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Abstract

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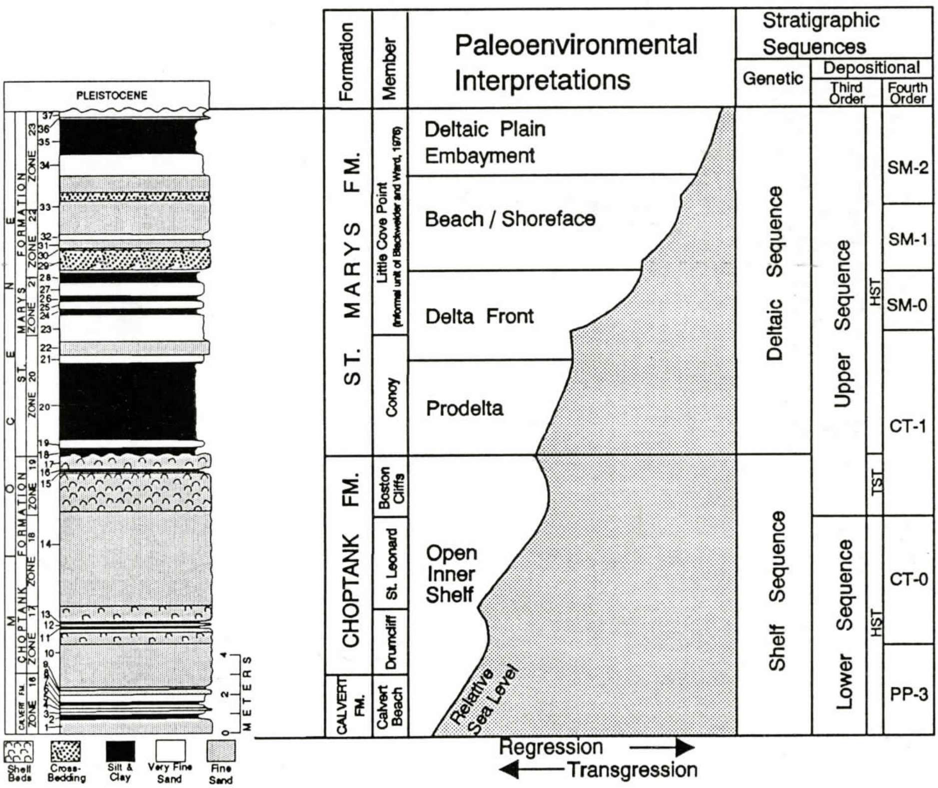

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SEDIMENTOLOGICAL INDICATORS OF PALEOENVIRONMENTS AND SILICICLASTIC STRATIGRAPHIC SEQUENCES IN SOME MIOCENE DEPOSITS OF THE CALVERT CLIFFS, SOUTHERN MARYLAND

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ABSTRACT

Middle Miocene siliciclastic deposits comprising the Calvert Cliffs section at the Baltimore Gas and Electric Company's (BG&E) nuclear power plant site in southern Maryland were analyzed in terms of lithostratigraphy, sedimentary structures, and granulometric parameters, to interpret paleo-environments within a sequence-stratigraphic framework. Lithosomes of the upper Calvert, Choptank, and St. Marys Formations (Shattuck's zones 16-23) constitute two distinct lithostratigraphic intervals characterized by differences in stratigraphic grain, cyclicity, and granulometric parameters. A disconformity separating the two intervals is a significant stratigraphic and sedimentological discontinuity that serves as an effective Choptank-St. Marys formational boundary. Paleoenvironmental interpretations of the two lithostratigraphic intervals indicate that they are also genetically distinct facies assemblages. The lower interval (zones 16-19) is an open, inner-continental shelf facies assemblage formed above storm wavebase; it is an overall regressive assemblage with superimposed higher-frequency transgressive phases. The upper lithostratigraphic interval (zones 20-23) is a regressive paralic-facies assemblage developed by a prograding delta lobe; the vertical facies succession ranges from basal prodelta muds to lower subaerial deltaic-plain deposits.

In terms of sequence-stratigraphic models, the BG&E section can be interpreted as consisting of two genetic stratigraphic sequences (Galloway model), namely, a shelf sequence (zones 16-19) and an overlying deltaic sequence (zones 20-23). Using the Exxon model, the section consists of two third-order (1-5 m.y. duration) depositional sequences. Component parasequences consist of six stacked fourth-order (<1 m.y. duration) transgressive-regressive cyclic successions. The lower third-order depositional sequence (zones 16-18) is an inner-shelf facies with a progradational parasequence set, indicating highstand systems tract deposits. The upper third-order depositional sequence (zones 19-23) is an inner-shelf and deltaic facies assemblage. It consists of a basal inner-shelf retrogradational parasequence set that represents a thin and condensed transgressive systems tract. An overlying deltaic facies with an aggradational to progradational parasequence stacking pattern represents distal to proximal high stand systems tract deposition. The stratigraphic sequences of the BG&E section reflect both relatively short-term eustatic transgressive events, as well as a long-term regressive trend with associated local deltation and coastal progradation. The regression probably signified a regional basinward shift of depocenters within the Salisbury embayment during Miocene time.

INTRODUCTION

Miocene deposits exposed in the Calvert Cliffs of southern Maryland are widely known for their highly abundant fossil content. Exposures of the Calvert Cliffs section, located along the western shore of Chesapeake Bay

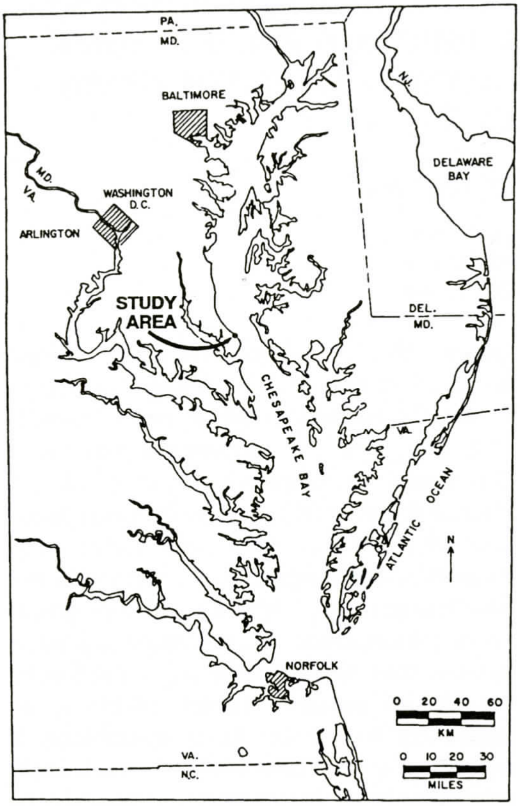

Figure 1. Location map of the Calvert Cliffs study area in Calvert County, Maryland.

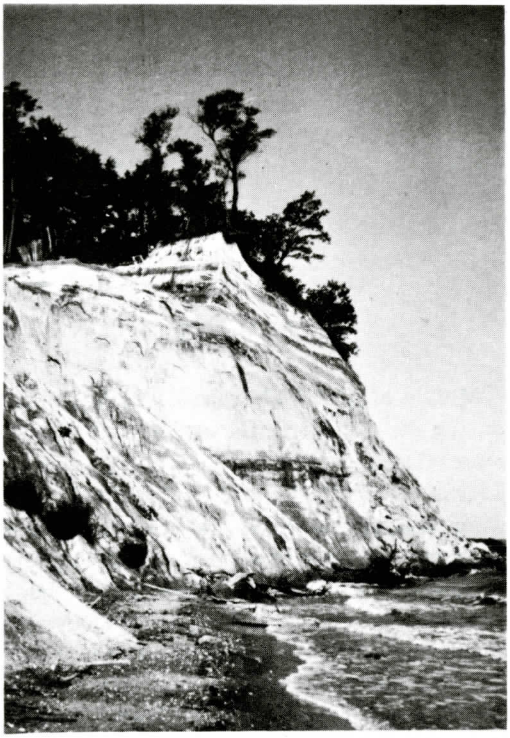

Figure 2. Bluff exposures of multicolored Miocene strata of the Choptank and St. Marys Formations in the Calvert Cliffs section. Site is located along the western shore of Chesapeake Bay immediately adjacent to the Baltimore Gas and Electric Company nuclear power plant.

(Figure 1), have long been favorite sites for collecting macrofaunal and microfaunal assemblages; these assemblages have formed the basis for many paleontological, paleoecological, and biostratigraphic studies. However, in comparison, studies focused primarily on the sedimentological aspects of the Calvert Cliffs section have been much more limited.

During construction of the Baltimore Gas and Electric Company's (BG&E) nuclear power plant at Calvert Cliffs, newly excavated exposures at the construction site afforded an excellent opportunity to conduct a detailed bed-by-bed sedimentological study of the exposed Miocene section. This study investigated the lithostratigraphy, sedimentary structures, and sediment grain size of that local section. The objective of the study was to synthesize these physical data, in an effort to interpret paleoenvironments, and to place the local BG&E section within a regional sequence-stratigraphic framework. This would contribute to a greater understanding of the evolution of the middle Atlantic Coastal Plain during Miocene time.

Regional Geologic Setting

The Calvert Cliffs section occurs along the western shore of Chesapeake Bay in southern Calvert County, Maryland (Figures 1, 2). The study area is located within the middle Atlantic Coastal Plain Province, a passive continental margin characterized primarily by a siliciclastic succession of eastward dipping and thickening Mesozoic and Cenozoic sedimentary deposits, which overlie a basement of Precambrian and Paleozoic crystalline rocks. The

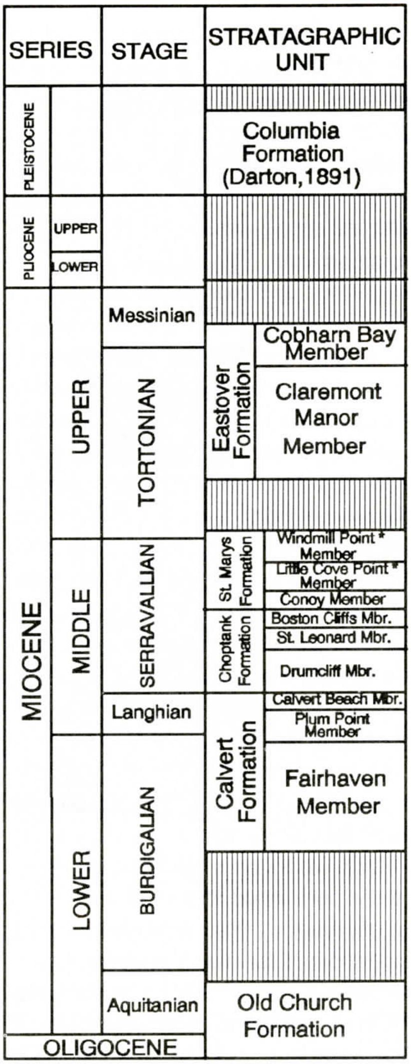

Figure 3. Miocene stratigraphic units in Maryland. *Informal unit of Blackwelder and Ward (1976). Modified from Ward and Powars (1989).

study area is within the Salisbury embayment, a structural downwarp of the Baltimore Canyon trough, which was an active depocenter during late Mesozoic and Cenozoic time (Ward and Powars, 1989; Poag, 1992). Throughout the Cenozoic, ancestral coastal-plain rivers supplied large quantities of terrigenous sediment to the Salisbury embayment, derived primarily from erosion of central Appalachian highland source areas to the west (Poag and Sevon, 1989).

Miocene deposits in the studied Calvert Cliffs section are part of the Chesapeake Group, which was originally named by Darton (1891). In ascending order, the group consists of the Calvert, Choptank, and St. Marys Formations (Figure 3). In a classic study of the Maryland Miocene section, Shattuck (1904) subdivided the section into 24 "zones" based on lithology and fossil abundance. In his classification, the Calvert Formation was represented by zones 1-15, the Choptank Formation by zones 16-20, and the St. Marys Formation by zones 21-24. The Choptank Formation zones were later redefined as formal stratigraphic members by Gernant (1970), who studied Choptank stratigraphy and paleoecology. Gernant's (1970) stratigraphic nomenclature for the Choptank Formation included the following: Calvert Beach Member (zone 16), Drumcliff Member (zone 17), St. Leonard Member (zone 18), Boston Cliffs Member (zone 19), and Conoy Member (zone 20). Later stratigraphic work (Blackwelder and Ward, 1976; Ward, 1984; Ward, 1992) resulted in reinterpretation of the Calvert Beach Member (zone 16) as the uppermost division of the Calvert Formation and the Conoy Member (zone 20) as the basal division of the overlying St. Marys Formation. Overlying the Conoy Member is the informal Little Cove Point unit of Blackwelder and Ward (1976), which represents zones 21-23 of the St. Marys Formation. One of the most conspicuous aspects of the Chesapeake Group is the presence of prominent molluscan shell beds within the Calvert and Choptank Formations. These shell beds have been studied in detail by various workers (Gernant, 1970; Kidwell 1979, 1982, 1984, 1989; Kidwell and Aigner, 1985). Other biostratigraphic studies in the immediate vicinity of the BG&E section described in this report were conducted on assemblages of diatoms (Andrews, 1976) and foraminifera (Gibson, 1982).

In terms of a regional sequence-stratigraphic framework, the Salisbury embayment of the Baltimore Canyon trough is an area where the presence of regional Miocene depositional sequences has been documented. A study of planktonic foraminiferal assemblages from cores and outcrops by Poag (1991) indicated the presence of 16 regional, unconformity-bounded sequences within the Paleocene to Miocene sedimentary section of the Virginia-Maryland portion of the Salisbury embayment. Poag correlated these sequences with trans-gressive and highstand systems tracts of the Exxon sequence-stratigraphic model (e.g., Haq, 1987). Multichannel seismic and bios-tratigraphic studies of the mid-Atlantic conti-nental margin further indicate the presence of at least five major middle Miocene and nine middle to uppermost Miocene sequence bound-aries on the New Jersey-Delaware-Maryland continental shelf and upper slope (Mountain and others, 1991; Miller and others, 1991). From the high-resolution multichannel seismic profiles, these sequences were characterized by unusually thin transgressive systems tracts (TST), thick highstand systems tracts (HST), and widespread incised canyons indicative of *type 1* sequence boundaries deeply eroded into the post-middle Miocene section of the outer shelf and upper slope (Mountain and others, 1991).

Methods

In the field, the exposed Miocene strata in the BG&E section were differentiated into Shattuck's (1904) stratigraphic zones, which served as the basic reference system for this study. After zonal differentiation, the section was then measured and its field characteristics (lithologic units, sedimentary structures, color) were described. Samples in a vertical sequence were obtained for granulometric analyses at 15-cm intervals and at observable changes in lithology throughout the exposed sections, both at the excavation site of the nuclear power plant and from the bluff area immediately adja-cent to the excavation site (Figure 2). Samples of approximately 50 grams were obtained by hammering 13-dram plastic vials into the sedi-ment. The excavation site exposure provided complete sample coverage of zones 16-19 of the Calvert and Choptank Formations, while the adjacent bluff exposure provided coverage of zones 20-23 of the overlying St. Marys For-mation. Sedimentary structures were studied by field observations and by obtaining box cores at selected stratigraphic horizons for lab-oratory impregnation.

In the laboratory, approximately 200 sequen-tial samples derived from the exposed compos-ite section were processed for granulometric analyses. All 15-cm interval samples obtained from the zone 16-19 interval were processed. However, within the zone 20-23 interval, some adjacent samples obtained from megascopi-cally homogeneous lithologic units were occa-sionally deleted in an effort to reduce processing time and costs. The samples were wet-sieved to remove the size fractions smaller than 62 µm (4.0 ø). The remaining sand frac-tion of each sample was then digested in a 10% HCl solution to determine the total carbonate content by weight. Following sample prepara-tion, size-frequency distributions of the non-calcareous sand fractions were determined with a Rapid Sediment Analyzer, employing a set-tling tube 12 cm in diameter and 1 m in length. Analyses were performed at a 0.25 ø interval, using the technique described by Schlee (1966). Reduction of the size-frequency distri-bution data was accomplished by a computer program, which permitted derivation of the sand modal diameters and moment measures (mean, standard deviation, skewness, kurtosis), as well as the total weight percentages of car-bonate, sand, and silt-clay (mud) in each sam-ple. All derived parameters were plotted as variability graphs with a common scale, in order to illustrate the vertical variations in sedi-ment properties throughout the exposed BG&E composite section. Sedimentary structures were examined in the laboratory by means of impregnated box cores, using an epoxy medium in accordance with techniques pre-sented by Burger and others (1969). Several box cores were impregnated, resulting in vary-ing degrees of penetration and relief, depend-ing upon lithology and permeability. In

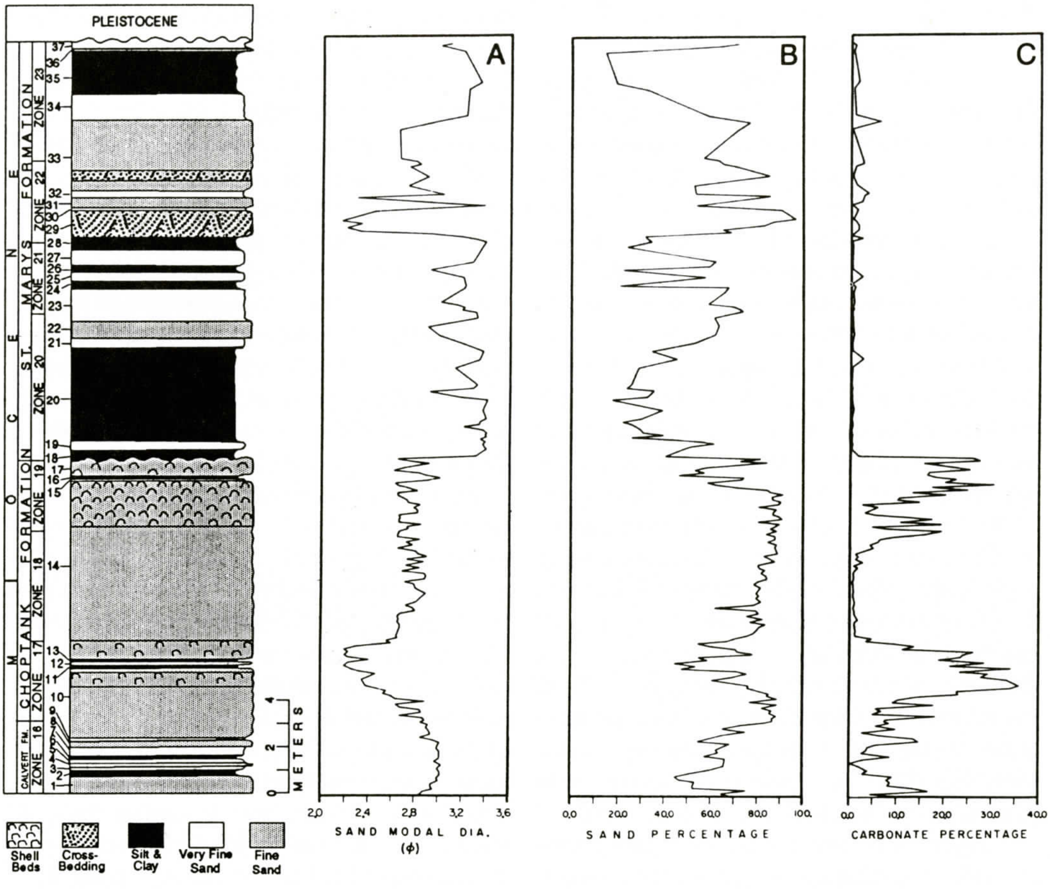

Figure 4. Lithostratigraphic columnar section of exposed Miocene strata at the study site illustrating 37 identified lithologic units and major sedimentary structures; reference zones (16-23) are those of Shattuck (1904). Also shown are variability graphs illustrating variations in: A) modal diameters of the noncalcareous sand fractions, B) weight percentages of the total noncalcareous sand fraction; and C) weight percentages of the total carbonate content.

conjunction with the original field descriptions, all derived parameters were utilized in the construction of a stratigraphic columnar section of the exposed Miocene strata.

LITHOSTRATIGRAPHY

A columnar section, based on field observations and laboratory analyses, illustrates the lithostratigraphic characteristics of exposed Miocene deposits in the BG&E composite section (Figure 4). In addition to field observations, granulometric analyses of the vertically sequential samples formed the basis for differentiation of the section into 37 lithologic units. Unit differentiation is based on the relative percentages of sand and mud present; further differentiation of the sand units is based on their modal diameters. In lithologic unit descriptions, the modifiers argillaceous, arenaceous, and calcareous are used when that respective component exceeds 20 percent of a unit's bulk composition. All color terminology is in accordance with the Munsell system (Goddard and others, 1948).

The studied composite section consists of 32 m of multicolored, typically unconsolidated strata; the deposits are middle Miocene (Langhian to Serravallian) in age (Ward and Powars, 1989). The section extends from zone 16 in the Calvert Formation through zone 23 in the overlying St. Marys Formation, which is unconformably overlain by Pleistocene(?) deposits.

Lithologically, the composite section consists of three types of stratified sediment: silt and clay (mud), very fine sand, and fine sand. In addition, variable amounts of bioclastic carbonate admixtures are also present. Alternations of these sediments result in 37 distinguishable lithologic units that comprise the section. The section is predominantly arenaceous, with sand units representing 73.6% of the total section. The fine sand units represent the most common lithology; they attain an aggregate thickness of 18 m accounting for 55.8% of the total section. The next most abundant lithology is silt and clay; mud units attain an aggregate thickness of 8.5 m, representing 26.4% of the total section. Very fine sand units are the least abundant, attaining an aggregate thickness of 5.8 m, which represents 17.8% of the total section. Prominent shell beds occur in zone 17 and zone 19 in the Choptank Formation, and they are molluscan coquinas with fine-sand matrices. Rather than being classified as biogenic limestones in this study, they were designated as fossiliferous fine sands, based on textural analyses of their matrices. The overall stratigraphic grain (broad vertical arrangement of lithologic components) of the section illustrates a general two-fold division into a lower relatively homogeneous interval (zones 16-19), and an upper relatively heterogeneous interval (zones 20-23). This two-fold division is also reflected in the modal diameters of the sand fractions (Figure 4A), which are generally coarser in the more homogeneous lower interval (zones 16-19).

A variety of prominent large-scale structures are observable throughout the stratigraphic section. Two disconformities occur, one at the zone 19-zone 20 contact (the Choptank-St. Marys formational boundary), and the second at the contact of the St. Marys Formation and the overlying Pleistocene deposits. The lower interval (zones 16-19) in the upper Calvert Formation and the Choptank Formation consists of large-scale cyclic successions of shell-poor strata, followed by highly conspicuous concentrated shell beds; this cycle is repeated twice throughout the interval, once as a zone 16-17 couplet, and again as a zone 18-19 couplet. In contrast, similar cyclic successions are not apparent within the overlying zone 20-23 interval of the St. Marys Formation, which is characterized greater lithologic variability.

Small-scale structures, such as horizontal stratification, cross-bedding, and biogenic structures, are locally present within individual zones. In general, the section is highly fossiliferous, with both invertebrate and vertebrate faunal populations. Molluscan fossils are dominant, and reach their highest concentrations in the conspicuous shell beds of zones 17 and 19 within the Choptank Formation. Other biogenic structures resulting from bioturbation and burrowing activities are relatively common in some zones; these include a variety of burrows, root casts, and mottled structures.

A significant point for further discussion is the position of the Choptank-St. Marys formational boundary. Shattuck (1904), and most subsequent workers, have included zone 20 within the Choptank Formation, establishing the Choptank-St. Marys boundary at the zone 20-21 contact. However, this contact at the study site does not appear to have any particular sedimentological or stratigraphic significance. Although the zone 20-21 contact appears to be a disconformity in some nearby exposures (e.g., Gernant, 1970; Kidwell, 1984), it has generally been reported as a conformable gradational contact. This was the case in the present study, where Shattuck's (1904) zone 20-21 contact is gradational and occurs within a uniform lithologic interval (lithologic unit 23) that exhibits no significant sedimentological discontinuities. Therefore, a more discernable and stratigraphically meaningful formational boundary would be the top of the conspicuous zone 19 shell bed and the associated disconformity. This disconformity at the zone 19-20 contact is associated with major sedimentological discontinuities and a gross change in the lithostratigraphic grain of the studied section, which appear to reflect the termination of characteristic Choptank deposition and the initiation of a new phase of sedimentation. Lithologic and paleoenvironmental attributes suggest that zone 20 has greater genetic affinities with overlying St. Marys strata, rather than with underlying Choptank deposits. The distinctiveness of zone 20 (Conoy Member) compared to underlying zone 19 (Boston Cliffs Member) was noted earlier by Blackwelder and Ward (1976), who proposed zone 20 as a separate informal unit. Subsequently, the Choptank-St. Marys formational boundary was placed at the zone 19-20 contact (Ward, 1984, 1992); this boundary position is supported by the results of the present study.

PALEOENVIRONMENTAL INTERPRETATIONS

The highly fossiliferous nature of the Miocene Chesapeake Group comprising the Calvert Cliffs section has resulted in numerous paleontological studies of both its macrofaunal (e.g., Gernant, 1970; Kidwell, 1984, 1989; Ward, 1992) and microfaunal (e.g., Andrews, 1976; Abbott, 1978; Gibson, 1982; DeVerteuil and Norris, 1992) assemblages. In general, the Chesapeake Group faunas indicate deposition within relatively shallow open-marine to marginal-marine (paralic) environments. The biota indicate a temperate marine climate, possibly similar to present conditions along the southern Delmarva Peninsula of the mid-Atlantic coast. This paleoenvironmental setting based on paleontological evidence provides a general framework for the interpretations presented in this discussion, which are based mainly on a synthesis of the physical sedimentological properties of the studied section. Although sedimentological evidence, by itself, may not necessarily establish the boundary conditions of a unique depositional environment, it can provide insight regarding ancient hydraulic regimes. This information, taken within the context of known paleoecological conditions, can form the basis for reasonable interpretations.

In formulating paleoenvironmental inferences of the BG&E section, emphasis was placed on a synthesis of its lithologic variability (Figure 4), sedimentary structures of individual lithologic units (Figure 5), and the temporal variability of granulometric parameters (Figure 6). The lithostratigraphic grain of the section suggests that it is composed of two genetically distinct stratigraphic intervals representing different facies assemblages. The two intervals are separated by a disconformity at the zone 19-20 contact, representing a significant sedimentological and lithostratigraphic discontinuity. Therefore, paleoenvironmental interpretations of the two intervals are discussed individually.

Sedimentary Environments of the Zone 16-19 Interval

The lithosomes of the lower zone 16-19 interval appear to have been deposited within an open, inner-continental shelf environment in water depths above storm wavebase. The relatively low standard deviations and highly aberrant values of skewness and kurtosis for the sand fractions (Figure 6) probably reflect an environment whose sediment input was size-filtered by passage through intracoastal water bodies. Upon arrival in the shelf environment, these sediments then probably underwent prolonged reworking by wave surge and nearshore currents, resulting in further truncation of their size-frequency distribution and improved sorting. Final deposition occurred as thin laminae produced by ripple migration. The net effect of the reworking phase was to reduce the standard deviation of the size distributions at a given locality, and to fractionate the sand into thin alternating laminae of finely skewed fine sand, and coarsely skewed coarser sand. During sampling, such laminae were remixed, and the resultant size distributions experienced either constructive or destructive interference, thus producing the highly aberrant skewness and kurtosis values that characterize the zone 16-19 interval. An interpretation of the individual

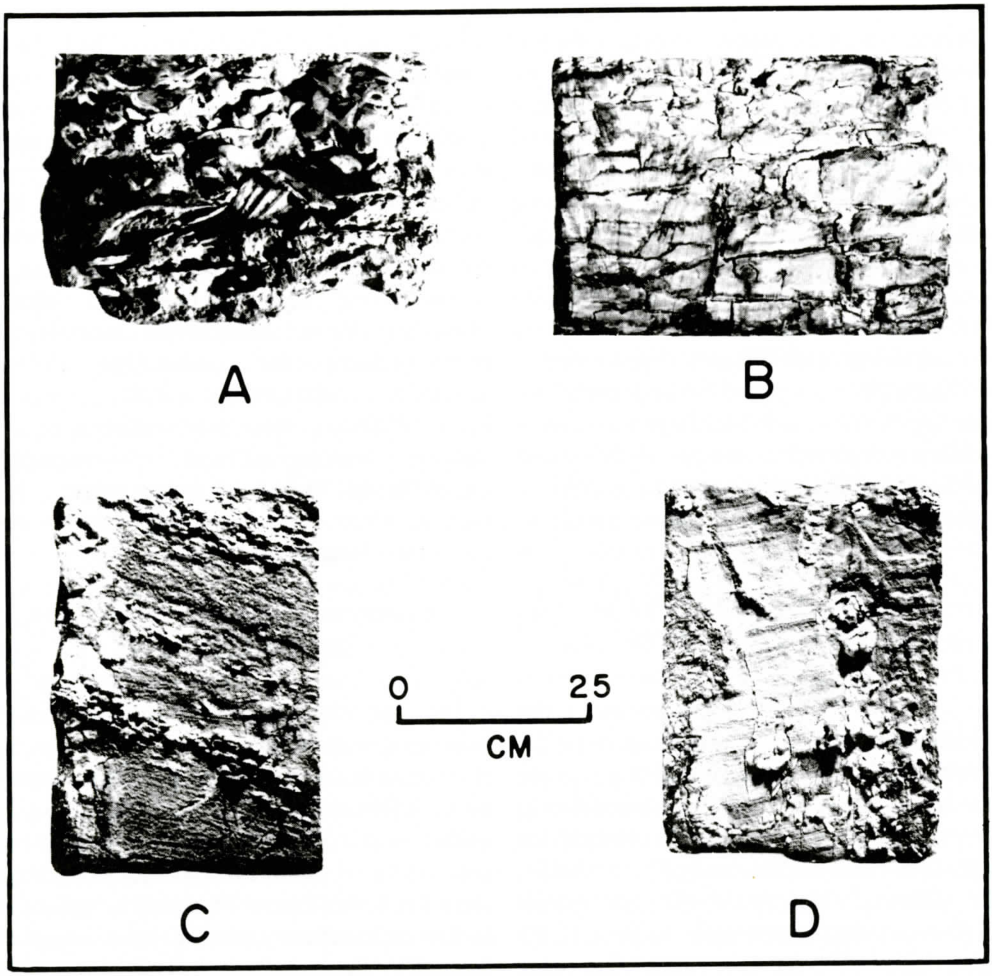

Figure 5. Epoxy-impregnated relief box cores of individual lithologic units:
A) Shell bed with fine sand matrix from upper portion of lithologic unit 14 (zone 19). Lower one-third of core consists of an intact framework of stratified *Lycropecten* valves; upper two-thirds of core consists of a nearly intact framework of *Anadara* valves.
B) Argillaceous fine sand from unit 22 (zone 20) with very thinly bedded to laminated horizontal stratification; desiccation cracks are oriented both parallel and normal to bedding planes.
C) Fine sand from unit 29 (zone 22) showing large-scale, low-angle cross-laminae sets (3-8 cm thick) with intercalated clay laminae (1-3 cm thick); discrete clay pebbles are incorporated within the clay laminae.
D) Fine sand from lower portion of unit 33 (zone 22) showing large-scale, low-angle (10°) cross-stratification; present are tubular *Callianassa* type burrows and branching tubular root casts.

zones and paleoenvironmental transitions follows.

Zone 16

This zone (Calvert Beach Member of the Calvert Formation) consists mainly of a dark-gray argillaceous fine to very fine sand. Sedimentary structures consist of organic burrows, and small-scale cross-laminae sets generated by migrating ripples; pelecypod shells are disseminated throughout the zone. The gross lithology of this zone appears to reflect a characteristic shelf lithosome of the Atlantic Coastal Plain, such as exemplified by the Caro-

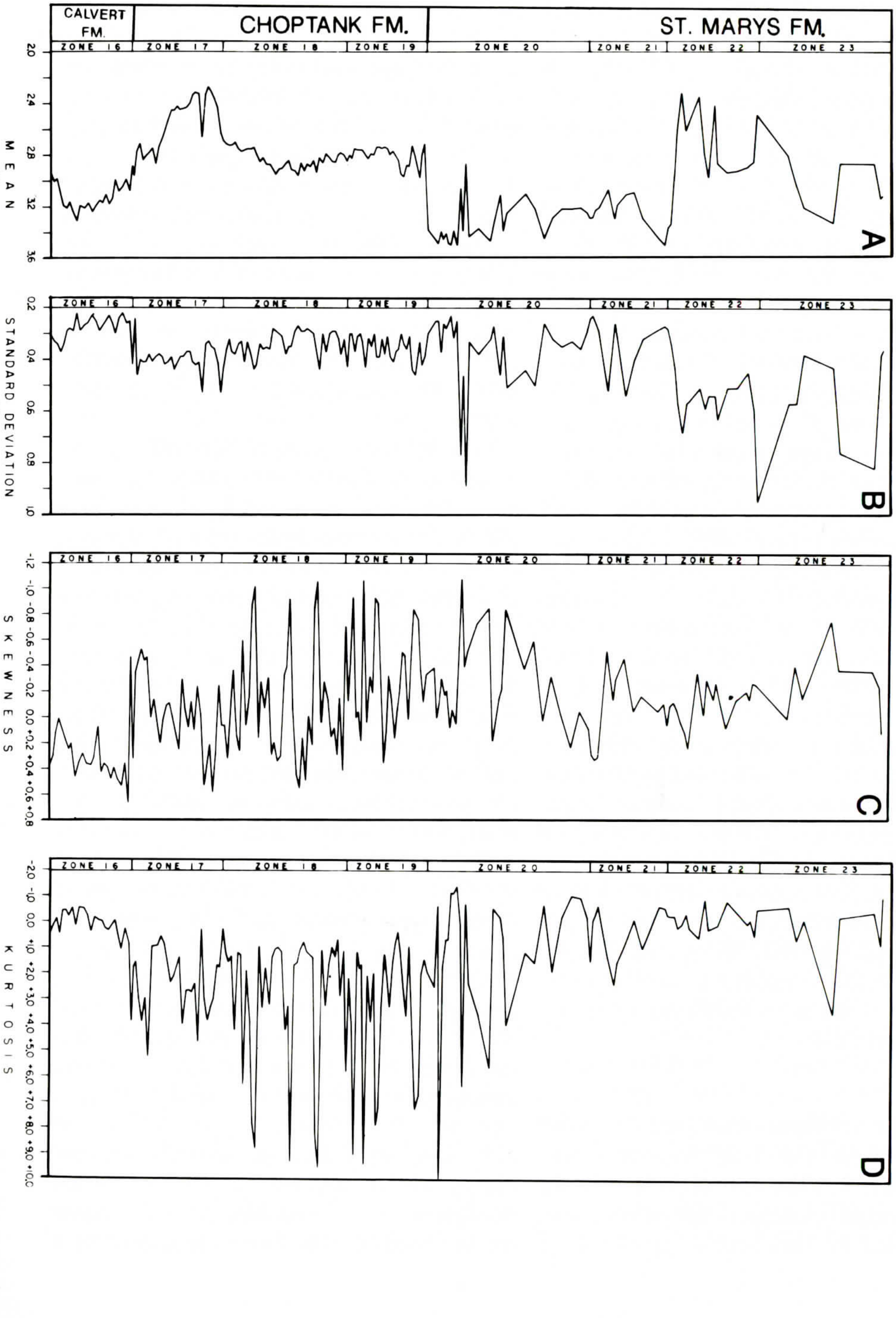

Figure 6. Granulometric variability graphs illustrating variations in statistical movement measures of the non-calcareous sand fractions: A) Mean diameter, B) Standard deviation, C) Skewness, D) Kurtosis.

lina Cretaceous Peedee Formation (Swift and others, 1969; Swift, 1970). In contrast to modern shelf deposits, this shelf lithosome developed whenever the rate of sediment input was sufficiently high relative to the rate of transgression or regression of the shoreline, so that the seafloor sediment pattern could attain a state of equilibrium (Swift, 1970). Under such conditions, sand supplied by coastal rivers diffuses seaward under the impetus of wave-generated, tide-generated, and storm-surge currents. Suspended argillaceous sediment also supplied from river mouths diffuses seaward, where it eventually settles to the sea floor and is worked into the substrate by burrowing organisms (Swift and others, 1969). Regarding the ripple cross-laminae sets, a study of the modern mid-Atlantic shelf hydraulic regime suggests that deposition could have occurred in depths less than 20 m, under the combined influence of oscillatory wave surge and unidirectional nearshore currents (Swift and others, 1986). Sediment transport was probably intermittent, occurring mainly during storm events.

From the standpoint of detailed lithology, zone 16 represents the most heterogeneous zone of the interval, being comprised of 10 relatively thin (<1 m) lithologic units. Its lithologic heterogeneity indicates a relatively high degree of environmental energy variability, possibly related to water-depth variations. Energy variations are supported by the variability of the central tendency measures (modal and mean diameters) for the sand fractions (Figures 4A, 6A) and by variations of the sand and carbonate percentages (Figures 4B, C). An overall upward increase in sand percentages suggests a shoaling trend during zone 16 deposition. A shoaling trend within zone 16 is also indicated by faunal assemblages (Gernant, 1970; Kidwell, 1989).

Zone 17

This zone constitutes the basal Drumcliff Member of the Choptank Formation. The lithology and sedimentary structures of the zone indicate an open inner-shelf environment, fully exposed to wave action. Lithologically, the lower half of the zone consists of a fossiliferous fine sand. With increasing fossil content, the sand grades upward into the conspicuous lower molluscan shell bed. The shell bed consists of strata with an intact framework of both fragmented and whole shells (coquina), interbedded with strata containing dispersed and generally fragmented shells. The matrix is generally a fine sand, which contains substantial argillaceous and calcareous admixtures (Figures 4A, B, C); the sand appears to be structureless and is coarser than the fine sands of adjacent strata. Two small intervals exist within the shell bed where argillaceous matrices predominate (lithologic units 11, 13). The paleontological attributes and internal stratigraphy of the zone 17 shell bed (and the younger zone 19 shell bed) have been discussed in detail by Gernant (1970) and Kidwell (1979, 1982, 1984, 1989).

Kidwell's (1989) study of this shell bed indicated an open-shelf environment, in water depths above storm wavebase. The environment may have been somewhat shallower than during deposition of zone 16, as suggested by an increase in average sand percentage, as well as an increase in the average grain size of the sand fraction. The increase in average sand standard deviation (Figure 6B) also might reflect shallower conditions, possibly indicating poorer sorting as a result of a more variable and turbulent hydraulic regime. In addition, a change in average sand skewness (Figure 6C) from positive values (fine skewed) to normal or slightly negative values (coarse skewed) further suggests shallower conditions. In a study of the Upper Cretaceous Peedee Formation (Swift and others, 1969), it was noted that the shallower proximal shelf sands exhibit a greater degree of negative skewness than distal shelf sands because the proximal transport distance was not sufficient for the progressive sorting process to remove the coarser sand fractions.

A progressive increase in environmental energy levels appears to have occurred throughout zone 17 deposition, culminating at the shell-bed horizon. This is suggested by a continuous increase in modal and mean diameters of the sand fraction. Relatively high-energy conditions during development of the shell bed are further indicated by the high carbonate content of the shell-bed matrix, indicating substantial *in situ* shell abrasion. The increase in energy level is interpreted as the combined result of shoaling, with superimposed transient storm effects observable at the shell-bed horizon. A detailed study of the shell bed in the Drumcliff Member by Kidwell (1989) supports the influence of storm events during its formation. The internal microstratigraphy of the shell bed includes numerous scoured and burrowed discontinuous surfaces of corroded shells, indicating multiple episodes of shell reworking with intervening intervals of sedimentation and recolonization. Kidwell (1989) further noted that the frequency and intensity of shell reworking decreased upward through the shell bed, as indicated by an upward increase in unbroken bivalves and in the percentage of infaunal bivalves in life positions. It appears that transient high-energy storm events had substantial influence on the shell-bed concentration process. Kidwell (1989) interpreted this shell bed as a transgressive deposit. This interpretation is supported by the reduction in average sand percentages of the shell bed relative to the lower half of the zone; however, the maximum water depth probably was somewhat shallower than during zone 16 deposition. Deposition of the argillaceous shell bed matrices, comprising lithologic units 11 and 13, apparently occurred during long quiescent fairweather intervals following storm events, when fine suspended sediment settled out of the water column.

The origin of the shell beds in the Choptank Formation, which include both the zone 17 shell bed and the overlying zone 19 shell bed, is compatible with a conceptual model of an open inner-shelf environment, containing a relatively high molluscan population, that was subject to periodic storms. A hypothesis for the origin of the shell beds was proposed by Kidwell (1979, 1982, 1989), who explained them as transgressive deposits that result from stratigraphic condensation. This process requires a long-term sedimentary regime characterized by zero net sedimentation, resulting from either sediment starvation or dynamic bypassing, whereby shell material is not diluted by terrigenous sediment. Under these conditions, a vertical telescoping of fossils derived from different migrating biofacies will occur, resulting in major shell-bed accumulations that represent time-averaged amalgamations of successive death assemblages. The present writer envisions a shell-concentration mechanism similar to Kidwell's (1979, 1982, 1989) stratigraphic condensation mechanism, but with greater emphasis on storm-winnowing processes rather than a reduction in sediment supply; this is suggested by the sedimentological parameters, which indicate a shoaling hydraulic regime and closer proximity to coastal sediment sources.

Zone 18

This zone (St. Leonard Member of the Choptank Formation) consists of alternating beds of clean and argillaceous fine sands, which contain sparsely disseminated pelecypod shells. The zone's gross lithology and sedimentary structures are essentially the same as those described for zone 16, probably reflecting a similar open, inner-shelf environment. However, water depths appear to have been shallower than during deposition of the subjacent zones, thus indicating continued regression. Continued regressive shoaling is suggested by the progressive increase in average sand percentage throughout the zone. The notable reduction in average grain size of the sand fraction near the base of the zone is difficult to interpret, but it could reflect a period of aggradation by waning storm currents after the final winnowing episode of the underlying zone 17 shell bed. Following the initial reduction in average sand grain size, there is a slight coarsening upward trend throughout the remainder of the zone, suggesting a subtle increase in the environmental energy level. This trend is most apparent on the sand mean-diameter graph (Figure 6A), and lends support to continued regressive shoaling. Kidwell's (1989) study also indicated a regressive succession for zone 18 deposits.

Zone 19

This zone (Boston Cliffs Member) constitutes the youngest molluscan shell bed of the Choptank Formation (Figure 5A), which is similar in gross lithology to the shell bed of zone 17. The shell bed matrix is generally fine sand with argillaceous and calcareous admixtures, except in two small intervals where very fine sand and argillaceous matrices occur (lithologic units 15, 16). The only significant granulometric difference between the zone 19 shell bed and the older zone 17 shell bed is that the fine sand matrix of the latter is coarser. A disconformity, exhibiting as much as 1 m of relief, occurs at the top of zone 19 and is marked by scattered blocks of carbonate-cemented sandstone. The upper part of the shell bed beneath the disconformity exhibits a relatively high degree of induration, compared with other portions of the shell bed. The highly indurated upper layers of the shell bed are in sharp contact with the nonresistant argillaceous deposits of overlying zone 20.

The previous interpretation of the origin of the zone 17 shell bed also applies to the zone 19 shell bed. The lithology and sedimentary structures of zone 19 support the interpretation of an open inner-shelf environment, fully exposed to storm-wave activity. However, the environment appears to have been shallower than previous shelf environments (zones 16-18), suggesting progressive shoaling. The fluid energy level reflected by zone 19 seems to have been higher than during deposition of zone 18, as suggested by the high carbonate content of the shell bed sandy matrix, reflecting substantial local shell abrasion by wave activity. Increasing sand percentages throughout the lower half of the zone also support higher energy conditions. The reduction of sand in the upper half of the zone could reflect mud infiltration resulting from organic burrowing associated with the disconformity at the top of the zone. Differences in the paleontological attributes of the zone 17 and zone 19 shell beds also indicate a shallower environment. As noted by Gernant (1970), the macrofaunal assemblage of the zone 19 shell bed generally has lower faunal diversity, fewer epifaunal individuals, and considerably fewer gastropods than the zone 17 shell bed assemblage. Paleoecologically, the zone 19 shell bed fauna reflects a more onshore environment with a greater fresh water influence than the older zone 17 shell bed faunal assemblage (Kidwell, 1989). In the present study, the zone 19 shell bed is interpreted as representing the shallowest shelf environment of the entire regressive zone 16-19 interval.

Sedimentary Environments of the Zone 20-23 Interval

Sedimentary deposits of the zone 20-23 interval appear to be genetically distinct from the unconformably underlying inner-shelf interval of zones 16-19. The basal disconformity separating zone 20 from underlying zone 19 constitutes a stratigraphic and sedimentological discontinuity, indicating a new phase of sedimentation. There is an abrupt change in the general stratigraphic grain and granulometric signature of the section across the disconformity (Figures 4, 6). It should be noted that some minor differences in the granulometric signature (vertical pattern of granulometric parameter values) of the two sequences may be an artifact resulting from a slightly lower sample density within some of the homogeneous units of the upper sequence. However, this would have only minor influence on some of the highest frequency variations, and would not significantly effect the overall signatures of the two intervals, which appear to reflect true genetic differences. Major changes in the granulometric signature of the zone 20-23 interval, relative to the underlying interval, consist of the following: 1) a notable increase in sand percentage variability; 2) a notable decrease in carbonate percentage variability; 3) a notable reduction in average grain size of the sand fractions; 4) poorer and more variable sorting of the sand fractions; and 5) a notable reduction in aberrant skewness and kurtosis values of the sand fractions.

The hiatus represented by the basal disconformity of the zone 20-23 interval is unknown but is probably relatively minor. No obvious evidence of subaerial exposure (i.e., paleosols, root casts) was observed at the study site. The disconformity is here interpreted as probably reflecting an episode of submarine erosion or nondeposition, possibly storm related, prior to the inception of zone 20 sedimentation. The lithosomes comprising the zone 20-23 interval indicate a succession of paralic (marginal marine and coastal) deposits. An interpretation of the paleoenvironmental transitions among individual zones follows.

Zone 20

This zone is represented by the Conoy Member, the basal member of the St. Marys Formation. The zone consists predominantly of argillaceous deposits that disconformably overlie the zone 19 shell bed, and which are gradational with overlying zone 21 deposits. The units comprising the zone are largely devoid of traction-generated structures, indicating they are mainly the result of suspension transport. The main zonal structure is well-defined horizontal stratification (Figure 5B), which ranges from thin bedded to laminated (terminology of Ingram, 1954). The deposits are variegated and consist of dark greenish gray, light olive gray, and light olive brown strata. The stratification appears to be rhythmic, and it is not associated with small-scale variations in sand content; it could reflect temporal variations in the rate of sedimentation or variations in the nature of flocculated argillaceous materials. The deposits are also relatively free of bioturbation effects and have a low shell carbonate content (Figure 4C); this could indicate an impoverishment of benthic fauna, as a result of high sedimentation rates, abnormal salinity, or reduced oxygen levels. These zonal deposits are interpreted as a muddy prodelta facies grading upward into a more sandy delta-front facies (terminology of Coleman and Prior, 1980) of a basinward prograding delta lobe. The relatively high rates of sedimentation and strong salinity stratification associated with a delta lobe could explain an impoverishment of benthos and minimal bioturbation effects. The variegated stratification probably reflects seasonal variations in flood levels and the suspended loads of the lobe distributary system. The relatively wide sorting range of the sand fractions in the zone, compared to underlying zones (Figure 6B), suggests more variable current velocities over relatively short time intervals, characteristics compatible with a deltaic environment.

Delta development apparently began locally during the regression following deposition of the underlying transgressive Boston Cliffs Member shell bed (zone 19). This is supported by paleoecological evidence presented by Kidwell (1984, 1988, 1989), who interpreted the top of the shell bed as representing the period of maximum water depth attained during that transgression; the shell bed faunal assemblage reflects shallow to very shallow sublittoral environments. In addition, Kidwell (1989) noted that some of the assemblage components suggested a significant fresh-water influence (e.g., presence of *Crassostrea*, rarity of stenohaline corals and echinoids). Such conditions might be expected seaward of the mouth of a distributary channel on a prograding delta lobe. Delta development at this locality may reflect a regional southerly shift in Appalachian source areas and depocenters within the Salisbury embayment during Miocene time, as discussed by various workers (e.g., Gibson, 1982; Poag and Sevon, 1989). Subsequent regional progradation of a delta system appears to have continued to the eastern shore of Chesapeake Bay southeast of the Calvert Cliffs area during late Miocene-Pliocene time; this is indicated by interpreted deltaic deposits of that age along the lower Delmarva Peninsula of Maryland and Virginia (Owens and Denny, 1979; Mixon, 1985).

Zone 21

This zone in the St. Marys Formation (part of the informal Little Cove Point unit of Blackwelder and Ward, 1976) consists predominantly of argillaceous very fine sand with subordinate amounts of arenaceous mud. The dominant sedimentary structure within the zone consists of the same well-defined horizontal stratification characteristic of underlying zone 20, suggesting predominantly suspension transport and minimal bioturbation. However, the higher proportion of sand units in zone 21 probably indicates both a closer proximity to a source of detrital sand, and a higher average environmental energy level. The greater lithologic heterogeneity of zone 21 also suggests a higher degree of energy variability and may indicate a fluctuating hydraulic regime. These deposits are interpreted as a sandy delta-front facies of a delta lobe that prograded basinward over the zone 20 prodelta mud during continued regression.

Zone 22

This zone, also part of the Little Cove Point unit (Blackwelder and Ward, 1976), is a relatively homogeneous portion of the St. Marys Formation; it is composed almost entirely of sand units, some of which exhibit conspicuous large-scale cross-stratification. The deposits of this zone reflect a substantial increase in environmental energy level, as contrasted with lower energy conditions of subjacent zones 20 and 21. An increase in environmental energy is indicated by the paucity of argillaceous units, a substantial increase in average grain size of the sand fractions, and the presence of large-scale cross-stratification.

The deposits of zone 22 are interpreted as a littoral facies representing beach and uppermost shoreface environments. The sands could represent localized mainland beaches that developed marginal to a prograding subaerial delta plain during continued regression. The lithology and structures of the zone support a littoral facies. The most prominent zonal structures are the conspicuous large-scale cross-beds of lithologic units 29 and 33. The alternations of sand and clay laminae in the cross-bedded unit 29 (Figure 5C) suggest that the unit may have been deposited on the leading edge of a sand body, possibly in an inlet spit or migrating tidal delta. The discrete clay pebbles incorporated within the clay laminae may have been derived through storm erosion of the underlying argillaceous substrate. The clean cross-bedded unit 33 appears to represent a beach sand. This is supported by the large-scale and low-angle cross-bedding, burrows of the *Callinassa* type, and the presence of root casts that indicate subaerial exposure and the establishment of beach vegetation (Figure 5D).

Zone 23

This is the youngest exposed zone of the St. Marys Formation (upper part of the Little Cove Point unit of Blackwelder and Ward, 1976) within the studied section; the zone is disconformably overlain by Pleistocene sand deposits. The zone is fairly heterogeneous; it is composed predominantly of argillaceous fine to very fine sand, with a subordinate amount of mud. Strata comprising the zone have experienced a high degree of bioturbation; consequently, the only recognizable structures are some obscure cross-laminae sets several centimeters thick, which have been largely obscured by mottling effects. The average environmental energy level of the zone appears to have been substantially reduced from that of subjacent zone 22, approaching the previous lower energy levels of zones 20 and 21. This is indicated by the relatively higher proportion of argillaceous strata and by the reduction in average grain size of the sand fractions. The reduction in environmental energy levels suggests a more restricted environment than that reflected by the subjacent zone 22 deposits.

The lithosomes of zone 23 are interpreted as deposits that grade upward from a littoral facies, to a relatively low-energy, semi-restricted to restricted facies of a lower deltaic-plain environment, possibly an interdistributary embayment. The deltaic-plain facies appears to reflect the continued basinward progradation of a delta lobe during regression. The prevalent zonal structures are obscure cross-laminae that are largely obliterated by bioturbation, rather than the rhythmic stratification and minimal bioturbation characteristic of

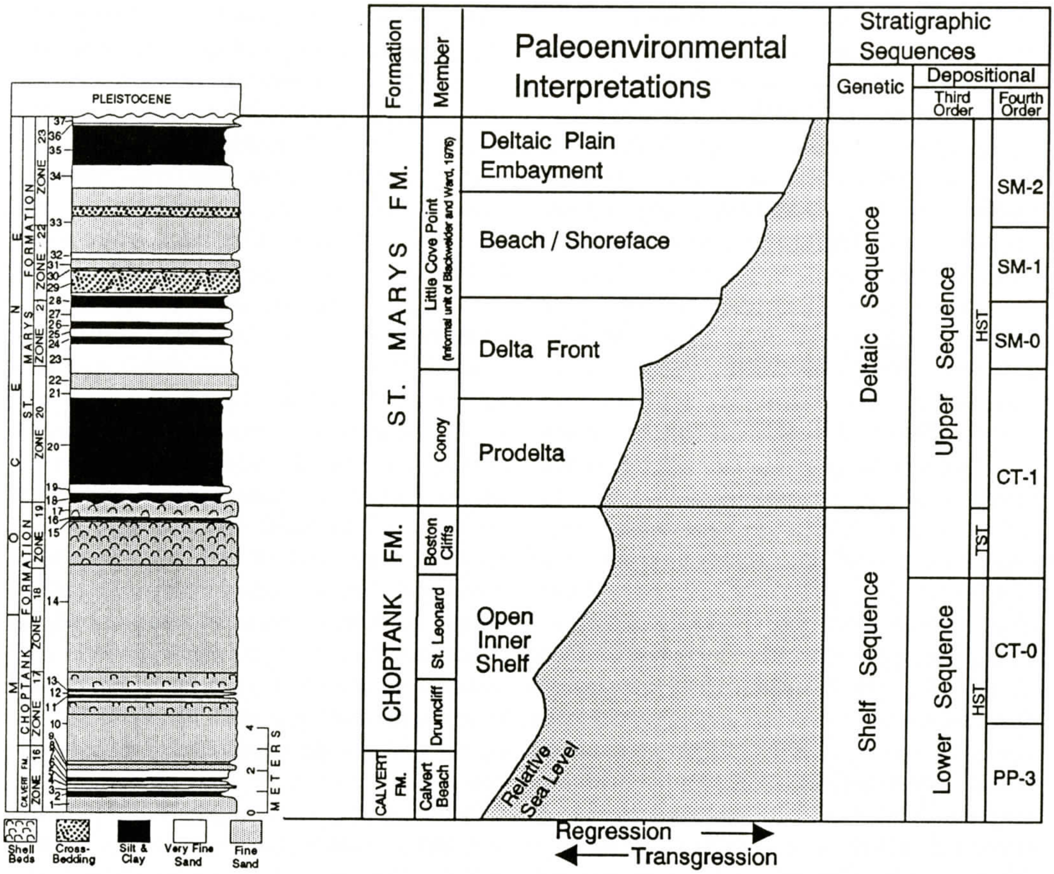

Figure 7. Summary diagram showing paleoenvironmental interpretations of Shattuck's (1904) zones 16-23 and the 37 lithostratigraphic units identified in the present study; the Choptank-St. Marys formational boundary is in accordance with Ward (1984, 1992). Also shown are interpretations of sequence stratigraphic models for genetic (Galloway model) and depositional (Exxon model) sequences; the fourth-order depositional sequences are from Kidwell (1989).

underlying zones 20 and 21. This would indicate substantial tractional transport and an increase in the benthic population. These characteristics are compatible with a lower deltaic-plain bay environment. With continued regression and coastal progradation, these lower deltaic-plain deposits of zone 23 were succeeded by fluvial-dominated upper deltaic-plain and alluvial-plain deposits. The overlying zone 24 of the St. Marys Formation was not preserved in the studied section because of truncation by overlying Pleistocene deposits. However, nearby exposed sections of the upper part of the St. Marys Formation were studied by Kidwell (1989), who characterized the deposits of zone 24 as primarily a fluvial-channel complex. This facies succession indicates continued regression and coastal progradation in the Calvert Cliffs area during Miocene time. A summation of the paleoenvironmental interpretations resulting from this study is presented in Figure 7.

SEQUENCE STRATIGRAPHY

The studied BG&E section of the Calvert Cliffs can be interpreted within the context of a sequence stratigraphic framework. The concepts and terminology of sequence stratigraphy, as well as the antecedent discipline of seismic stratigraphy, are discussed in detail elsewhere by several workers; these include Vail and others (1977), Haq and others (1987), Posamentier and others (1988), Posamentier and Vail (1988), Van Wagoner and others (1988, 1990), Galloway (1989), Swift and others (1991), and Thorne and Swift (1991). The work of Van Wagoner and others (1990) is especially relevant to the application of sequence stratigraphic concepts to individual outcrops, such as the BG&E section of the present study.

The following is a brief summary of a few sequence-stratigraphic concepts. The fundamental stratal unit of chronostratigraphic significance in the Exxon sequence model is the *depositional sequence*, which Mitchum and others (1977) defined as a relatively conformable succession of genetically related strata bounded at the top and base by unconformities or their correlative conformities. A depositional sequence is composed of subunits or *parasequences*, which Van Wagoner and others (1988, 1990) defined as relatively conformable, genetically related successions of beds or bedsets bounded by *marine-flooding surfaces* (across which an apparent water-depth increase is indicated) or their correlative surfaces; a *parasequence set* is a succession of genetically related parasequences that develops a distinct stacking pattern, which may exhibit either progradational, aggradational, or retrogradational facies relationships. Depositional sequences and their component parasequence sets can be subdivided into *systems tracts*. The systems tracts are defined on the basis of their position within the sequence and the parasequence stacking patterns (Van Wagoner and others, 1988; Posamentier and Vail, 1988; Posamentier and others, 1988); they have characteristic stratal geometries and facies associations, and were developed during specific phases of eustatic sea-level cycles. Four systems tracts that are generally recognized are the *lowstand*, *transgressive*, *highstand*, and *shelf-margin* tracts. As an alternative to the *depositional sequence* of the Exxon model, Galloway (1989) has presented a model based on *genetic stratigraphic sequences*. This type of sequence is a genetically related facies assemblage that represents the product of a depositional episode. The defining boundaries of genetic stratigraphic sequences are *maximum flooding surfaces* (MFS), which represent hiatal surfaces developed during marine transgressions. Additional details regarding sequence-stratigraphic concepts and terminology can be obtained from the aforementioned works.

In utilizing sequence stratigraphic concepts, the present study of the BG&E section has certain constraints and limitations. This results from the fact that the study was focused on a single locality. Consequently, large-scale stratal geometry and lateral-facies relationships were not determined, and all efforts were concentrated on the vertical-facies relationships at the studied section. However, if taken within the context of the known regional and local sequence stratigraphic framework established by previous investigations, reasonable inferences can be made regarding the BG&E section.

In close proximity to the studied BG&E section, detailed stratigraphic studies by Kidwell (1984, 1988, 1989) provide insight into the local sequence-stratigraphic framework of the area. These studies were based on an analysis of numerous stratigraphic sections along the western shore of Chesapeake Bay and some of its northern tributaries, including a section near the BG&E section described in this study; the studies were focused primarily on the origin and significance of molluscan shell beds present in the Miocene Chesapeake Group of Maryland. Kidwell's studies indicated that the Miocene section of Maryland is composed of 10 disconformity-bounded "depositional sequences," which reflect transgressive-regressive cycles. These are relatively short-term sequences on the order of 840,000 years duration, thus reflecting higher frequency (fourth order) sequences (Swift and others, 1991). Of Kidwell's 10 proposed transgressive-regressive cyclic sequences, parts of 6 of the sequences occur within the studied BG&E section of the upper Calvert, Choptank, and St. Marys Formations. The lithostratigraphy, paleoenvironmental considerations, and sedimentological parameters of the BG&E section indicate that the section can be interpreted in terms of both *genetic sequences* and *depositional sequences* (Figure 7).

Genetic Sequences

The BG&E section is composed of two distinct genetic sequences. These two sequences are represented by the zone 16-19 and zone 20-23 lithostratigraphic intervals, separated by the disconformity at the zone 19-20 contact. This disconformity constitutes a major discontinuity in the lithostratigraphic grain and sedimentological parameters of the section (Figures 4, 6). These two sequences are genetically distinct from a sedimentological perspective and represent two *sedimentologically genetic packages*, as defined by Walker (1990). A genetic sediment package implies a commonality in the rates and types of sediment input, and in the hydraulic regime and boundary conditions of the depositional environment. The two genetic packages comprising the studied section are the lower shelf sequence (zones 16-19), and the overlying deltaic sequence (zones 20-23). The genetic sequence boundary, namely the disconformity at the zone 19-20 contact, is interpreted as a maximum flooding surface (MFS). Kidwell (1989) interpreted this contact as reflecting the maximum water depth and turn-around point for a fourth-order transgressive-regressive cycle represented by the zone 19-20 couplet. This MFS is herein interpreted as a marine hiatal surface that constitutes a major discontinuity between two sedimentologically distinct genetic sequences. In terms of Galloway's (1989) sequence model, this MFS would be the boundary between two genetic stratigraphic sequences, which constitute two facies assemblages reflecting two different depositional episodes.

Depositional Sequences

Within the context of the Exxon sequence model, the BG&E section is composed of two depositional sequences. They appear to be third-order sequences, reflecting relative sea-level cycles of 1-5 million-year duration (Swift and others, 1991). The Langhian to Serravallian age (Ward and Powars, 1989) of the exposed sequences suggests that they occurred within the TB2 second-order sea-level cycle of Haq and others (1987).

Lower Sequence

The lower depositional sequence, represented by lithosomes of the zone 16-18 lithostratigraphic interval, constitutes an open inner-shelf assemblage reflecting water depths above storm wave base, as suggested by previous paleoenvironmental interpretations. The basal boundary unconformity of the sequence was not exposed in the studied section; consequently, the zone 16-18 interval represents a partial sequence. This third-order sequence encompasses parts of two of the fourth-order transgressive-regressive cyclic "sequences" identified by Kidwell (1984, 1988, 1989), and includes the Drumcliff Member (zone 17) shell bed (Figure 7). Kidwell interpreted the major shell beds of the Calvert and Choptank Formations as recording the transgressive phase of transgressive-regressive cycles, with maximum water depths reflected in the upper part of the shell bed or along its contact with overlying regressive shell-deficient beds; the bases of the shell beds are erosional disconformities. The lower third-order sequence of this study includes Kidwell's fourth-order cyclic sequence PP-3 (upper regressive phase only), which Kidwell included in the upper Calvert Formation, and the overlying cyclic sequence CT-O (entire cycle) of the Choptank Formation. The upper boundary of the third-order lower sequence is interpreted as the basal disconformity of Kidwell's CT-1 cycle at the base of the Boston Cliffs Member shell bed (zone 19); this disconformity has been characterized by Kidwell (1984, 1988, 1989) from nearby outcrops as a burrowed firmground surface that truncates underlying beds of the CT-O cyclic sequence.

Within the context of the present study results, Kidwell's (1984, 1988, 1989) two transgressive-regressive cyclic "sequences" (PP-3, CT-O) are here interpreted as upward-shoaling parasequences, separated by a marine flooding surface at the base of the Drumcliff Member shell bed (zone 17). These two parasequences constitute a set that appears to reflect a progradational stacking pattern for the lower depositional sequence. A progradational parasequence set is indicated by characteristics that suggest progressive upward shoaling throughout the sequence. These indicators include the following: 1) an overall trend of upwardly increasing sand percentages (increasing sand/mud ratios) throughout the sequence (Figure 4B); 2) an overall trend of upwardly increasing average grain size of the sand fractions (Figures 4A, 6A); 3) a general upward increase in the thickness of lithologic units; and 4) shallower and more fresh-water influenced paleoecological conditions reflected by fauna of the younger Boston Cliffs Member shell bed (zone 19) relative to the Drumcliff Member shell bed (zone 17), as noted by Kidwell (1989).

A progradational parasequence stacking pattern would indicate that during deposition of the lower third-order sequence, the local rate of sedimentation exceeded the rate of accommodation during that time interval. The rate of accommodation (space available for sediment accumulation) is a function of relative sea-level change which, in turn, reflects the resultant interactions of eustatic fluctuations, and local subsidence and uplift movements (Posamentier and others, 1988). Consequently, the progradational lower sequence appears to reflect a sedimentary regime characterized by an abundant sediment supply, the effects of which dominated over the resultant effects of eustatic change and local tectonism. In terms of shelf sedimentation regime models presented by Thorne and Swift (1991), the stacking pattern architecture of the lower sequence is the product of a *Q-dominated* regime. In this type of regime, variations of sediment supply are far more influential than variations in relative sea level.

The assignment of the lower sequence in the studied section to a specific systems tract is constrained by the fact that this study was focused on a single locality. However, on the basis of vertical-facies assemblages and parasequence stacking patterns, certain reasonable inferences can be made regarding systems tracts. By definition, the inner continental-shelf facies comprising the lower sequence would most likely indicate either a transgressive systems tract (TST) or a highstand systems tract (HST). However, the presence of a progradational parasequence set would suggest HST deposition, as opposed to TST deposits that are characterized by retrogradational parasequence sets; the lower sequence is interpreted as HST deposits.

Upper Sequence

The upper depositional sequence, represented by the zone 19-23 lithostratigraphic interval, is an inner shelf-deltaic assemblage. This upper third-order sequence encompasses parts of four of the fourth-order transgressive-regressive cyclic sequences identified by Kidwell (1984, 1988, 1989). These consist of a cyclic sequence (CT-1) that contains the Boston Cliffs Member shell bed of the Choptank Formation (zone 19) and the Conoy Member of the St. Marys Formation (zone 20), and three overlying cyclic sequences (SM-0, SM-1, SM-2) of the informal Little Cove Point unit (Blackwelder and Ward 1976) of the St. Marys Formation (zones 21-23). Sequences SM-0, SM-1, and SM-2 are interpreted by Kidwell (1988, 1989) to consist of only transgressive deposits and no preserved record of individual regressive phases, although the series of cyclic sequences represents a net regressive assemblage. In the present study, these fourth-order cyclic "sequences" are interpreted as parasequences.

The transgressive Boston Cliffs Member shell bed (zone 19) is herein interpreted as a retrogradational parasequence set that comprises a thin and highly condensed transgressive systems tract (TST). The microstratigraphy of the shell bed indicates progressively deepening water and an energy-level reduction; the top of the bed represents the maximum water depth at the end of the transgression (Kidwell, 1989). This trend is also indicated by the abrupt decrease in sand percentages toward the top of the shell bed (Figure 4B). Thus, in terms of the Exxon sequence model, the zone 19-20 contact is a maximum flooding surface (MFS) that separates the thin condensed TST deposits of zone 19 from the overlying relatively thick, highstand systems tract (HST) deposits of the zone 20-23 interval. Also, as previously discussed, this MFS is a hiatal surface that represents a major discontinuity in lithostratigraphic and sedimentological parameters, and it separates two genetically distinct sediment packages. Consequently, in terms of the Galloway (1989) model, the MFS would be interpreted as the boundary separating two genetic stratigraphic sequences.

A highstand systems tract for the overlying zone 20-23 interval is indicated by the deltaic facies assemblage and by the parasequence stacking pattern. The stacking pattern reflected by the parasequence set appears to be predominantly aggradational initially (distal HST deposits), but with an indication of upward transition into a progradational (proximal HST deposits) pattern. The evidence for progradation in the HST deposits of the upper sequence is weaker than that for the HST deposits of the lower sequence; however, there is some indication of overall upward-shoaling conditions throughout the zone 20-23 interval (Figures 4, 6). The evidence includes the vertical facies succession based on paleoenvironmental interpretations, and subtle upward-increasing trends in sand percentages, average grain size of the sand fractions, and general thickness of the sand units. The inferred parasequence stacking pattern indicates that during deposition of the lower part of the zone 20-23 interval, the local rate of sedimentation equaled the rate of accommodation. This suggests a balanced sedimentary regime where sediment influx was just sufficient to balance the effects of relative sea-level changes. During deposition of the upper part of the interval, either the sediment supply increased or relative sea level was lowered, or both occurred, resulting in a basinward shift of the depocenter and coastal progradation.

CONCLUSIONS

The studied BG&E section of the Calvert Cliffs consists of 32 m of predominantly arenaceous deposits comprising the upper Calvert, Choptank, and St. Marys Formations of Langhian to Serravallian age. The lithostratigraphic grain and granulometric parameters of the section indicate a general two-fold division into a relatively homogeneous lower interval (Shattuck's zones 16-19), and a more heterogeneous upper interval (zones 20-23). The lower interval is characterized by a cyclic succession of shell-poor strata and concentrated molluscan shell beds, a cyclicity that is absent from the upper interval. A disconformity at the zone 19-20 contact separating the two lithostratigraphic intervals is a major stratigraphic and sedimentological discontinuity that serves as an effective Choptank-St. Marys formational boundary. Paleoenvironmentally, the lower and upper lithostratigraphic intervals represent two distinct sedimentary facies assemblages. The lower interval is an open, inner-continental shelf facies formed above storm wavebase. Two prominent molluscan shell beds (in the Drumcliff and Boston Cliffs Members) in the interval resulted from stratigraphic condensation and storm-winnowing processes. The lower interval is an overall regressive assemblage with superimposed higher frequency transgressive phases reflecting eustatic events. The upper lithostratigraphic interval is a regressive paralic-facies assemblage developed by a prograding delta lobe. The vertical facies succession consists of basal prodelta muds, grading upward into sandy delta front and littoral deposits, and overlain by semirestricted to restricted embayment deposits of a lower subaerial deltaic plain.

The BG&E section can be interpreted within the context of a siliciclastic sequence-stratigraphic framework. Using Galloway's (1989) sequence model, the section is composed of two genetic stratigraphic sequences that reflect two different depositional episodes; these consist of a shelf sequence (zones 16-19) and an overlying deltaic sequence (zones 20-23). In terms of the Exxon sequence model, the section is composed of two partial third-order (1-5 m.y. duration) depositional sequences, which may occur within the TB2 second-order sea level cycle of Haq and others (1987). Component parasequences consist of parts of six stacked fourth-order (<1 m.y. duration) transgressive-regressive cyclic successions identified by Kidwell (1984, 1988,1989). The lower third-order depositional sequence (zones 16-18) is an inner-shelf facies with a progradational parasequence stacking pattern, indicating highstand systems tract (HST) deposition. The upper third-order depositional sequence (zones 19-23) is an inner-shelf and deltaic facies assemblage. It consists of a basal inner-shelf retrogradational parasequence set (Boston Cliffs Member shell bed of zone 19) that constitutes a thin, condensed transgressive systems tract (TST). Overlying deltaic deposits (zones 20-23) reflect a highstand systems tract (HST); the parasequence set exhibits an aggradational to progradational stacking pattern, indicating a transition from distal to proximal HST deposition. The two third-order depositional sequences of the BG&E section denote an overall regressive section, reflecting local deltation and coastal progradation that probably signified a basinward shift of Miocene depocenters.

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PALEOGENE SEDIMENTS ON THE AXIS OF THE CAPE FEAR ARCH, LONG BAY, NORTH CAROLINA

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ABSTRACT

Core holes seaward of the mouth of the Cape Fear River in Long Bay, penetrate two previously unnamed Paleocene units, herein named the Yaupon Beach Formation and the Bald Head Shoals Formation, and two units of the Castle Hayne Limestone. The Yaupon Beach and Bald Head Shoals Formations are included in a new Paleocene group herein named the Beaufort Group that also includes the Jericho Run and Moseley Creek Formations. The oldest Paleocene unit, the Yaupon Beach Formation, is an olive green, glauconitic, very fine to fine-grained slightly argillaceous quartz sand; it has a minimum thickness of 16 ft (4.9 m). A moderately well-preserved, low diversity, nannofossil assemblage that includes the lower Danian taxa *Cruciplacolithus primus, C. tenuis, Ericsonia cava, Biscutum* spp. and *Neochiastozygus* sp., and Cretaceous survivor species *Placozygus sigmoides, Markalius inversus* and *Cyclogelosphaera reinhardtii,* in the absence of *Chiasmolithus danicus,* suggests correlation of the unit to the lower Danian *Cruciplacolithus tenuis* Zone (NP2, CP1b) and Global Coastal Onlap Cycle TA1.2 of Haq and others (1987).

Disconformably overlying the Yaupon Beach Formation and underlying the Castle Hayne Limestone is medium to dark gray, sandy, molluscan (turritellid)-mold limestone, the Bald Head Shoals Formation; it has a maximum thickness of 23 ft (7 m). Although microfossils in the Bald Head Shoals Formation are poorly preserved and generally recrystallized, the occurrence of the benthic foraminifers *Cibicides neelyi, Eponides lotus, Anomalinoides umboniferus,* and *Cibicidina* sp. indicates an age between calcareous nannofossil zones NP5 and NP13. As these foraminifers are most abundant in late Paleocene zones NP8-9, the Bald Head Shoals Formation is interpreted to be Thanetian age. Mollusks in the unit including *Mesalia biplicata* Bowles, *Barbatia (Cucullaearca) cuculloides* (Conrad), and *Acanthocardia (Schedocardia) tuomeyi (*Aldrich) also suggest a Thanet age. The Bald Head Shoals Formation is assigned to Global Coastal Onlap Cycle TA2.1.

Two depositional sequences of the Castle Hayne Limestone are disconformable on the Bald Head Shoals Formation. The oldest is well-indurated, cross-bedded, bryozoan grainstone; it has a minimum thickness of nine ft (3 m). Although this sequence contains no age-diagnostic fossils, based on superposition and its lithology, it is correlated to middle Eocene Global Coastal Onlap Cycle TA3.5/3.6. The youngest depositional sequence of the Castle Hayne Limestone is disconformable on the older Castle Hayne sequence or the Bald Head Shoals Formation, has a broader distribution, and ranges in thickness to over 10 ft (3 m). This sequence is typically an unlithified to well-lithified megafossil-rich packstone and contains the diagnostic terebratulid brachiopod *Terebratula wilmingtonensis,* large pectinids (*Chlamys* spp.), and the clypeasteroid sand dollar *Periarchus lyelli.* These megafossils are typical of those previously described from middle/upper Eocene sediments that have been assigned to Global Coastal Onlap Cycle TA4.1.

INTRODUCTION

The Cape Fear arch (or Carolina platform) in

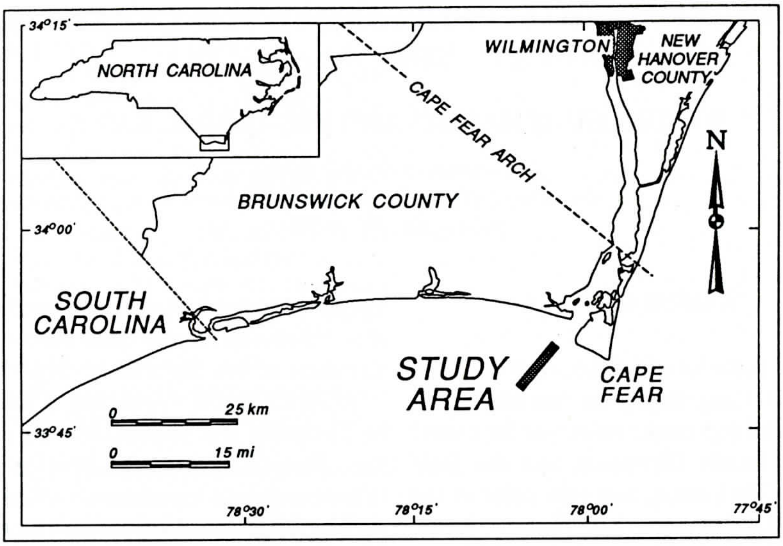

Figure 1. Approximate location of study area in Long Bay, North Carolina. The study area is enlarged in Figure 2.

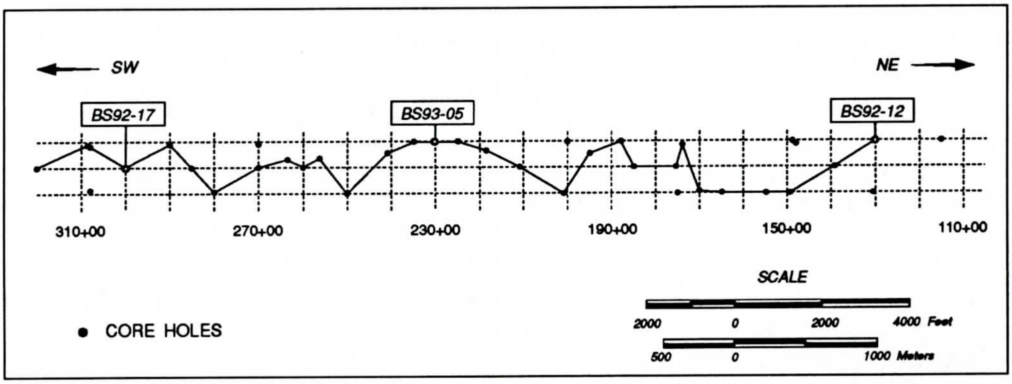

Figure 2. Core-hole locations along Bald Head Shoals Channel, Long Bay, with three cores identified for reference. Line connecting core holes represents the line of section that is shown in Figure 3. The three parallel dashed lines approximate the channel margins and the channel center. Locational data is the U. S. Army Corps of Engineers scheme and is given in feet. For example, the distance between 150+00 and 190+00 is 4000 ft Location of core-holes in latitude and longitude is given in Appendix A.

southeastern North Carolina divides the Albemarle embayment centered in northeastern North Carolina from the Charleston embayment which is centered in South Carolina. This northwest-southeast trending feature exposes Cretaceous sediments and rocks along its axis and Paleocene and Eocene sediments north and south of the axis. Meisburger (1981) recognized two unnamed Paleocene lithofacies on the axis of the Cape Fear arch in Long Bay, an older fine to very fine quartz sand and younger fine to coarse glauconitic sand and sandy limestone. On the basis of benthic and planktonic foraminifers, he assigned the sediments an early Paleocene (Danian) age. Although he suggested both rock types were Danian in age, he indicated that "...they were deposited under different environmental conditions and probably at different times."

Harris and others (1986) and Zarra (1991) recognized Paleocene sediments in core holes in southern Brunswick County, and Zarra (1991) mapped their onshore distribution. Zarra (1991) identified two rock types, argillaceous siltstone and fine-grained sandstone, and assigned the sediments to the Beaufort Formation; however, he did distinguish the superpositional relationship of the sediments. Based on the occurrence of planktonic foraminifers *Morozovella pseudobulloides* and *Globoconusa daubjergensis,* he placed these sediments in Danian planktonic zone P1.

This paper presents data on the distribution, occurrence, and characterization of Paleogene sediments in a series of core holes from the axis of the Cape Fear arch at Bald Head Shoals in Long Bay, North Carolina. These cores were obtained by the U.S. Army Corps of Engineers in Bald Head Shoals Channel, seaward of the mouth of the Cape Fear River (Figure 1). Based on our study, two new formations are identified and named, the Danian Yaupon Beach Formation and the Thanetian Bald Head Shoals Formation. We also recommend that the Beaufort Formation be elevated to the rank of group, that the Jericho Run and Moseley Creek Members be elevated to the rank of formation, and that the Yaupon Beach and Bald Head Shoals Formations be included in the Beaufort Group.

Original core descriptions were made by W. B. Harris and V. A. Zullo; sedimentologic and petrologic characterization by W. B Harris, and calcareous nannofossil biostratigraphy by R. A. Laws. Thomas R. Gibson (U.S. Geological Survey) provided identification of foraminifers from selected samples and Warren D. Allmon (Paleontogical Research Institute) identified mollusks in selected samples. Preliminary information on these core holes was reported by Harris and others (1993a).

Procedure

Forty core holes were logged and described, and samples containing Paleocene sediments in 15 core holes (Figure 2) were collected for further study and analysis. Core hole locations are given in Appendix A. Elevations in the text for the tops of the units are referenced to below mean low water (BMLW). Texture, fabric, sedimentary structures, micro- and megafossils were described for each core. Insoluble residues for Paleocene sediments were obtained from cores BS92-12 and BS92-21 by dissolving between 60 and 120 g of sample in 10% HCl. Weight percent sand and weight percent silt plus clay were determined. Sand-size residues from core hole BS92-12 were sieved on optically calibrated screens at 1.0 phi unit intervals to determine size distribution. Sixteen thin-sections of the Bald Head Shoals Formation from core holes BS92-12 and BS92-21 were prepared by impregnation with blue epoxy to distinguish porosity, and number frequency of components were determined by counting 300 points per slide. Because of the unconsolidated nature of the Yaupon Beach Formation, thin selections were not prepared and bulk sediment was examined and described for constituents under a binocular microscope. The limestone and terrigenous terminology used are those of Dunham (1962) and Folk (1968), respectively; porosity terminology is that of Choquette and Pray (1970). Selected samples were prepared and analyzed for micro- and megafossils by standard techniques. We use the calcareous nannofossil zonations presented in Perch-Nielsen (1985).

GEOLOGIC SETTING

The study area is located on the axis of the Cape Fear arch in Long Bay, seaward of the mouth of the Cape Fear River, along a 19,000 ft (5.8 km) northeast-southwest transect of the ship channel that connects to the Cape Fear River (Figure 1). The core holes were drilled in 1990, 1992, and 1993 by U. S. Army Corps of Engineers and extend from their station number 120+00 southwest to 320+00 (Figure 2). Core hole spacing along this transect is generally less than a 1000 ft.

STRATIGRAPHY

Beaufort Group

The Beaufort Formation is herein elevated to the rank of group and the Jericho Run and Moseley Creek Members are elevated to the rank of formation. The new Beaufort Group includes the Danian Jericho Run and Yaupon Beach Formations, the Thanetian Moseley Creek and Bald Head Shoals Formations, and the unnamed sediments in the subsurface of the Albemarle embayment recognized by Zarra (1989). In defining groups, the only requirement of the North American Commission on Stratigraphic Nomenclature (1983, p. 858) is that they are defined to "...express the natural relationships of associated formations..." Although the North American Stratigraphic Code has no other requirement for recognizing groups, the International Stratigraphic Guide (1976, p. 34) indicates that the term "...is applied most commonly to a sequence of two or more contiguous associated formations with significant unifying lithologic features." The formations herein named and recognized in Long Bay meet the requirements of the North American Stratigraphic Code (1983) for comprising a group. In addition, as suggested by the International Stratigraphic Guide (1976), formations assigned to the Beaufort Group have in common a fine to coarse siliciclastic component, are dark-gray to gray-green in color and are contiguous. The pertinent question about recognition of two new lithostratigraphic units in Long Bay is their assignment to the rank a formation. Formation, according the North American Stratigraphic Code (1983, p. 858) "...is a body of rock identified by lithic characteristics and stratigraphic position..." which "...is mappable at the Earth's surface or traceable in the subsurface." Units assigned to the Beaufort Group in Long Bay are identified by their distinctive lithologic characteristics and stratigraphic position, and are mappable at the earth's surface and in the subsurface. Also by elevating the Jericho Run and Moseley Creek Members to formation, and combining them into a group with the Yaupon Beach and Bald Head Shoals Formations, Paleocene stratigraphy of North Carolina is simplified and generalized which is a common goal of stratigraphic classification. Consequently, lithologic units of Paleocene age in the vicinity of Bald Head Shoals, North Carolina, fit the requirements of the North American Stratigraphic Code for formal designation as formations. As these sediments were previously included in the Beaufort Formation (Zarra, 1991), "when a single formation is subdivided into formal lithostratigraphic units of formational rank, the old formation is raised to the rank of group..." (Schoch, 1989, p. 157). The Beaufort Group includes the Yaupon Beach, Jericho Run, Bald Head Shoals, and Moseley Creek Formations.

Beaufort Group sediments occur in 15 core holes along Bald Head Shoals channel and include two distinctive sediment types. A lower very fine to fine argillaceous quartz sand is herein designated the Yaupon Beach Formation, and an upper sandy turritellid-mold limestone is herein designated the Bald Head Shoals Formation. The Yaupon Beach Formation is thickest in core hole BS93-05, and the Bald Head Shoals Formation is thickest in northernmost core hole (BS92-12) and southern most core hole (BS92-21). As no cores penetrate the Cretaceous-Tertiary boundary, the maximum observed thickness for the Yaupon Beach Formation is considered a minimum for the unit.

Disconformably overlying the Beaufort Group is either the Castle Hayne Limestone or Recent sediments; in one core hole sediments considered to represent the Waccamaw Formation overlie the Castle Hayne Limestone. Along the channel, Castle Hayne Limestone or the Bald Head Shoals Formation crop out on the sea floor or beneath a thin veneer of Recent sediment (Figure 3).

Yaupon Beach Formation

Sediments between -62.5 and -78.3 ft in core hole BS93-05 are herein designated the holostratotype of the Yaupon Beach Formation of

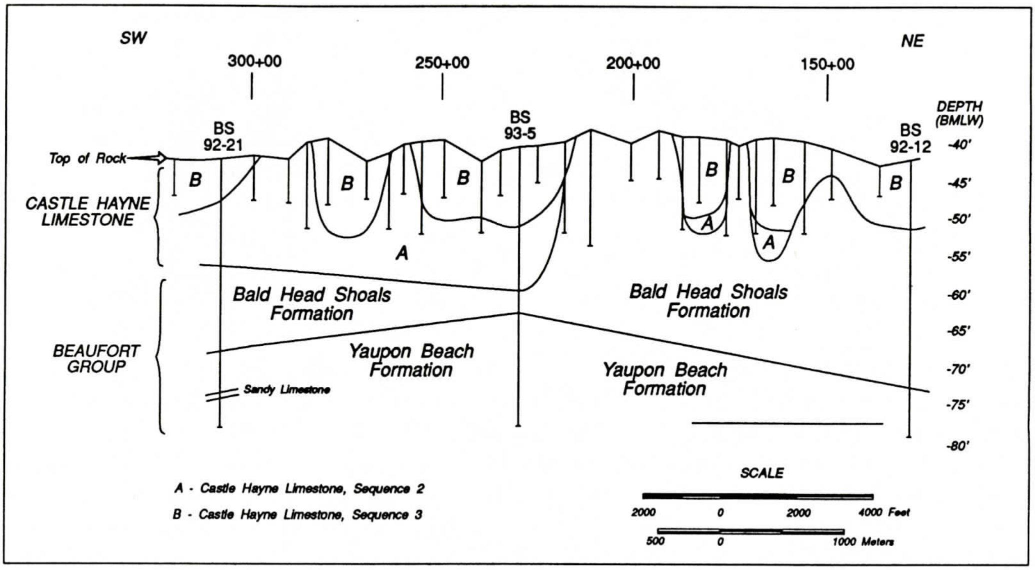

Figure 3. Structure section along Bald Head Shoals Channel, Long Bay, illustrating the stratigraphy of the Paleocene and Eocene units encountered. Three core holes are identified for reference. Vertical exaggeration is 200.

the Beaufort Group. Cores holes BS92-12 and BS92-21 are designated hypostratotypes. The name Yaupon Beach is taken from the beach located three miles to the west, in Brunswick County. This formation occurs in three core holes that extend the length of the channel (Figure 3, Appendix A). It has a maximum thickness of 16 ft (4.88 m) in core-hole BS93-05; however, as the lower contact of the unit with the Peedee Formation has not been observed in the cores, it is considered a minimum thickness. The Yaupon Beach Formation is disconformably overlain by the Bald Head Shoals Formation. Although the Yaupon Beach Formation does not crop out on the sea floor in the study area, it is probably equivalent to the seaward part of Unit 1 of Meisburger (1981) which crops out further south in Long Bay.

The Yaupon Beach Formation is predominantly an olive green to gray, glauconitic, very fine to fine-grained slightly argillaceous bioturbated quartz sand. Lithified intervals less than a foot in thickness (30 cm) may occur in the unit (core hole BS92-21). These intervals generally have higher concentrations of mollusks, preserved as molds, and calcite cement than the surrounding very fine to fine quartz sand. Insoluble residue study of four samples from core holes BS92-12 and BS92-21 indicates that the unit contains little soluble material (average 4.82%) and has a size distribution of the insoluble that is dominated by very fine to fine quartz sand (average 84.12%); however, silt and clay-sized material is an abundant component of the insoluble fraction (Table 1). Study of smear slides from the unit indicates that most of the carbonate fraction is made up of foraminifers, calcareous nannofossils, and ostracods.

The Yaupon Beach Formation contains a moderately well-preserved, low diversity nannofossil assemblage that includes species with first appearances in the Danian, species which persist across the Cretaceous/Tertiary boundary, and redeposited Cretaceous species. Lower Danian taxa include *Cruciplacolithus primus*, *C. tenuis*, *Ericsonia cava*, *Biscutum* spp. and *Neochiastozygus* sp. Cretaceous survivor species include *Placozygus sigmoides*, *Markalium inversus* and *Cyclogelosphaera reinhardtii*. Redeposited Cretaceous taxa include *Arkangelskiella cymbiformis*, *Crirosphaerella danias*, *Prediscosphaera spinosa*, *P. cretacea*, *Microrhabdulus decoratus* and *Micula decus-*

Table 1. Insoluble residue data, Yaupon Beach and Bald Head Shoals Formations, Beaufort Group.

UNIT	% INSOLUBLE	% SAND					% SILT & CLAY
		v. crse.	crse.	med.	fn.	v. fn	
Bald Head Shoals Fm.	35.78	0.13	1.20	14.27	60.68	23.73	15.40
Yaupon Beach Fm.	95.18	0.00	0.00	0.22	27.03	72.75	15.69

sata. This assemblage is very similar to lower Danian nannofossil assemblages described from Cretaceous/Tertiary boundary sections in Texas (Jiang and Gartner, 1986), Denmark, Spain, Tunisia and deep-sea cores (Perch-Nielsen, 1985). In the absence of *Chiasmolithus danicus* this assemblage correlates to the lower Danian *Cruciplacolithus tenuis* Zone (NP2, CP1b) and Global Coastal Onlap Cycle TA1.2 of Haq and others (1987).

Bald Head Shoals Formation

The Bald Head Shoals Formation disconformably overlies the Yaupon Beach Formation and disconformably underlies the Eocene Castle Hayne Limestone. The unit is present in 15 core holes along the entire length of the ship channel, but it is thickest and best developed in the northernmost core hole (BS92-12). In this core it is almost 23 ft (7 m) thick extending from -73.7 ft to -51.1 ft, (Figure 3). As this core hole contains the thickest section of the Bald Head Shoals Formation, it is herein designated the holostratotype; core hole BS92-21 is designated a hypostratotype (Appendix A). The name Bald Head Shoals Formation is derived from the shoals that occur seaward of Bald Head Island, North Carolina, in the area of the ship channel which connects to the Cape Fear River.

The Bald Head Shoals Formation is a moderately to well indurated, medium to dark gray, sandy molluscan-mold mudstone, wackestone, to packstone (Figure 4); packstone is the most abundant lithology (Figure 5a and b). The contact with the underlying Yaupon Beach Formation is sharp and abrupt and is interpreted as an unconformity; however, it does not contain features typical of unconformities found elsewhere in the coastal plain. Most unconformities in the North Carolina Coastal Plain generally are highly irregular, microkarstic surfaces with phosphate and glauconite mineralization coating the surface. The unconformities often are sharp lithologic breaks overlain by phosphatized and glauc-

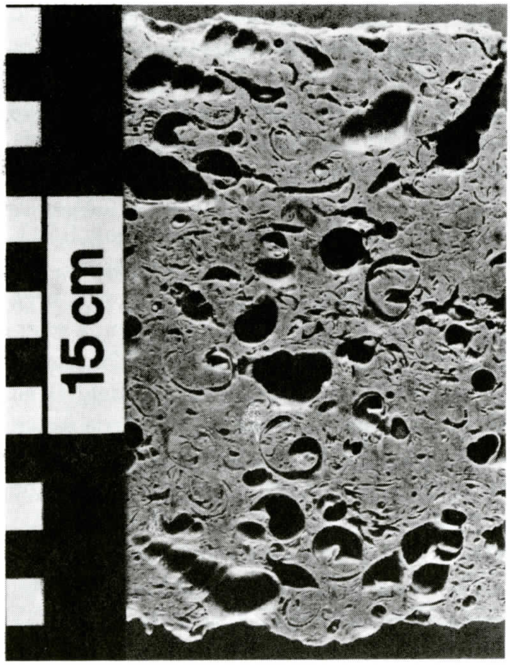

Figure 4. Hand sample of sandy turritellid-mold packstone, Bald Head Shoals Formation, Core hole BS92-08, 46.4-46.8'. Gastropod and pelecypod molds are easily recognizable as well as geopetal fabrics that preserve shelter porosity within molds. Gastropods represent a new species.

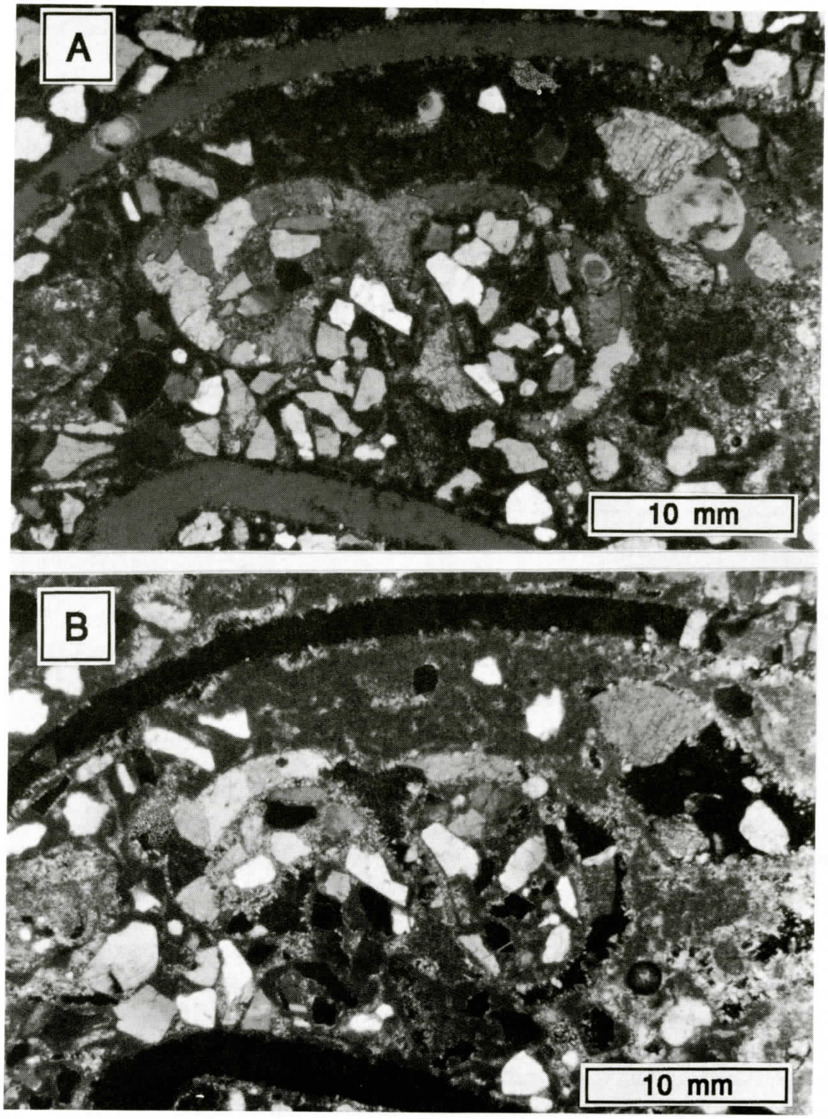

Figure 5. Thin section of sandy molluscan-mold packstone, Bald Head Shoals Formation, Core hole BS92-21, 62'. Pelecypod molds are recognizable as well as gastropod molds that are partially reduced by calcite spar. A. uncrossed nicols, B. crossed nicols.

onitized lithoclasts. In some cases younger sediment fills underlying burrows or solutioned areas in the older rock (Harris and others 1986; Zullo and Harris, 1987). The lower contact of the Bald Head Shoals Formation is interpreted as an unconformity on the basis of the sharp lithologic break between it and the underlying Yaupon Beach Formation. In addition, the distinct age difference with the underlying Yaupon Beach Formation indicates a gap in the sedimentary record. The upper boundary of the unit with the overlying Castle Hayne Limestone is a highly irregular and solutioned disconformity with some phosphatization and glauconitization, and sediment-filled solution cavities extending almost two feet (0.6 m) below the boundary. In some places, the Bald Head Shoals Formation crops out on the sea

Table 2. Compositional data for the Yaupon Beach and Bald Head Shoals Formations, Beaufort Group. Bald Head Shoals data were determined by point counts of 16 thin sections; Yaupon Beach data were determined by binocular microscope examination of four samples.

	FRAMEWORK									MATRIX		CEMENT		POROSITY			
	Siliciclastics		Allochems														
UNIT	Quartz	Others	Pelecypods	Gastropods	Foraminifers	Bryozoans	Echinoderms	Ostracods	Phos./Glauc.	Micrite	Neomorphic Spar	Whisker	Dogtooth Spar	Vuggy	Moldic	Interparticle	Intraparticle
Bald Head Shoals Fm.																	
Packstone	A	R	R	*	T	T	T		T	A	R	T	R	A	A	T	T
Wackestone	C	T	R	*		R	T		T	A	R	R	R	A	T		
Mudstone	A	T	R	*	T		T		R	A	A	T	T	R	R	T	T
Yaupon Beach Fm.																	
Sand	A	R	T		T			T	R		T						

A = Abundant, >25%
C = Common, 10-24.9%
R = Rare, 1-9.9%
T = Trace, <1%
* Although not tallied above in the point counts, most molds and vugs are gastropods
Blank Spaces = Not observed

floor forming the base of the ship channel (Figure 3).

Siliciclastic framework constituents of the Bald Head Shoals Formation consist almost exclusively of subangular to subrounded quartz with minor plagioclase, potassium feldspar, muscovite, and various subordinate heavy minerals (Table 2). Point counting indicates that most allochemical constituents are pelecypods and bryozoans; however, this is somewhat misleading as most molds and many vugs were originally gastropods that have been solution-enlarged (Table 2). Micrite and neomorphic calcite spar comprise the major non-framework components of the formation (Table 2). Porosity varies from zero percent just below the Paleocene/Eocene boundary to a high of 36% lower in the unit and is principally vuggy and moldic (Table 2). Molds are of gastropods or pelecypods and vugs are probably solution-enlarged gastropods.

Weight percent insoluble residue averages 35.6% in core hole BS92-12 and 36.1% in core hole BS92-21, and varies from a low of about 25% to slightly higher than 50%. Percent sand of the insoluble residue averages 84.3% and 85.2% in BS92-12 and BS92-21, respectively, and varies from a low of about 65% to a high of about 95%. The percent sand of the insoluble residue decreases upward from the base of the unit for several feet than increases to the top of the unit in BS92-12 (Figure 6). In core hole BS92-21 there is an overall upward decrease in the percent sand of the insoluble. The size distribution of the sand fraction in BS92-12 indicates that it is dominated by fine to very fine subangular to subrounded quartz sand. However, there is a marked increase in medium- and coarse-grained sand from -61 ft upward to the top of the unit at -51.5 ft. Subordinate silt and clay also occur in the unit and show an increase in abundance from the base of the unit upward to -66 ft, and then a general decrease in abundance to the top of the unit (Figure 6). Insoluble percents and grain-size data are given in Table 1 and Figure 6.

The Bald Head Shoals Formation contains very sparse calcareous nannofossils and fora-

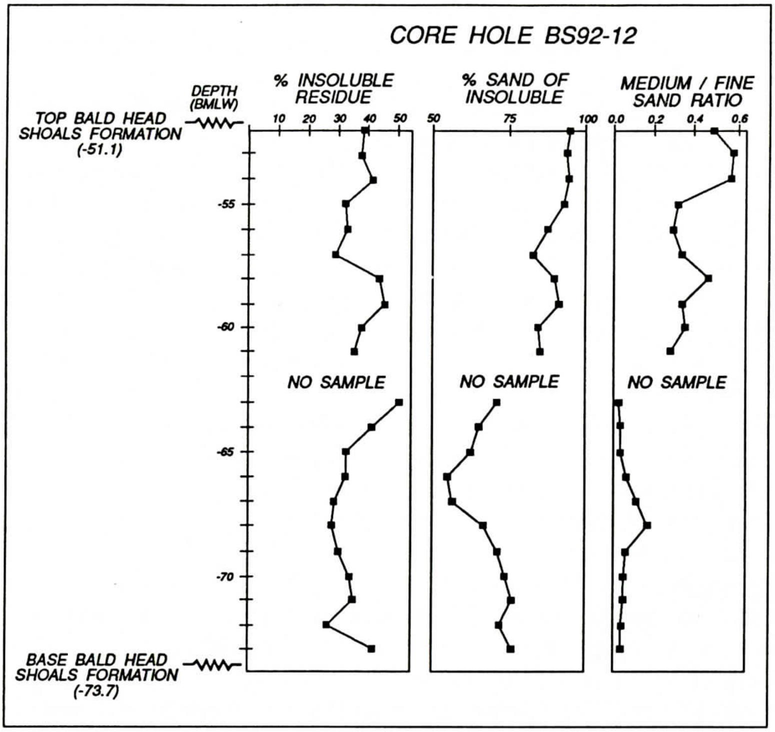

Figure 6. Percent insoluble residue, percent sand of insoluble, and medium/fine sand ratios, the holostratotype of the Bald Head Shoals Formation, Core-hole BS92-12.

minifers but abundant gastropods and pelecypods; however, most mollusks are preserved as molds and are not age-diagnostic. The most abundant mollusk is an undescribed species of a turritellid gastropod (*Turritella* sp.) that is most similar to *Turritella mingoensis* Bowles, but is quite distinct from it (Warren D. Allmon, 1994, personal communication). Three mollusks that are age-diagnostic in the Gulf Coastal Plain occur in the Bald Head Shoals Formation; the gastropod *Mesalia biplicata* Bowles which occurs in the Nanafalia Formation, and the pelecypods *Barbatia (Cucullaearca) cuculloides* (Conrad) which occurs in the Greggs Landing Member of the Tuscahoma Formation and *Acanthocardia (Schedocardia) tuomeyi* (Aldrich) which also occurs in the Nanafalia Formation (Warren D. Allmon, 1994, personal communication). These units are considered to be Thanetian in age (Mancini and Tew, 1988).

Although the foraminifers in the Bald Head Shoals Formation are sparse, poorly preserved and generally recrystallized, the occurrence of the benthic species *Cibicides neelyi, Eponides lotus, Anomalinoides umboniferus*, and *Cibicidina* sp. in core holes BS92-12 and BS92-21 (Thomas R. Gibson, 1994, personal communication) suggest an age for the unit from middle Paleocene to middle Eocene (NP5-NP13). As these species are generally most abundant in the late Paleocene, the age also indicated by the mollusks, we suggest that the Bald Head Shoals Formation is Thanetian in age, and is assignable to Global Coastal Onlap Cycle TA2.1. This sequence is the most widespread Paleocene sequence in the North Carolina Coastal Plain (Harris and others, 1993b).

Castle Hayne Limestone

Castle Hayne Limestone disconformably overlies the Bald Head Shoals Formation in most core holes along the length of the channel (Figure 3, Appendix A). Two depositional sequences are represented by the Castle Hayne Limestone; a lowermost sequence herein referred to as unit A, and an upper sequence herein referred to as unit B. Unit A is best developed in the southernmost core holes from about location 230+00 south to 310+00 where it is disconformable on the Bald Head Shoals Formation (Figure 3). Small outliers of Unit A occur north in core holes BS93-1 and BS93-3 in low areas that are developed on the underlying Bald Head Shoals Formation. Unit A has a maximum thickness of almost nine ft (2.74 m) in core holes BS93-05 and BS92-21 (Figure 3). The lower disconformity is marked by either an irregular, phosphate-coated surface, or a karstic cobble zone extending up to 1.5 ft (0.5 m) into the underlying Bald Head Shoals Formation. Unit A is typically a well-indurated, cross-bedded, well-washed, bryozoan grainstone with only calcitic skeletal material preserved. Calcite spar or in some rare cases whisker cement partially reduces interparticle porosity in the unit. Locally, in the lower part of the unit, micrite is more abundant but not to the point of making the unit a packstone, perhaps a mud-lean packstone.

Unit A of the Castle Hayne Limestone is characterized by an abundant and diverse bryozoan fauna that is typical of middle Eocene sequence 2 of Zullo and Harris (1987); however, no age-diagnostic fossils were observed in the core hole samples.

Unit B of the Castle Hayne Limestone disconformably overlies and is incised into Unit A. Unit B has a broader distribution in the study area than Unit A, but also appears to have a discontinuous distribution on either Unit A of the Castle Hayne Limestone or the Bald Head Shoals Formation. Unit B ranges in thickness to over 10 ft (3 m) (Appendix A). The contact between Unit A and Unit B is a corroded surface that is commonly bored often with a phosphatic crust. The unconformable nature of this contact is much better developed in core holes located shoreward than seaward.

Unit B of the Castle Hayne Limestone is more heterogeneous than Unit A, but is typically a megafossil-rich packstone with local lenses of bryozoan grainstone. The packstone ranges from relatively unlithified to dense and well-lithified. Where it occurs, it is highly bioturbated with micrite-filled burrows, and contains large pectinids (scallops), brachiopods, and echinoids. Bryozoan grainstone is poorly lithified or unlithified and is not crossbedded as is the grainstone in Unit A.

Diagnostic fossils in Unit B include the large terebratulid brachiopod *Terebratula wilmingtonensis*, large pectinids (*Chlamys* spp.), and the clypeasteroid sand dollar *Periarchus lyelli.* These megafossils are typical of those described by Zullo and Harris (1987) in middle/upper Eocene sequence 3 of the Castle Hayne Limestone.

Waccamaw Formation

Sediment questionably referred to the Waccamaw Formation was observed in a single core hole (BS92-12). At this site, six inches (12.65 cm) of fossiliferous, phosphatic, calcareous quartz sand disconformably overlies a phosphatized and solutioned surface developed on Unit B of the Castle Hayne Limestone. Although most of the fossils in this unit are fragmented, the barnacles *Balanus venustus* and *B. calidus* are common. As neither of these two fossils are known to occur in strata older than the Pleistocene, and as the sediment compares favorably with sediment of the Waccamaw Formation onshore, it is suggested that this unit is probably the Waccamaw Formation.

DISCUSSION AND CONCLUSIONS

Paleocene sediments in North Carolina have been rarely studied principally because of few outcrops and their limited distribution. They were first recognized in the subsurface of the Albemarle embayment of North Carolina in a core hole drilled at Chocowinity, Beaufort County, by Brown (1958), and subsequently, in outcrop in Craven and Lenoir Counties (Swift, 1964; U. S. Geological Survey, 1972; Harris and Baum, 1977; Brown and Miller, 1986). Harris and Baum (1977) provided sedimento-

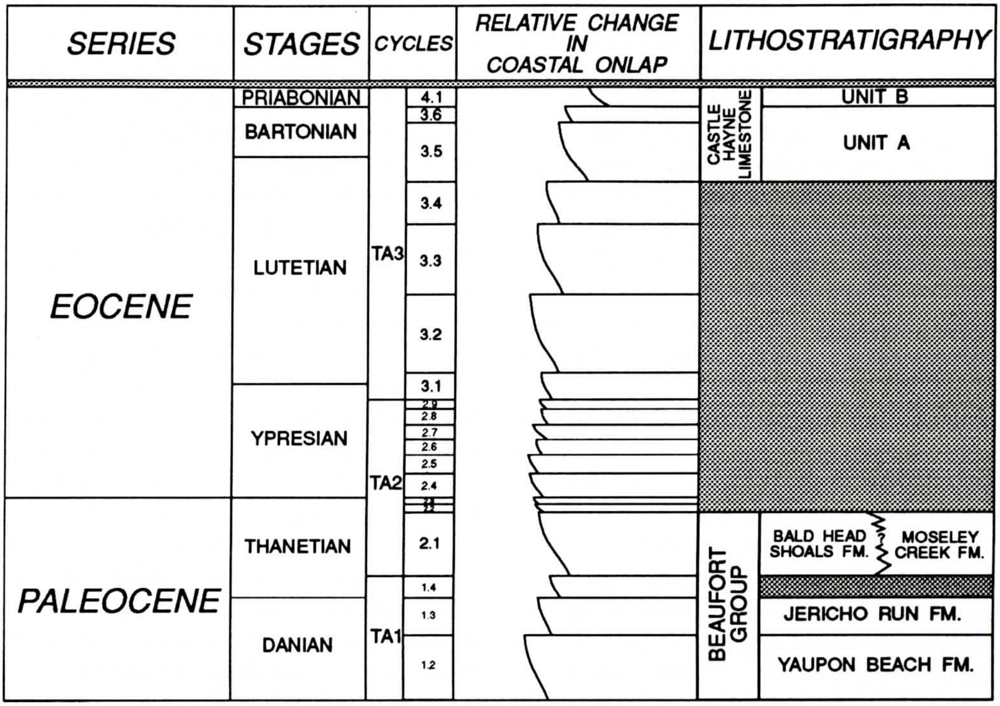

Figure 7. Correlation of Paleocene and Eocene stratigraphic units in the core holes to units recognized in the North Carolina Coastal Plain and to the Global Cycles of Coastal Onlap of Haq and others (1987).

logic, paleontologic, and geochronometric information on the Paleocene along Moseley Creek, Lenoir-Craven County-Line. Brown and others (1977) recognized and discussed wrench-style deformation of Cretaceous and Paleocene rocks in the same area. Zarra (1989) mapped the distribution of Paleocene sediments in the subsurface of the outer part of the Albemarle embayment. Harris and others (1993b) assessed the distribution and age of sediments assigned to the Paleocene Beaufort Formation, named the Moseley Creek Member, and assigned the sediments to global cycles of coastal onlap. McLaurin (1993) mapped the distribution of Danian and Thanetian sediments in the Lenoir and Craven County area, and related their distribution to faults associated with the Graingers wrench zone.

As currently recognized, the Beaufort Formation consists of the Danian Jericho Run Member and the Thanetian Moseley Creek Member (Harris and others, 1993b). With recognition of Beaufort Formation sediments in southeastern North Carolina (Zarra, 1991), and recognition of mappable units of Paleocene age at Bald Head Shoals in Long Bay, we recommend that the Beaufort Formation be elevated to the rank of group. We also recommend elevation of the Jericho Run and Moseley Creek Members to the rank of formation and that the Yaupon Beach and Bald Head Shoals Formations be included in the Beaufort Group. The newly designated Paleocene Beaufort Group consists of four formations, the Danian Yaupon Beach Formation of this study, the Danian Jericho Run Formation of Brown and others (1977), the Thanetian Moseley Creek Formation of Harris and others (1993b), and the Thanetian Bald Head Shoals Formation of this study. Very fine to fine glauconitic quartz sand (Yaupon Beach Formation) recognized in core holes at Bald Head Shoals is lithologically different from the Jericho Run (siliceous claystone and shale) and the Moseley Creek (sandy, foraminiferal-glauconitic sediments and foraminiferal biosparite) Formations that occur in Lenoir-Craven Counties. It is lithologically similar to the seaward part of Meisburger's (1981) Unit 1 that occurs in Long Bay and is probably correlative. Meisburger (1981) identified foraminifers from these sediments that indicated a Paleocene age including the benthic species *Anomalinoides newmanae, Cibicides* cf. *C. howelli* and *Gyroidinoides octacamerate*, and the planktonic species *Globoconusa daubjergensis, Planorotalites compressa*, and *Subbotina (Globorotalia) pseudobulloides*. Calcareous nannofossils from lithologically similar material in core holes from the Yaupon Beach Formation indicate correlation to the lower Danian *Cruciplacolithus tenuis* Zone (NP2, CP1b). Therefore, based on benthic foraminifers and calcareous nannofossils, the Yaupon Beach Formation is Danian in age and is assigned to Global Coastal Onlap Cycle TA1.2 of Haq and others (1987) (Figure 7). Assignment of the Yaupon Beach Formation to the TA1.2 cycle indicates that it is older than the Jericho Run Formation of the northern North Carolina Coastal Plain which Harris and others (1993b) assigned to Global Coastal Onlap Cycle TA1.3 (Figure 7). The lithology of the Yaupon Beach Formation is similar to the lithology recognized by Zarra (1991) onshore in southern Brunswick County which he also assigned to P1 planktonic foraminiferal zone. The Jericho Run Formation is an indurated siliceous claystone and shale, ranges up to about 36 ft (11 m) in thickness (McLaurin, 1993), and has only been recognized in outliers in Craven and Lenoir Counties. The formation is correlated downdip to a lithologically different, unnamed clastic section of very fine-grained sandstone to sandy siltstone that has a thickness between 131-197 ft (40 and 60 m) Zarra (1989).

The Moseley Creek Formation consists of alternating unconsolidated, sandy, foraminiferal-glauconitic sediments and thinner foraminiferal biosparite and sandy biosparite (Harris and Baum, 1977); it ranges to over 13 ft (4 m) in thickness in the type area. In the outer Coastal Plain of the Albemarle embayment, an unnamed medium- to coarse-grained sand that is overlain by silty clay and very fine-grained sand to 131 ft (40 m) thick is correlated to the Moseley Creek Formation (Harris and others, 1993b). The Moseley Creek Formation was assigned to Global Coastal Onlap Cycle TA 2.1 by Harris and others (1993b). Bald Head Shoals Formation sediments are lithologically different from the Jericho Run Formation and the Moseley Creek Formation. Although the latter contains limestone, it is significantly different from the limestone in the Bald Head Shoals Formation (sandy molluscan-mold mudstone to packstone). The Bald Head Shoals Formation overlies the Yaupon Beach Formation along a sharp surface that is a disconformity in Long Bay. Benthic foraminifers *Cibicides neelyi, Eponides lotus, Anomalinoides umboniferus*, and *Cibicidina* sp. in the Bald Head Shoals Formation suggest a middle Paleocene to middle Eocene (NP5-NP13) age for the unit. Three mollusks that are age-diagnostic of the Thanetian in the Gulf Coastal Plain are present in the Bald Head Shoals Formation. Therefore, on the basis of benthic foraminifers and mollusks, the Bald Head Shoals Formation is considered to be Thanetian in age and assignable to Global Coastal Onlap Cycle TA2.1. Although the stratigraphic relationship of the Bald Head Shoals Formation to the Moseley Creek Formation has not been observed, and as the units are assigned to the same cycle of sea level change (Figure 7), they are considered to be age equivalent. It is important to note that neither Meisburger (1981) nor Zarra (1991) recognized Thanetian age sediments in southeastern North Carolina. The Bald Head Shoals Formation may be lithologically similar to the sandy limestone that Meisburger (1981) recognized south in Long Bay which contained the Danian planktonic foraminifer *Subbotina (Globorotalia) pseudobulloides*; however, the Bald Head Shoals Formation is younger in age.

Zullo and Harris (1987) recognized five depositional sequences in the Castle Hayne Limestone based on their contained mega- and microfossils. Their sequences 0, 1, and 2 were interpreted to be exclusively middle Eocene, sequence 3 both middle and late Eocene, and sequence 4 exclusively late Eocene. Core holes along Bald Head Shoals channel indicate that two depositional sequences are present that can tentatively be correlated to two of the sequences recognized by Zullo and Harris (1987). Unit A of the Castle Hayne Limestone, although not containing any age diagnostic flora or fauna, contains lithologic characteristics and superpositional relationships that suggest it correlates to sequence 2 of Zullo and Harris (1987) or Global Coastal Onlap Cycle TA3.5/3.6. Unit B of the Castle Hayne Limestone is correlated to sequence 3 of Zullo and Harris (1987) or Global Coastal Onlap Cycle TA4.1 based on the presence of *Periarchus lyelli, Terebratula wilmingtonensis*, and one species of *Chlamys*. This sequence straddles the middle-late Eocene boundary with the series boundary being represented by a marine hardground within the condensed section. A phosphatized surface at -46.7 ft in core hole BS92-12 may be represent the surface of maximum flooding within the condensed section.

SUMMARY

Core holes from Bald Head Shoals channel, seaward of the mouth of the Cape Fear River, penetrate a section of undescribed Paleocene sediments and rocks on the axis of the Cape Fear arch that sheds light on the geologic history of the area during the early Paleogene. The following summarizes the major points of this study:

1) Two Paleocene lithologic units are present, lower very fine to fine, glauconitic quartz sand herein designated the Yaupon Beach Formation, and upper sandy molluscan-mold mudstone, packstone, and wackestone herein designated the Bald Head Shoals Formation.

2) The Yaupon Beach Formation is a widespread unit in Long Bay and onshore in southern Brunswick and New Hanover Counties. It contains a calcareous nannoflora indicating correlation to the lower Danian *Cruciplacolithus tenuis* Zone (NP2, CP1b) and Global Coastal Onlap Cycle TA1.2

3) The Bald Head Shoals Formation is not known from wells or core holes onshore, but appears to occur in much of Long Bay, north of the North Carolina-South Carolina state line. It is assigned a Thanetian age because of the occurrence of the benthic foraminifers and assigned to Global Coastal Onlap Cycle TA2.1.

4) The Beaufort Formation is elevated in rank to group with concomitant elevation of the Jericho Run and Moseley Creek Members to formation. The Beaufort Group includes the Yaupon Beach, Jericho Run, Moseley Creek, and Bald Head Shoals Formations.

5) Two sequences of the Castle Hayne Limestone which occur in the cores disconformably overlie upper Paleocene sediments. The lower sequence is tentatively correlated to Global Coastal Onlap Cycle TA3.5/3.6 on the basis of lithology and superposition. The upper sequence is correlated to Global Coastal Onlap Cycle TA4.1 on the basis of megafossils.

ACKNOWLEDGMENTS

We thank the University of North Carolina at Wilmington for providing time and support for this research. The U. S. Army Corps of Engineers and Tong Haw are gratefully acknowledged for providing access to the cores, and making other data available to us for study. In addition, we also thank Thomas R. Gibson for examining selected samples for foraminifers and Warren D. Allmon for examining selected samples for mollusks. We gratefully acknowledge the comments of Don Colquhoun. This is contribution #114 from the Center for Marine Science Research, the University of North Carolina at Wilmington.

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Appendix A. Location and stratigraphy of core-holes used in this study. All locations are given in degrees latitude and longitude and all depths are referenced to below mean low water (BMLW).

CORE HOLE	LOCATION		WACCAMAW FM.	CASTLE HAYNE LS.		BALD HEAD SHOALS FM.	YAUPON BEACH FM.	TD
	Latitude	Longitude		B	A			
BS90-01	33.49.50.041	78.03.22.781				-38.30		-54.50
BS90-03	33.49.20.858	78.03.35.725		-41.40				-46.20
BS90-04	33.49.41.716	78.03.36.386		-41.00				-46.20
BS90-05	33.50.11.813	78.02.37.993		-41.20				-45.60
BS90-06	33.50.02.997	78.03.09.927				-38.40		-45.40
BS90-07	33.49.55.722	78.03.12.601				-40.30		-45.50
BS90-08	33.50.14.317	78.02.57.293		-40.40				-45.20
BS90-09	33.50.46.622	78.02.14.636		-43.60				-46.50
BS92-02	33.49.08.310	78.04.09.950		-42.90				-48.20
BS92-03	33.49.10.080	78.04.11.900		-41.50				-49.10
BS92-07	33.50.09.500	78.03.00.520		-39.40				-48.40
BS92-08	33.50.33.020	78.02.30.050		-40.80		-44.30		-48.00
BS92-09	33.50.17.730	78.02.54.070				-40.70		-48.00
BS92-10	33.49.20.930	78.03.51.570		-39.80				-48.00
BS92-11	33.49.35.270	78.03.43.450		-41.20				-47.80
BS92-12	33.50.50.698	78.02.17.893	-42.10	-42.70		-51.10	-73.70	-79.50
BS92-13	33.49.15.630	78.04.01.660			-40.40			-47.70
BS92-14	33.48.59.520	78.04.16.170		-39.60				-49.00
BS92-15	33.48.55.520.	78.04.28.270			-42.40			-48.70
BS92-16	33.48.48.970	78.04.35.330		-41.00	-43.20			-48.00
BS92-17	33.48.32.500	78.04.50.660		-42.70				-47.90
BS92-18	33.48.42.980	78.04.42.580		-42.20				-48.00
BS92-19	33.48.47.600	78.04.33.520		-41.80	-43.10			-48.40
BS92-20	33.50.22.120	78.02.42.290		-39.00				-48.70
BS92-21	33.48.39.681	78.04.38.219		-42.80	-48.00	-56.50	-68.50	-78.70
BS92-22	33.50.43.170	78.02.22.510		-43.10				-47.70
BS93-01	33.50.15.537	78.02.53.609		-39.50	-46.60	-49.00		-52.80
BS93-02	33.50.07.888	78.03.05.663		-39.50		-48.20		-52.00
BS93-03	33.50.18.956	78.02.46.804		-40.00	-50.30			-52.60
BS93-04	33.50.39.494	78.02.29.611		-40.00		-46.10		-52.20
BS93-05	33.49.38.466	78.03.39.125		-40.30	-50.80	-59.70	-62.50	-78.30
BS93-06	33.49.46.050	78.03.27.815		-40.00	-43.60	-44.00		-52.70
BS93-07	33.49.19.853	78.03.58.499		-40.00	-47.70			-52.80
BS93-10	33.49.12.920	78.04.06.859		-41.70	-42.00			-51.90
BS93-11	33.48.57.116	78.04.23.266			-40.00			-52.00
BS93-14	33.48.42.961	78.04.40.949		-41.80	-47.00			-52.10
BS93-15	33.49.30.065	78.03.49.043		-42.80				-52.50
BS93-16	33.50.00.178	78.03.14.722				-40.20		-52.60
BS93-17	33.50.28.517	78.02.34.958		-40.00		-47.60		-52.40
BS93-18	33.50.38.409	78.02.31.090		-40.70	-50.00	-50.70		-52.30

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ARTHROPOD TRACKWAYS IN A CROSSBEDDED SANDSTONE, BREATHITT FORMATION (MIDDLE PENNSYLVANIAN), EASTERN KENTUCKY COAL FIELD

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ABSTRACT

Trackways of probable arthropod origin occur on exposed foresets of a crossbedded sandstone in the Breathitt Formation below the Whitesburg coal zone (upper Westphalian B), near Hindman, Kentucky. Because the preservation potential of trace fossils in crossbedded sandstones is low, these traces afford a significant opportunity to understand the paleoecology of a Carboniferous sandstone directly, rather than by indirect inferences based on trace fossils from laterally equivalent, lower energy deposits.

The tracks are tentatively assigned to *Tasmanadia*? and consist of pairs of transverse indentations preserved in epirelief and arranged obliquely in parallel rows 2.2 to 2.8 cm wide. Some of the indentations appear to contain three to four smaller marks, each less than 2 mm long and oriented perpendicular to the indentations. Tracks are oriented parallel and mostly into inferred paleocurrent direction, with two sets of trackways oriented up and down exposed foresets parallel to paleoflow.

Tracks are inferred to have been made by arthropods walking on foresets of subaqueous dunes in a minor distributary channel. Trackways aligned approximately parallel to current flow on several different foresets may indicate a systematic scavenging or feeding habit on an inclined slope and possibly a method of feeding in low-velocity shadows in the lee of subaqueous dunes during waning flow. Movement of the arthropods in a preferred, flow-parallel direction on foresets may also have been a means of achieving hydrologic stability on inclined foresets during low flow.

INTRODUCTION

Arthropod walking tracks have been described from upper Carboniferous, thin-bedded, essentially horizontally laminated sandstones and siltstones in many basins (Willard, 1935; Bandel, 1967; Goldring and Seilacher, 1971; Archer and Maples, 1984; Miller and Knox, 1985; Devera, 1989). In these reports, the arthropods are interpreted as having lived in quiet-water environments. However, the discovery of several arthropod trackways in a crossbedded sandstone of the Breathitt Formation provide evidence of arthropod activity in higher energy environments.

The trackways were found in a sandstone along Kentucky Highway 160 north of Hindman, Kentucky (Figure 1). Stratigraphically, the sandstone occurs in the Breathitt Forma-

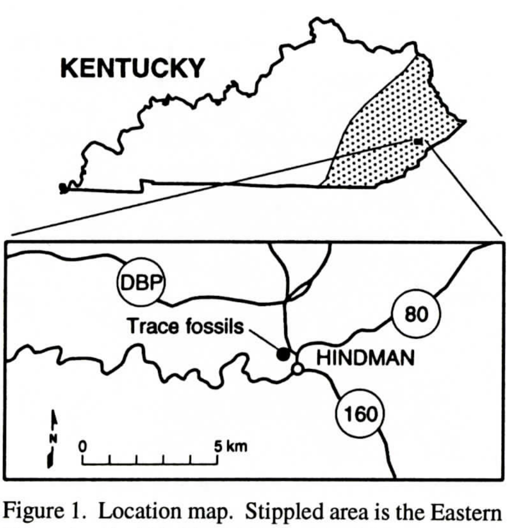

Figure 1. Location map. Stippled area is the Eastern Kentucky Coal Field. DBP is the Daniel Boone Parkway.

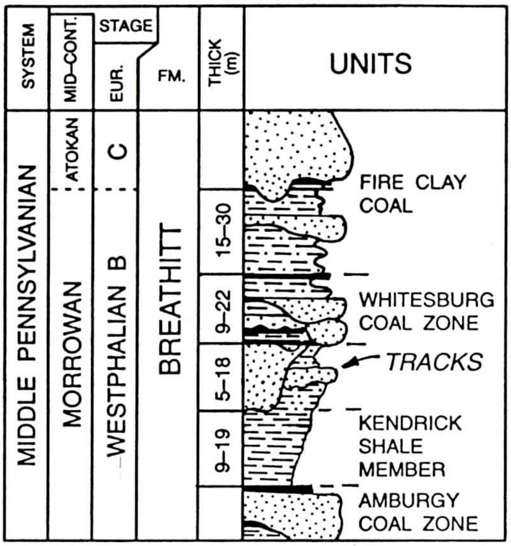

Figure 2. Stratigraphic column of the middle part of the Breathitt Formation showing the position of the track-bearing sandstone (after Danilchik, 1976).

tion, just above the Kendrick Shale Member and just below the lowest coal of the Whitesburg coal zone (Figure 2). The Kendrick Shale is a regionally extensive coarsening-upward shale to sandy shale that often is capped by crossbedded sandstones (Danilchik, 1976; Rice, 1980; Cobb and others, 1981).

Purpose

The purpose of this study is to describe the tracks and sedimentology of the host sandstone in order to make paleoecological interpretations on the origin of these tracks. Because the preservation potential of trace fossils in crossbedded deposits is low, these traces afford a significant opportunity to understand the paleoecology of a Carboniferous sand bar directly, rather than by indirect inferences based on lateral, lower energy deposits.

SANDSTONE DESCRIPTION

The sandstone containing the trackways is 3.1 to 4.3 m thick where exposed (Figures 2-3). It is a sublitharenite, fine to medium grained, and exhibits a sharp basal scour with shale rip-up clasts. The lower half of the unit consists of large (0.8 to 1.3 m) trough crossbed sets oriented to the northeast. The upper half of the unit consists of thinner trough and planar crossbeds (0.3 to 0.6 m thick) also oriented to the northeast (Figure 3). Crossbeds in the upper half of the unit are truncated by overlying crossbeds or are capped by parting lineations, and current ripples in rib-and-furrow patterns. Parting lineations and current ripples both exhibit northeast trends similar to the trend of the crossbeds (Figure 3). Exposed foresets in thin (0.3 to 0.5 m) crossbeds at the top of the sandstone commonly exhibit parting lineations. In two cases parting lineations on foresets were overlain by washed-out ripples, which had essentially straight crest lines oriented subparallel to foreset slope. In two cases, deep (25 to 90 mm) elongate grooves were also noted toward toesets. The grooves parallel foreset dip, and are similar to rill marks but lack the upward-branching, dendritic pattern common to rill marks (Reineck and Singh, 1980). At least four exposed foresets also exhibit fossil trackways (locations A, B, C, and D on Figure 3).

The sandstone is overlain by 3.2 to 3.8 m of unfossiliferous, silty, dark-gray shale, a thin (< 1 m), mottled (rooted) and crossbedded, fine-grained sandstone with similar crossbed orientations as the studied sandstone, and the Lower Whitesburg coal (lowest coal of the Whitesburg coal zone).

TRACKWAY DESCRIPTIONS

The trackways consist of two parallel rows of obliquely arranged, epirelief pairs of transverse indentations, 2.2 to 2.8 cm wide (Figures 4A-B). Each indentation is 0.2 to 1.1 cm in length. The medial regions between indentations are featureless (Figures 4A-B). Several of the transverse indentations contain two to four deeper, linear to V-shaped depressions (insets in Figures 4A-B). These depressions are each less than 5 mm long and 3 mm wide, and

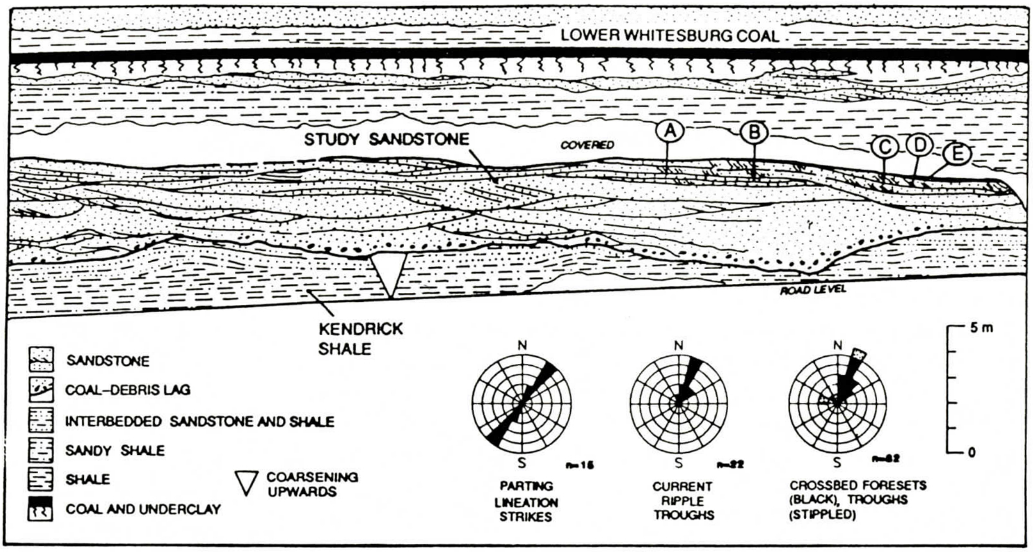

Figure 3. Illustration of the track-bearing sandstone based on an outcrop photomosaic showing the position of walking traces (A, B, C, D, and E) in Figure 4, and rose diagrams of various sedimentary structures in the track-bearing sandstone.

are oriented subperpendicular to the orientation of the transverse indentations (Figures 4A-B).

Several sets of trackways are preserved on the middle to upper parts of crossbed foresets, at dip angles of 12 to 18° (Figure 5). Foresets are 30 to 75 mm thick, and aside from possible shale filling in some of the tracks, show little evidence of a clay drape. Tracks were not noted on the lower parts of foresets (at angles < 10°), topsets, or bottomsets. Trackways at location B are the most completely exposed (Figure 5B). The long axes of the trackways are oriented along compass bearings of 18 to 50°. Trackways are oriented subparallel to the dip of the foreset (43 to 47°), to erosional grooves carved into the lower part of theforeset (15 to 19°), and to current ripples capping the crossbed (13 to 35°).

The long axis of the trackway at location A had an azimuth of 34° on a foreset dipping toward 30° (Figure 5A). At location C, trackways were oriented at 14 and 12° on a foreset

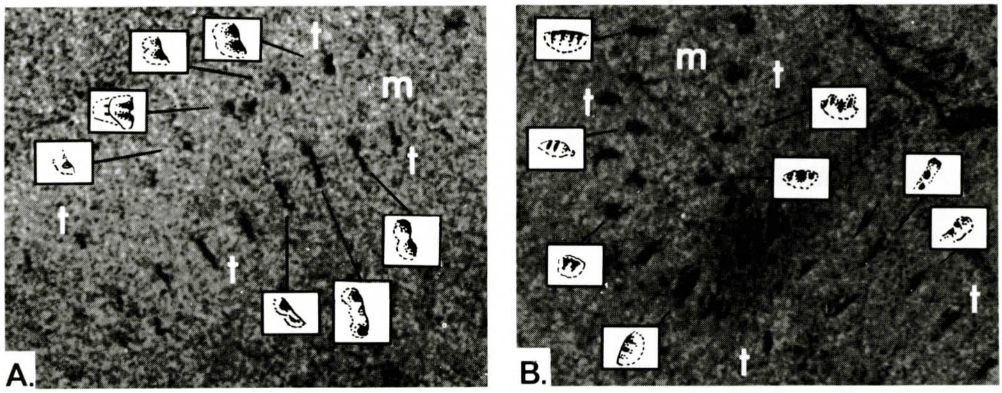

Figure 4. Photographs of trackways at location B. Inset illustrations show details (black indicates deeper indentation). The trackways (A-B) are composed of pairs of transverse indentations (T) that may contain three to four smaller marks (see insets) separated by featureless medial axes (M). One of the tracks (B) shows evidence for a side-step (arrow) during ascent.

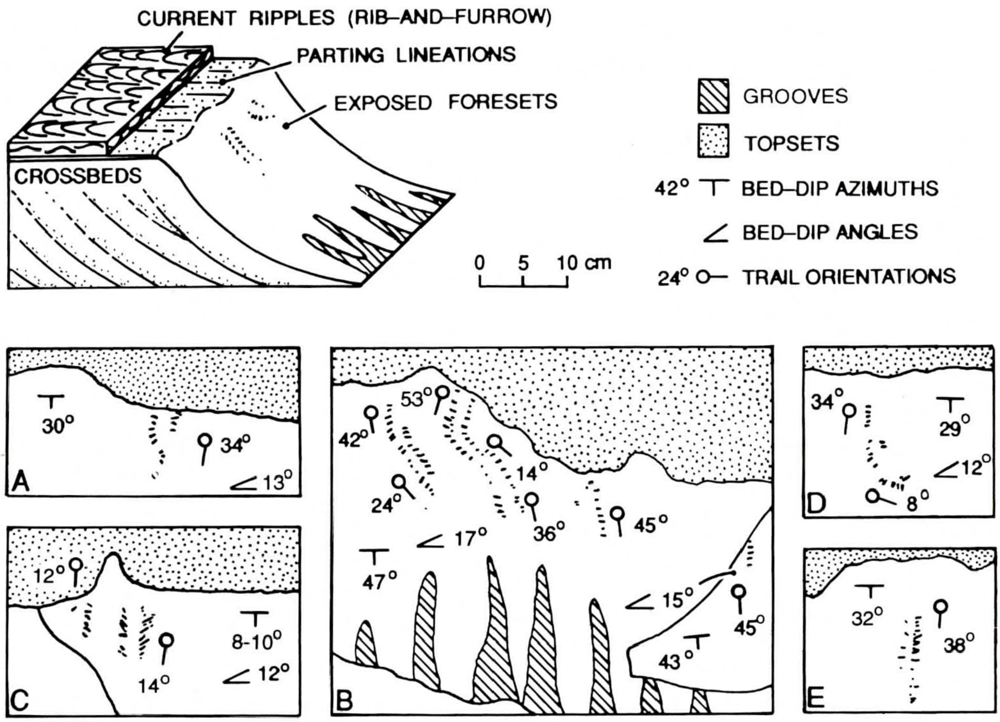

Figure 5. Sketches of tracks A, B, C, D, and E in Figure 3. All tracks occur on inclined foresets. Each figure is oriented parallel to bed dip.

dipping toward 9° (Figure 5C). A faint trackway at location D was slightly curved toward the middle of the foreset, but on the upper foreset it had a long axis of 34° on a foreset dipping at 29° (Figure 5D). The orientation of the possible trackway at location E only deviated from bed dip by 6° (Figure 5E).

At locations B and C parallel trackways are preserved. At location B, three trackways parallel each other. The arrangement of tracks in a "V" or chevron pattern shows continuous movement up and then down the dip of the bed (Figure 5B). Two trackways at location C also exhibit chevron patterns up and down bed dip (Figure 5C).

TAXONOMY

The taxonomic placement of the these tracks is uncertain. The parallel rows of transverse indentations share similarities with *Incisifex* (Dahmer, 1937, p. 525), *Koupichnia* (Nopsca, 1923, p. 146), *Maculichna* (Anderson, 1975, p. 265), *Merostomichnites* (Packard, 1900, p. 67), *Tasmanadia* (Chapman, 1929, p. 5), and *Umfolozia* (Savage, 1971, p. 221). *Koupichnia* commonly contains rows of circular impressions adjacent to transverse indentations and may contain telson and tail-drag marks along the medial axis of the trackways, which are not found in the tracks at the Hindman locality. *Maculichna* also contains circular markings adjacent to transverse indentations and may contain telson drag marks (Anderson, 1975). Most of the tracks at Hindman are not spindle shaped, as defined for *Merostomichnites*. Also, most of the tracks are narrower, and do not occur in repetitious sets as in *Umfolozia*.

The tracks are most similar to *Incisifex* and *Tasmanadia*. *Incisifex* is defined as two parallel rows of obliquely arranged indentations with a smooth medial region between indentations formed by the sliding ventral side of the arthropod (Dahmer, 1937; Häntzschel, 1975). The tracks at Hindman are mostly obliquely arranged and have a featureless medial axis.

However, the medial axis has a similar texture as the rest of the foreset upon which the tracks occur, so it cannot be determined whether the medial axis represents the body drag mark defined for *Incisifex* or not. *Tasmanadia* is defined as a double row of sharp indentations with rare indentations forming bifid impressions (Glaessner, 1957; Häntzschel, 1975), although several examples from the specimens originally defined as *Tasmanadia* contain broader indentations and lack distinctive bifid markings (Chapman, 1929, plate 1; Glaessner, 1957). In order to err on the side of caution, the tracks are tentatively assigned to *Tasmanadia*, which does not require a medial drag mark. Also, *Tasmanadia* has been documented in Carboniferous strata (Häntzschel, 1975), whereas *Incisifex* was defined in Lower Devonian strata (Dahmer, 1937; Häntzschel, 1975).

For the purposes of paleoecological interpretation, the distinctions may not be significant, since all the genera investigated are interpreted as the tracks of arthropods (Packard, 1900; Caster, 1938; Glaessner, 1957, p. 103; Bandel, 1967; Hardy, 1970; Goldring and Seilacher, 1971; Savage, 1971; Anderson, 1975, 1981; Häntzschel, 1975; Anderson, 1985; Archer and Maples, 1984).

PALEOECOLOGY

Depositional Environment

The Kendrick Shale Member is one of several regionally extensive marine zones in the Breathitt Formation. The coarsening-upward trend of these units has been interpreted as coastal progradation into restricted marine seas or bays (Horne and others, 1978; Rice, 1980; Cobb and others, 1981). Regional facies distributions in the Kendrick Shale suggest a deltaic source in Martin County (70 km northeast of the study area), with prograding distributaries oriented to the west, southwest, and southeast in the study area (Rice, 1980). However, the complexity of local distributary orientations can be seen by paleocurrent measurements of exposed fluvial-distributary sandstones capping the Kendrick Shale west of the study area, which exhibit northwesterly paleocurrents (Cobb and others, 1981).

The stratigraphic position of the sandstone between marine shales of the Kendrick Formation and fresh-water peats of the Whitesburg coal zone could place the sandstone in a wide range of coastal environments. The sharp, irregular scour with shale and coal clasts at the base of the sandstone studied near Hindman is interpreted to represent the base of a minor channel system that truncates the upper part of the Kendrick Shale Member. A lack of exposure across paleocurrent strike precludes definition of channel scale, but the relative thinness of the deposit would seem to indicate a small channel. The northeastward paleocurrent mode of the sandstone is oblique or opposed to fluvial-distributary trends measured at this stratigraphic interval (Rice, 1980; Cobb and others, 1981), which may indicate a tidal or storm origin for the channel. However, the sandstone does not contain storm-wave-formed or combined-flow features, continuous clay drapes, bundled crossbed foresets, sigmoidal crossbeds, herringbone crossbedding or other sedimentary structures with evidence for reversing or opposing flows, as may occur in modern tidal or storm-influenced channels (Reineck and Singh, 1980; Van den Berg, 1981; Nio and Yang, 1991). Also, the immediately overlying shale does not contain dwelling or feeding traces common in Breathitt clastics interpreted to have a marine or brackish-water origin, although the absence of the traces is not absolutely diagnostic (Cobb and others, 1981; Greb and Chesnut, 1992, 1994; Martino and Sanderson, 1993). In the absence of supporting paleontological or sedimentological data to suggest tidal or storm sedimentation, the northeast paleocurrent mode is interpreted to represent current flow in a northeastward branch or meander of a minor distributary channel.

The fining- and thinning-upward nature of bedding within the sandstone is interpreted to represent upward shallowing within the channel. The vertical succession of bedding in each crossbed set, from crossbeds to parting lineations to ripples, is interpreted as resulting from shallowing, with plane beds developed during initial shallowing and then ripples reworking crossbed topsets when flow velocity fell below the plane-bed threshold. The rib-and-furrow pattern of ripples preserved on top of the uppermost crossbeds is similar to ripple patterns preserved in very shallow-water conditions (Tanner, 1962), indicating that flow depth fell to just above bar height, which was probably less than a meter during migration of the uppermost dunes. The grooves toward the toe of two of the exposed foresets are interpreted to have resulted from increased flow velocity during falling water. During maximum shallowing, paleoflow was sometimes reoriented around the crest of the migrating dunes and ripples migrated across foresets approximately perpendicular to high-stage flow.

Subaqueous versus Subaerial Tracks

The uppermost crossbeds are overlain by parting lineations, and all the crossbeds show erosion of foreset toes and topsets, indicating fluctuations in discharge and flow velocity within the channel. The fact that all of the tracks are preserved on the upper parts of foresets is evidence for preservation bias, regardless of the setting in which the bar was deposited. But were the tracks made subaqueously or subaerially? Each of the tracks is eroded at the top of the foreset. No tracks (or other traces) were noted on the tops of the crossbeds. If the tracks were made when the dunes were exposed, it is likely that the arthropods, having climbed the inclined slope of the foreset, would have continued up onto the top of the bedform. In that case, the arthropods would have been walking across the parting lineations or current ripples capping the dunes, and presumably tracks would cut across those sedimentary features.

In contrast, if the tracks were formed subaqueously (before shallowing) then any tracks that continued onto the tops of the dunes would have been destroyed by the currents that deposited the parting lineations and current ripples during shallowing. Also, because tracks fade or are truncated toward the base of foresets by parting lineations and rare rill-like grooves, the tracks are interpreted to have formed prior to these structures, and hence prior to shallowing: when the dunes were still submerged.

Limited studies of animal locomotion on subaerial, inclined surfaces have shown that millipede and small quadriped tracks often differ in upslope and downslope directions because the arthropods use their bodies to slow themselves down during descent (McKee, 1944, 1947). Downhill locomotion tracks were rarely preserved because they were obliterated by sand avalanching as the arthropods descended the slope (McKee, 1947). In contrast, the tracks investigated in this study are similar in upslope and downslope orientations, with no significant change in their appearance. This might indicate that the arthropods making the tracks were not greatly affected by gravity, or had their own buoyancy relative to their environment, as would be expected in a subaqueous environment.

Controls on Track Orientations

The similar orientation of the tracks on the upper parts of different foresets is a clue to a possible life habit of the trace-making organisms. The tracks are interpreted as the traces of arthropods moving up and down the dipping slopes of foresets: the foresets presumably represented the front of a subaqueous dune when the traces were made. The tracks were formed when the sand dunes were not accreting, at current velocities below the threshold for dune migration. Walking traces on different foresets attest to numerous periods of relatively low velocity (below the threshold for dune migration) during deposition of the uppermost crossbeds. Each trail is subparallel to the direction of foreset dip and assumed paleoflow. There are several possible explanations for the preferred directions of the trace makers.

The trace makers may have adapted the dip-

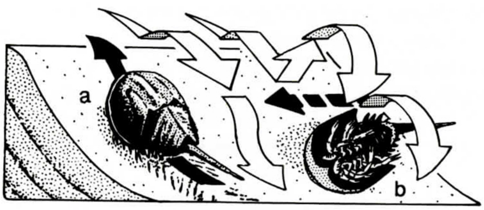

Figure 6. Interpretive diagram of arthropod locomotion on a subaqueous dune front. Bilaterally symmetrical arthropods walking parallel to flow (a) may have been more hydrodynamically stable than orientations perpendicular or random to flow (b). Black arrows indicate walking direction and white arrows indicate flow paths around the arthropod.

Figure 7. Lee-side velocity shadows might have provided shelter for feeding arthropods during periods of low current energy when the dunes had ceased to migrate. Nutrients might also have fallen out of separation eddies at the crest of the dunes or accumulated at the toes of the foreset following grain avalanching.

parallel, up-and-down feeding habit as a way of systematically scavenging or feeding along the foreset surface, with slope as a primary control on orientation. This is a difficult hypothesis to test because there is little information on subaqueous arthropod locomotion relative to slope. Most ancient arthropod tracks have been studied from relatively flat surfaces. The few examples of arthropod traces on inclined slopes have been from eolian environments. Photographs of modern arthropod (crane flies, crickets, scorpions) locomotion tracks on subaerial sand dunes invariably show irregular paths or paths oriented oblique to slope (Brady, 1939; McKee, 1944; Ahlbrandt and others, 1978), but these few examples are hardly conclusive. Intuitively, it might seem that a side to side or obliquely oriented locomotion pattern would be more efficient on an inclined slope.

The slight side-step and subsequent shift in orientation in the tracks shown in Figure 4B, could indicate that the arthropod slipped and was adjusting to the increasing slope of the foreset. Also, the relative increase in depth and width of tracks upward on each foreset could have resulted from the arthropod's appendages digging more deeply into the foreset as slope increased. However, the relative fading of tracks downward on the foreset could just as easily be explained by partial erosion during the next accretion of the dune face.

Another possibility is that current orientation was the major control on the movement of the arthropods. Most arthropods, such as the limulids commonly interpreted as the makers of *Koupichnia* tracks, exhibit bilateral symmetry along the long axis of their exoskeleton, and have an enlarged, anterior exoskeleton. These types of arthropods might be more likely to be flipped over when oriented perpendicular to flow, whereas they would be stable in directions parallel to flow (Figure 6). If the orientation of the arthropods was related to low-velocity currents at the dune front, then the side-step and subsequent shift in orientation of the trail shown in Figure 4B could be the result of the arthropod adjusting to low-velocity currents or periodic turbulent eddies across the dune crest. Increasing resistance caused by low-velocity currents might also explain the upward curve of the tracks in Figure 4D: the arthropod may have adjusted to a flow-parallel orientation as foreset slope increased.

The position of the tracks on dune foresets might also indicate that the arthropods were feeding on nutrients dispersed in small separation eddies at the bar front (Figure 7) during periods of low-velocity or no net flow (below the threshold for foreset migration). The lee of a subaqueous sand bar would have provided shelter from relatively higher velocity currents in the shallower water across the top of the bedform during feeding, and would have been an area where organic detritus could have accumulated. As any fisherman knows, many modern aquatic animals rest and feed in velocity shadows in the lee of sand bars and other obstacles in shallow water.

CONCLUSIONS

Trackways exposed on foresets of a cross-bedded sandstone just below the Whitesburg coal zone indicate that arthropods inhabited environments of moderate to high current energy during the Carboniferous, in addition to the quiet-water environments that they have been most commonly inferred to inhabit. The orientation of the tracks shows that some arthropods adapted to environments of periodically high current energy by moving in directions parallel to flow in the lee of subaqueous dunes so as to achieve hydrologic stability.

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