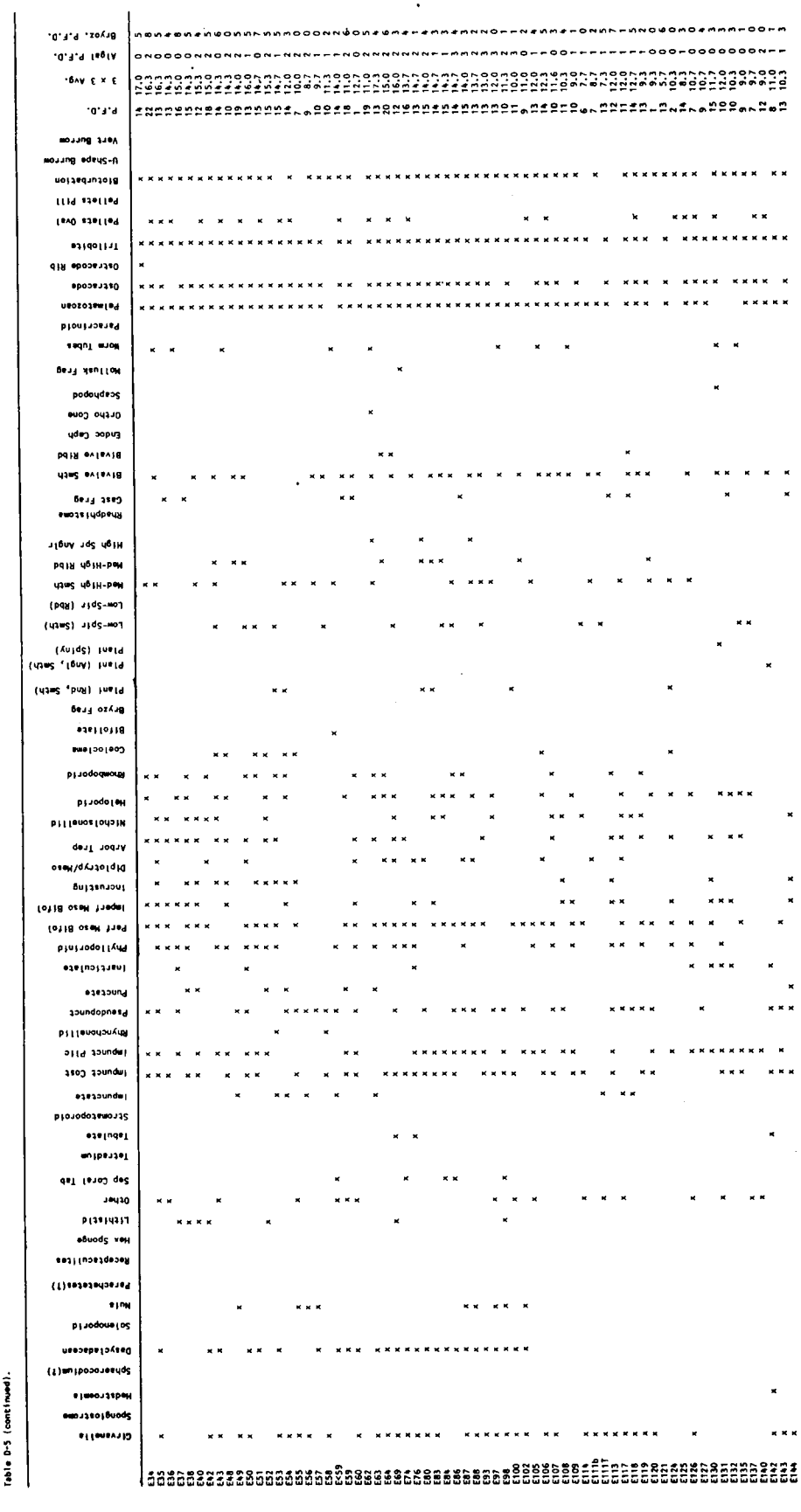


Table D-5 (continued).

	Girvanella	Spongiostroma	Hedstroemia	Sphaerocodium(?)	Dasycladacean	Solenoporid	Nuia	Parachaetetes(?)	Receptaculites	Hex Sponge	Lithistid	Other	Sep Coral Tab	Tetradium	Tabulate	Stromatoporoid	Impunctate	Impunct Cost	Impunct Plic	Rhynchonellid	Pseudopunct	Punctate
E145	x			x								x						x				
E146	x						x											x				
E147	x		x				x					x						x			x	
E148	x		x				x											x			x	
E149	x			x														x			x	
E152	x																	x				
E153																		x				
E154																		x				
E155																			x			
E156												x										
E157																						
E158				x		x													x			
E159																						
E160				x		x																
E161																						
E162																			x			
E163																						
E164																		x	x			
E165																		x			x	

	Inarticulate	Phylloporinid	Perf Meso Bifol	Imperf Meso Bifol	Incrusting	Diplotryp/Meso	Arbor Trep	Nicholsonellid	Heloporid	Rhomboporid	Coeloclema	Bifoliate	Bryzo Frag	Planl (Rnd, Smth)	Planl (Angl, Smth)	Planl (Spiny)	Low-Spir (Smth)	Low-Spir (Rbd)	Med-High Smth	Med-High Ribd	High Spr Anglr	Rhadphistoma
E145																	x					
E146			x	x			x															
E147			x						x										x			
E148																						
E149					x			x				x					x					
E152													x									
E153		x	x																			
E154		x	x				x			x												
E155																						
E156																						
E157																						
E158	x				x		x															
E159																						
E160	x																					
E161				x	x			x														
E162																						
E163													x									
E164														x						x		
E165													x									

	Gast Frag	Bivalve Smth	Bivalve Ribd	Endoc Ceph	Ortho Cone	Scaphopod	Mollusk Frag	Worm Tubes	Paracrinoid	Pelmatozoan	Ostracode	Ostracode Rib	Trilobite	Pellets Oval	Pellets Pill	Bioturbation	U-Shape Burrow	Vert Burrow	P.F.D.	3 x 3 Avg.	Algal P.F.D.	Bryoz. P.F.D.
E145			x							x	x		x			x			10	11.7	2	0
E146	x	x				x				x	x					x			12	12.0	2	3
E147			x							x	x		x			x			14	12.0	3	2
E148	x	x								x	x					x			10	12.7	3	0
E149		x	x					x		x	x					x			14	10.3	2	3
E152										x			x	x		x			7	8.0	1	0
E153																			3	6.3	0	2
E154										x	x		x			x			9	5.7	0	4
E155		x						x		x						x			5	6.0	0	0
E156		x									x					x			4	3.7	0	0
E157																x	x		2	6.0	0	0
E158	x	x						x		x	x		x						12	4.7	2	1
E159																			0	6.0	0	0
E160							x				x					x			6	5.0	2	0
E161		x					x	x		x	x		x						8	5.3	0	3
E162																			1	5.0	0	0
E163							x	x		x	x								5	6.0	0	1
E164		x					x	x		x	x		x	x		x			12	9.3	0	0
E165	x	x					x	x		x	x		x			x			11	7.6	0	1

Dissimilar fossil types recognized in thin-section (in order used):

1. Girvanella algae
2. Spongiostroma algae
3. Hedstroemia algae
4. Sphaerocodium(?) algae
5. Dasycladacean algae
6. Solenoporid algae
7. Nuia (problematical algae)
8. Parachaetetes(?) algae
9. Receptaculites algae
10. Hexactinellid sponge
11. Lithistid sponge
12. Other sponge (usually disaggregated spicules)
13. Tabulate coral with separate corallites
14. Tetradium
15. Tabulate coral
16. Stromatoporoid
17. Impunctate brachiopod
18. Impunctate costellate brachiopod (not used if other impunctate types present)
19. Impunctate plicate brachiopod (not used if other impunctate type present)
20. Rhynchonellid brachiopod
21. Pseudopunctate brachiopod
22. Punctate brachiopod
23. Inarticulate brachiopod (chitino-phosphatic)
24. Phylloporinid bryozoan
25. Bifoliate bryozoan with perforate mesotheca
26. Bifoliate bryozoan with imperforate mesotheca
27. Bifoliate bryozoan
28. Incrusting bryozoan
29. Diplotrypa (or Mesotrypa) bryozoa
30. Arborescent trepostome bryozoan
31. Nicholsonellid bryozoan
32. Heloporid bryozoan
33. Rhomboporid bryozoan
34. Coeloclema bryozoan
35. Bryozoan fragment
36. Round, smooth planispiral gastropod
37. Angular, smooth planispiral gastropod
38. Smooth, ow-spired gastropod
39. Ribbed or ornamented, low-spired gastropod
40. Smooth, medium-high spired gastropod
41. Ribbed or ornamented, medium-high spired gastropod
42. High-spired gastropod, angular whorls
43. Rhaphistoma gastropod
44. Gastropod fragment
45. Smooth bivalve (pelecypod)
46. Ribbed bivalve (pelecypod)
47. Endocerid cephalopod
48. Orthocone cephalopod
49. Scaphopod
50. Mollusk fragment
51. Worm tubes (Spirorbis?)
52. Paracrinoid
53. Pelmatozoan
54. Ostracode
55. Ostracode (ribbed)
56. Trilobite
57. Pellets (oval)
58. Pellets (pill)
59. Bioturbation
60. U-shaped burrow
61. Vertical burrow

Table D-6. Constituent Particle Analysis Data for Selected Samples.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Constituent / Sample	Micrite	Spar	Intra	Pelloid	Ooid	Non-foss.	Oncolite	Hedstroemia	Dasycladacean	Solenopora	Nuia	Girvanella	Algal Total	Tabulate	Brachiopod	Sponge	Bryozoa	Gastropod	Bivalve	Cephalopod	Mollusk	Pelm.	Ostracode	Trilobite	UnID	Foss.	Dolomite	Quartz	Chert	Stylo.	Other Foss.	Other Min.
A-1	6.5	25.9	8.1			14.6									1.8							19.2	3.0	.7	33.3	59.1	.2				1.1	
A-2	4.7	5.1	8.3			13.0	.4			.8			1.2		3.2		3.2				.4	37.1	4.3	2.8	26.1	79.1					2.0	1.6
A-4	8.2	24.2	.4			8.6									.9		2.6					3.0	1.3	.4	21.6	29.8	14.3	16.4				2.1
A-14	.9	18.0	16.4			17.3		.6		.6			3.4				18.6	2.8			7.7	22.0	.9	5.9	3.1	61.0						
A-17	38.8	6.2	.3			39.1		1.3					1.3		.8		2.4	.8			8.3	11.8	1.3	6.2	17.1	48.7		.3		4.3		
A-19	2.7	12.8	2.2	.5		5.4	18.8				3.3	22.1			1.1		12.8					36.2	1.1	.5		51.7			6.8			1.1
A-20	15.5	8.0	1.7			17.2	6.5						6.5		1.0		10.6	.2			.2	25.9	2.9	2.2		43.0				14.5	10.6	
A-24	9.2	19.0	1.9			11.1	.6					6.9	7.5		1.9		8.9				.3	31.4	5.1	.9	13.0	61.5				.6		
A-25	.3	25.5	1.3			1.6			.9				.9		2.6		27.7	.6			.6	25.5	1.3	4.5	4.5	67.3						
A-26	19.5	19.5	2.6			22.1	2.3						2.3		1.6		10.1	.3			1.3	22.4	1.9	2.9	14.3	54.8				.9		
A-27	14.8	11.2	2.0			16.8						.3	.3		2.1		20.4					25.4	3.5	3.2	13.3	67.9	.9			3.2		.9
A-28	18.4	14.4	4.3		.5	23.2						6.7	6.7		1.6		5.9				2.9	29.9	2.9	2.1	10.2	55.5						
A-31	10.8	22.7	2.6			13.4	10.8					10.8		1.3		12.2	.2					20.9	3.4	1.6	8.2	47.8				.5		4.5
A-33	40.3	1.3		4.5		44.8									10.3	.9					1.3	.	1.3	1.3	33.2	48.3			5.4			
A-41	49.5	13.4	2.5			52.0																1.0	1.5		26.2	28.7		2.5		3.5		
A-53	1.2	15.7	6.4			7.6								2.1		19.4						30.6	11.8	2.7	10.0	76.6						
A-56	25.6	5.9		2.3		27.9								2.9		15.1					1.0	34.4	2.9	1.6	8.2	66.1						
A-59	13.4	11.1	1.6	5.8		20.8								8.1		8.8						27.0	3.2	1.9	10.7	59.7		.6		7.5		
B-8	28.3	2.5	4.2	2.8		35.3	.8				3.5	1.7	6.1		1.4		8.9				7.2	10.8	.8	2.5	18.6	50.2			5.8			
B-10	23.6	10.4	.3	2.0		25.9									.3	.6	26.2				3.7	18.1	1.4	.6	12.7	63.6						
B-15	3.7	14.1	4.9	.6		9.2									.9		10.1				1.8	42.0	2.1	3.4	16.2	76.5						
B-24	16.0	28.4				16.0									10.6		11.2				1.5	25.7	.9	1.5	4.1	55.5						
B-25	3.6	31.4	3.3		15.3	22.2	9.3	.6	3.3	4.5		.6	18.3		4.5		4.2				1.2	11.1		2.1	5.1	28.1						
B-38	1.2	12.6	5.6			6.8				1.9			1.9				5.3	.3				58.5	7.2	3.4	3.8	78.5						
B-40	5.4	22.4	.3	17.3		23.0									1.9		19.5				.3	20.2	1.3	1.6	9.0	53.8				.6		
B-45	12.3	10.8	11.7	4.9	.3	29.2	7.0						7.9				5.6	4.7			2.3	31.1	.6	1.5	6.1	52.8						
B-50	18.3	25.6	.6	6.7		25.6									1.5		6.4				.3	34.4	2.4	.3	3.0	48.3		.3				
B-64	48.2	12.3		4.8		53.0	5.7		.3				6.0			.3	.6	.6			4.2	10.5	3.3		9.0	28.5						
B-70	46.7	12.7	.3	2.3		49.3				3.6	1.0		4.6				.6				.6	13.1	2.9	1.3	13.1	31.6				2.3		
B-72	34.5	5.6	1.3	3.9		39.7										4.9	2.0				3.3	6.6	.6	1.3	22.4	41.1			13.5			
B-78	60.9	4.1	.6			61.5					2.2		2.2				1.6	.6			6.6	10.9	.9	.6	10.9	32.1						
C-7	50.3	2.0	.6	.3		51.2	12.0						12.0		.8	7.7	2.0	1.1			3.4	13.1	1.7	1.1	3.7	62.7						
C-9	38.8	7.6		3.0		41.8	15.4				1.2		16.6		.9		.6	.3			5.7	11.8	2.7	3.9	7.9	33.8						
C-12	3.1	20.8	2.8	4.6		10.5	2.0						2.0		1.7		19.4	.8			.3	38.3	.8	2.0	3.1	66.4						
C-13	25.7	10.5	.3	6.3		32.3	4.4						4.4		3.2		14.9	1.9	1.3		1.3	21.3	2.2	.6	3.5	50.2				2.5		
C-14	23.0	11.4	1.7	3.8		28.5	4.4						4.4				10.8	.6			.6	31.5	.5	3.8	7.0	54.9				.9		
C-22	17.2	3.2		5.5		22.7	2.0						2.0			1.4	19.2					41.4		.3	.6	62.9				9.0		
C-30	26.9	22.9				26.9											13.3					35.4	.3	.3	.9	50.2						
C-34	58.9	4.7				58.9	3.5						3.5			12.5	7.0					11.9	.3	.3	.6	32.6				.3		
C-35	63.4	7.5				63.4	1.6						1.6		.3		8.3	.8			.6	14.7	1.3	.8	.8	27.5						
C-37	3.6	36.5	1.5	1.8		6.9	3.6		4.5				8.1		.6		14.8	.6			1.8	24.2	1.5	3.6	1.2	48.3						
C-41	34.9	5.2	.9	2.5		38.3	8.6		3.4				12.0		2.5	7.7	9.6	1.2			1.2	20.1	.9	.6	.3	44.1						
C-46	1.0	31.8		3.9		4.9	5.0		1.3				6.3				9.7	.5				36.8	3.2	3.7	2.9	56.8						
C-50	31.5	4.8	.6	3.1		35.2	4.5		1.7				6.2		1.4	.3	1.4	.3			3.7	26.1	2.6	3.1	4.8	43.7				9.9		
C-55	18.3	18.3	.9	5.1		24.3	6.9		2.7				9.6		.9		5.7				1.2	30.6	1.2	3.3	2.7	45.6				2.1		
C-60	17.7	11.9	1.5	4.3		23.5	3.3						3.3		2.4		7.3	.3				36.0	3.6	1.8	3.3	54.7				2.1		4.3
C-62	15.1	19.3	.6			15.7			.6				.6		1.0		11.5				.6	45.2	1.6	2.3	1.0	63.2	1.0					
C-65	31.1	11.9		2.7		33.8									.6	1.8		.6			3.8	28.5	3.0	.6	3.8	42.7				9.5		
D-1	27.1	20.6	.3	.3		27.7						.3	.3		1.5		4.6				.9	32.9	2.5	2.5	6.5	51.4						
D-5	68.7	3.7		.3		69.0									.3	9.4						4.7	1.2	.6	8.4	24.6				2.5		
D-9	77.6	1.0				77.6									1.9	3.6					.3	9.4	.3	1.0	4.2	20.7				.6		
D-13	51.7	8.7				51.7	.9						.9		5.9	4.7						7.5	1.2	3.1	9.3	31.7				6.8		
D-17	16.3	19.8	1.2	1.7		19.2	2.3		.23				25.3		2.9		2.9	.9				22.1	2.6	2.0	2.0	35.4						

Table D-6 (continued).

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Constituent / Sample	Micrite	Spar	Intra	Pelloid	Ooid	Non-foss.	Oncolite	Hedstroemia	Dasycladacean	Solenopora	Nuia	Girvanella	Algal Total	Tabulate	Brachiopod	Sponge	Bryozoa	Gastropod	Bivalve	Cephalopod	Mollusk	Pelm.	Ostracode	Trilobite	UnID	Foss.	Dolomite	Quartz	Chert	Stylo.	Other Foss.	Other Min.
D-20	9.2	12.4	.6			9.8	.6		.3		.9		1.8		1.2		7.1	.3				51.2	1.2	1.5	2.9	65.4				10.6		
D-27	35.6	4.4	1.2	1.8		38.6	2.1						2.1		3.6		8.0	1.2			2.7	21.9	3.3	3.0	7.1	50.8				4.1		
E-1	31.8	8.2		11.9		43.7									1.6		22.9	.3				21.4	.9		.9	48.0						
E-4	72.7	1.9		.3		73.0									6.1	2.9	5.8					7.1	.3	1.0	1.6	24.8						.3
E-5	54.1	13.4		1.2		55.3									1.2	2.0	5.3					17.8	1.2	.6	3.2	31.3						
E-9(1)	23.7	11.1		5.3		29.0									8.2		3.2	.6				31.1	2.9	1.7	2.0	49.7				8.5		1.5
E-13	26.2	12.8		5.6		31.8									14.6		2.9					25.0	1.2	1.8	3	48.5				6.8		
E-18	1.8	14.5		.9		2.7									5.4		10.3					53.5	1.8	2.4	1.2	74.6	6.6			1.5		
E-19(1)	37.6	8.7		6.9		44.5	1.2						1.2		5.4	.6	15.7	.6				12.9		1.8	1.2	38.2				7.2		
E-20	28.7	8.9		2.2		30.9									1.6		5.4	1.6			2.5	15.9	1.3	3.2	1.6	33.1				27.1		
E-27	1.8	15.8	4.8			6.6	3.0						3.0		3.6		7.2	8.9			.3	42.7	.3	1.8	2.1	66.9	7.8					
E-30	4.5	20.2		3.3		7.8									6.8		12.5				.3	40.8	1.2	2.4	1.2	65.2	6.8					
E-33	52.2	12.6				52.2										4.1	11.9					5.3	.9	.9	1.8	24.9						10.1
E-36	26.3	17.8	2.6	5.5		34.4									4.4	.6	12.9					24.3	.9	.6	1.2	44.9				2.9		
E-38	18.6	7.0	3.3	8.5		3.04									1.5	2.1	12.2				.6	19.8	1.8	2.7	4.0	44.7				17.7		
E-42	40.6	12.9	.3	1.6		42.5	6.6						6.6		.3	.3	8.5				2.2	16.7	1.6	1.6	2.5	33.7				4.1		
E-48	20.9	4.8	.6	11.8		33.3									2.1	.3	17.6				.6	21.8	.3	.3	1.5	44.5		1.2		16.1		
E-49	18.3	16.1	6.6	7.2		32.1	8.8				.6		9.4		.9		2.2	.6			.9	30.9	.6	.9	5.0	42.0						
E-51	59.6					59.6									5.2		7.3	.6			2.1	22.0	.3	.9	.9	39.3				.9		
E-52	20.7	10.6	.3	4.9		25.9									2.7	1.2	6.1	.6				29.2	1.5	2.7	2.7	46.7				16.7		
E-54	25.5	7.2	.9	3.4		29.8									5.9		10.9					27.1	1.9	2.5	3.7	52.0				10.9		
E-55a	38.4	1.7		1.2		39.6	.6						.6		2.9		11.6	2.3			.6	27.3	.6	.6	6.4	52.3						5.8
E-55b	27.8	13.6	7.9			35.7	10.2						10.2		1.7	1.1	.6				.6	21.6	.6	4.0	10.2	40.4						
E-56	4.1	19.7	4.8	20.4		29.3	6.0				.3		6.3		.3		1.9					29.0	.6	1.3	9.2	42.3	2.2					
E-57	35.4	7.3	1.2	1.2		37.8	.6		.9		.9		2.4		5.0		2.0	.9			.6	22.2	.6	2.9	8.2	42.4				10.2		
E-58	59.5	4.5	.6	1.3		61.4									4.2		3.5				1.3	11.0	.3	2.6	5.5	28.4				5.5		
E-59	79.9	4.9				79.9			1.9				1.9			.3	4.9					3.0	.5	.8	1.6	11.1				1.9		
E-60	33.2	8.7	1.5	8.1		9.6			.3				.3		3.0	.3	14.2	.3			.9	24.2	1.5	1.5	2.1	48.0						
E-69(2)	56.3	3.2		2.3		58.6	.9		.9				1.8		1.6		12.0	.3			2.6	3.9	.3	1.3	.9	22.9				13.0		
E-74	63.0	5.7				63.0			15.4				15.4	5.1	.3		3.9				.9	.6	.6	.3	.6	12.3				3.3		
E-80	29.0	15.2		7.9		36.9	.7		4.2				4.9	2.2	2.7		5.9	2.7			.5	14.1	1.2	3.0	3.5	33.1	4.5					
E-83	72.0	4.6	.3	.9		73.2	.9						.9	.9	.6		1.8	.6			1.5	6.1	.3	.9	1.8	14.5				6.5		
E-87(1)	28.4	22.4	1.0	10.9		40.3								2.2	.5		12.0				.5	14.7	1.0	1.6	3.8	35.3				.5		
E-87(2)	77.4	1.1		1.1		78.5	1.1		1.1				2.2		1.1		.6				1.1	6.2	.6	3.4	3.9	16.9				1.1		
E-88	77.8	.3				77.8	1.1		5.9				7.0		.5		1.6	.3			.8	3.5	.3	.3	5.4	12.7				2.2		
E-93	73.7	3.3				73.7			.6			2.1	2.7		.3		2.7	.6				3.6	.9	.9	11.8	20.8						
E-97	56.7	5.4				56.7	8.8		2.1		.3		11.2		.3		2.4				.3	11.8	.3	2.4	8.2	25.7				.9		
E-100(1)	36.6	4.3	1.2	22.6		60.4	1.8		3.6				5.4		1.2		5.5	.6			1.8	8.5	.6		11.6	29.8						
E-100(2)	60.6	19.1				60.6			.5				.5		.5	.5	3.8					7.6	.5	2.2	.5	15.6				3.8		
E-105	82.4					82.4									1.0	.3	4.2	.3				3.8		.6	1.0	11.2		1.0		6.4		
E-106	37.7	12.2		6.2		43.9	1.3						1.3	4.1	6.8		1.6					14.1	.3	1.6	4.6	33.1		.5		8.9		
E-108	60.4	.9				60.4									.6		18.7					4.2	.3	.6	4.8	29.2				9.3		
E-109	56.7	1.5				56.7									9.5		13.8				1.5	4.2		2.4	1.5	32.9				8.9		
E-114	43.7	4.4		.9		44.6	11.3						11.3		.6	.3	3.1	2.5			1.2	15.4	.9	1.6	5.9	31.5				7.8		
E-113	16.9	28.2	5.0	1.8		23.7	5.0						5.0		3.3		17.8					19.3	.6	.9	.9	42.8				.3		
E-118(1)	20.5	3.8		8.3		28.8											3.3				5.5	10.0	1.7	1.7	2.8	21.7						
E-118(2)	51.3					51.3	9.7						9.7		2.7		1.6				.5	4.3	1.6	1.1	7.0	18.8				20.0		
E-120	5.1	25.7	12.9	9.6		27.6	6.6						6.6		6.0		4.2	3.0			.3	20.3	1.5	1.5	3.0	39.8				.3		
E-126(1)	39.6	10.3		1.1		40.7	.6						.6		5.7		12.0	1.1			2.3	20.7	1.1	1.7	3.4	48.1						
E-126(2)	64.6	.5				64.6									1.5	3.0	13.1	8.6				2.5		5.0	1.0	34.7						
E-135	86.8	.3				86.8									8.1		.7						.7	2.4	.3	12.2		.7				
E-142(1)	5.2	8.2	1.5	14.1		67.6	33.6						33.6		6.0			.7	2.2		.7	16.4		2.2	2.2	30.4						6.7
E-142(2)	15.1	4.8		35.7		50.8									1.2		.6				.6	23.0	.6	2.4	10.3	38.7						5.4

Table D-6 (continued).

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Constituent / Sample	Micrite	Spar	Intra	Pelloid	Ooid	Non-foss.	Oncolite	Hedstroemia	Dasycladacean	Solenopora	Nuia	Girvanella	Algal Total	Tabulate	Brachiopod	Sponge	Bryozoa	Gastropod	Bivalve	Cephalopod	Mollusk	Pelm.	Ostracode	Trilobite	UnID	Foss.	Dolomite	Quartz	Chert	Stylo.	Other Foss.	Other Min.
E-142(3)	40.0	2.4		19.2		59.2											.8					1.6	.8		32.8	36.0				2.4		
E-143	63.9		1.6	.3		65.8	2.8						2.8		6.9		2.2	.3			.3	5.6		3.7	10.0	29.0		2.2				
E-144	11.2	23.9	2.1	12.4		25.7	3.2						3.2		14.4		1.7				3.8	19.8	.6	2.3	4.4	47.0						
E-145(1)	5.7	18.6	6.2	3.3		15.2	17.1						17.1		1.4	.5	10.0					34.8		.5	2.4	49.6						
E-145(2)	54.3	1.0	1.5	1.0		56.8	17.4						17.4		2.0	.5	2.0				.5	11.3	1.0	1.0	6.1	24.4						
E-147	32.8	.9	.6	7.0		40.4	8.3						8.3		10.8	3.2	2.5				.6	11.5	.6	2.9	18.1	50.2						
E-148	24.3	3.2	2.7	1.2		28.2	13.6	.3					13.9		13.0		10.3		.9		.3	11.5	.3		12.1	48.4				6.2		
E-149	28.3	2.4	.3	.9		29.5	11.6						11.6		9.1		4.9	1.5	8.2		.9	5.8	2.1		4.0	36.5				19.8		
E-152	87.7					87.7	1.3						1.3		1.0		.3					4.0		1.3	4.3	10.9						
E-153	21.1			49.5		70.6											2.4								26.5	28.9		.5				
E-154	5.2	19.7		37.5		42.7									1.9		17.8				1.6	13.3	1.6	.3	1.0	37.5						
E-155		25.6		57.3		57.3											.6				.3	1.6				2.5	14.6					
E-158(1)	5.6	15.6		36.8		42.4		3.0		.4			3.4		1.3		4.3		2.2		9.9	13.0	1.3	.4	.4	32.8	1.7	.9			3.0	
E-158(2)	11.6	6.1		42.2		53.8																6.1			25.2	31.3	3.4	5.4				
E-159	7.9	1.1				7.9																			28.1	28.1	2.2	9.0		51.7		
E-160	41.8	1.7	1.2	7.6		50.6							2.3								.3		11.7		11.1	23.1	12.6	1.6		8.2		
E-161	4.7	14.9	30.8			35.5											9.4	.4	7.3		13.2	4.3	1.7	.8	4.7	41.8	1.7	1.7			4.3	
E-162		30.0		48.0		48.0																					22.3					
E-163	2.8	12.2	1.2	48.9		52.9											1.2				1.2	2.5	.3		5.3	10.5	18.8			4.7	.6	
E-164	56.2	7.5				56.2									5.8		.6	4.9			5.5	2.3	.6	4.2	1.3	25.2				10.1	.6	
E-165(1)	46.0	5.0	1.0	34.0		81.0									10.0		1.0	2.0			4.0	7.0	2.0		18.0	44.0	8.0					
E-165(2)	14.0	13.0	17.0	30.0		61.0									3.0		1.0		10.0		2.0	10.0	2.0	1.0	1.0	30.0	3.0					
E-165(3)	2.0	24.0		84.0		86.0									8.0		8.0		3.0		12.0	3.0		1.0	20.0	55.0	8.0				1.0	

VITA

Ernest Leroy Ewing, Jr., was born in Nashville, Tennessee, on August 12, 1946. He attended elementary schools in that city and was graduated from Hillwood High School in June 1964. In the fall of 1964, he entered Vanderbilt University and received a Bachelor of Arts degree in Geology in June 1968. In the summer of 1968, he entered Peace Corps training in Oregon and in October left for a two-year tour of service in Bhopal, India. After a brief period in the United States Army upon his return from India, the author worked at various jobs until he entered the Graduate School of The University of Tennessee, Knoxville, in June 1978 on a part-time basis. He was a graduate teaching assistant from the fall of 1979 until the winter of 1981. He received his Master of Science degree in Geology in June 1985.