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INFLUENCE OF GLACIAL MELTWATER IN THE

ATLANTIC COASTAL PLAIN

By

William A. White
Department of Geology
University of North Carolina
Chapel Hill, North Carolina 27514

ABSTRACT

The large estuaries that distinguish the Embayed Section of the Atlantic Coastal Plain are atypical in that they occur only in the valleys of river systems whose trunk streams were trenched by great discharges of meltwater during low glacial sea levels. Tributaries to these rivers were also trenched when nick points moved rapidly up stream through unconsolidated sediment from their points of confluence with the incised trunk streams. Repetitive trenching of these stream systems during several episodes of glaciation accounts for the branching valley-side terraces which characterize the Embayed Section as contrasted with the beach ridge plains that typify the Sea Island Section.

The large estuaries of northeastern North Carolina occupy reestablished valleys of streams that were 1) trenched while tributary to a former southern extension of the meltwater-carrying Susquehanna River in pre-Pamlico time, 2) filled with estuarine sediment during high interglacial sea levels, 3) blanketed with shallow marine sediment by the Pamlico Sea, and 4) reexpressed as broad shallow estuaries by compaction of buried estuarine sedimentary fill.

The obtuse seaward protuberances of the three coastal compartments of the Embayed Section which apex at Rodanthe, North Carolina; Ocean City, Maryland; and Barnegat, New Jersey; result from the meltwater-cut trenches of the Susquehanna, Delaware and Hudson Rivers, where they extended across what is now the continental shelf. The northern segment of each of these coastal compartments has a mainland oceanic beach which is a relict of the western valley wall of the presently submerged part of the valley. Valleys that were tributary to these submerged valleys are estuarine.

INTRODUCTION

The burden of this paper is to explain those geomorphic peculiarities of the Embayed Section of the Atlantic Coastal Plain which distinguish it from other parts of the Coastal Plain and caused it to be differentiated as a discrete section of that physiographic province. These peculiarities include the great estuaries of the Delaware and Susquehanna Rivers (Delaware and Chesapeake Bays); the strange re-established estuaries of northeastern North Carolina; the dominance of valley-side terraces that are relicts of former great estuaries, rather than the coast-parallel terraces that are relicts of transgressions of the open ocean or coastal lagoons; the obtuse convexities of the oceanic shores of coastal compartments; and the general dearth of the multiple relict beach ridges that typify the more southerly parts of the Atlantic Coastal Plain in the Sea Island Section and in the Florida Peninsula.

Acknowledgments

I thank Ralph C. Heath, Roy L. Ingram and Walter H. Wheeler for their critical reading of the manuscript.

EFFECT OF MELTWATER ON STREAM VALLEYS OF THE EMBAYED SECTION

In describing the Atlantic Coastal Plain, Fenneman (1938) separates an "Embayed Section" north of Cape Lookout from a "Sea Island Section" to the south (Figure 1). He describes (Page 13) the Embayed Section as differing from the adjacent Sea Island Section in that it has been "so deeply indented by branching bays or estuaries that it is little more than a fringe of peninsulas narrowing to zero at New York and represented beyond that by islands." He attributes this embaying to a northward-increasing depression of the edge of the continent. Without doubting such depression I think the principal reason for the estuarine embayments is erosion by streams that either carried glacial meltwater or were tributary to those that did (White, 1966; Meade, 1969).

Delaware and Susquehanna Rivers

South of the immediate environs of the glacial terminus in northern New Jersey only two of the present streams, the Susquehanna and Delaware Rivers, carried glacial meltwater through the Atlantic Coastal Plain. During those glacial episodes when the front of the Laurentide Ice Sheet was within their drainage areas and sea level was low, these two arterial streams carried atypically large discharges when the Ice Sheet was melting. Assuming that the ice dome was centered over central Canada, the slope of its surface toward the heads of these streams could have increased the length of their effective drainage areas by some 2,000 kilometers. And, in summer when the ice sheet was waning under warmed climate, the discharges of the

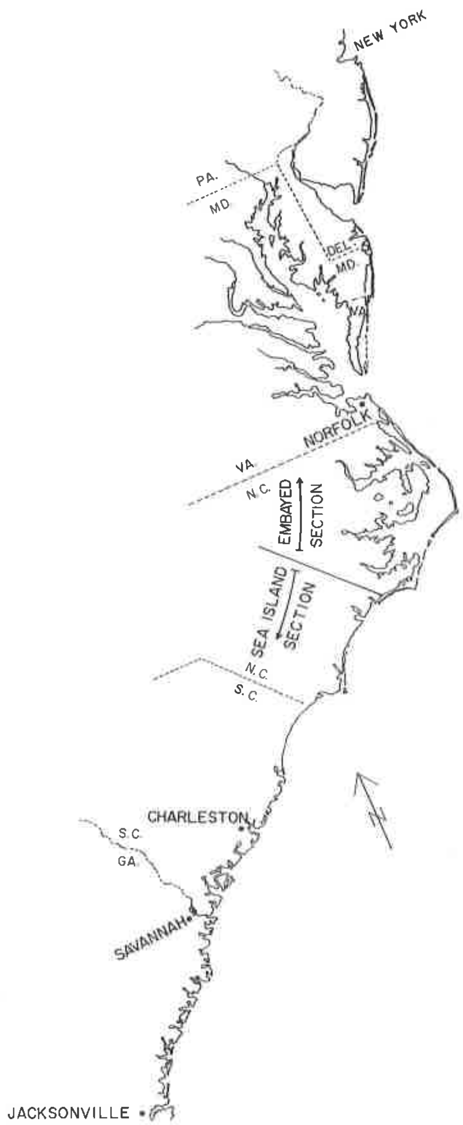


Figure 1. Map showing the contrasting shorelines of the Embayed and Sea Island Sections of the Atlantic Coastal Plain.

Delaware and Susquehanna Rivers were probably many times their present maxima. Not only were their drainage areas greatly enlarged, but the maximum run-off per unit area was probably much larger than that of nonglacial areas because, in addition to contemporaneous precipitation, it received great volumes of relict precipitation which had been long stored as glacial ice.

When the sea transgresses an ordinary dissected terrain, the valleys of most streams share the submergence to form an intricately embayed shoreline in which ridges tend to become branching peninsulas with lines of islands lying off their distal ends. Early-formed beaches wrap around outlying islands and exposed ends of headlands.

The Atlantic Coastal Plain doesn't have such a shoreline pattern (Figure 1). Its Sea Island Section has few and very small estuaries. Its Embayed Section, except for northeastern North Carolina, has only two estuary systems of any appreciable size; those of the meltwater-carrying Susquehanna and Delaware Rivers (Chesapeake and Delaware Bays). Streams that flow into Chesapeake Bay have long estuaries. Those that flow eastward from New Jersey and the axial divide of the Delmarva peninsula directly to the ocean have no appreciable estuaries except where they were tributary to former lower reaches of a meltwater-carrying Hudson or Delaware River. The outer coast line is not digitate but has nearly continuous barrier beaches on long gentle curves of seaward-convex oceanic shoreline.

This suggests that significant dissection of the Coastal Plain by streams flowing to the lowered base levels provided by low, glacial-age sea levels was limited to those stream systems whose trunk discharge was greatly increased by glacial meltwater. As the Delaware and Susquehanna Rivers were incised by their meltwater-increased discharge, the gradients of their tributaries would be steepened at the points of confluence with the main stream and nick points would quickly work their way headward through the unconsolidated sediment of the Coastal Plain. This explains the long estuarine reaches of streams that are tributary to Chesapeake Bay even though they themselves carried no meltwater. Thus, east-flowing rivers of the Embayed Section that are tributary to the Susquehanna or Delaware are drowned all the way to the Fall Line or seaward edge of the Piedmont.

Rivers of the Southern Part of the Embayed Section Which Were Affected by Meltwater During Early Glaciations but not During the Latest One

In the southern part of the Embayed Section in northeastern North Carolina, although estuaries are much longer than those of the Sea Island Section, their heads are remote from the Fall Line. However, the estuaries of these streams (the Meherrin-Chowan-Albemarle, Nottoway-Chowan-Albemarle, Roanoke-Albemarle, Tar-Pamlico and Neuse Rivers) did extend to the Fall Line during the interglacial sea level at which the Talbot terrace was formed (Figure 2). This can be seen on Stephenson's (1912) map of Coastal Plain terraces in North Carolina and Wentworth's (1930, Fig. 24) map of terraces in Virginia. Both these maps show the Talbot terrace reaching close enough to areas where crystalline Piedmont rocks are exposed in the valleys to make it plausible that estuaries reached to the Fall Line at the crest of the Talbot transgression, before fluvial sediment built up their headward reaches. By contrast, Stephenson's map (Figure 2) does not show the Talbot (Chowan) Terrace extending very far up the stream valleys of the Sea Island Section. In none of those valleys does it reach within 75 kilometers of the Fall Line, nor are its valley-side parts as wide as they are in the Embayed Section. Thus, during the low sea level of immediately pre-Talbot time, the more southerly rivers of the Embayed Section apparently had a stronger tendency to incise their valleys than they have had since, but the rivers of the Sea Island Section did not share it.

The present estuaries of these more southerly rivers of the Embayed Section in northeastern North Carolina probably owe their unusually large size to having formerly been tributary to a deeply-incised, meltwater-carrying Susquehanna River. There is reason to think they were destroyed in Pamlico time and have been reestablished or relocated since.

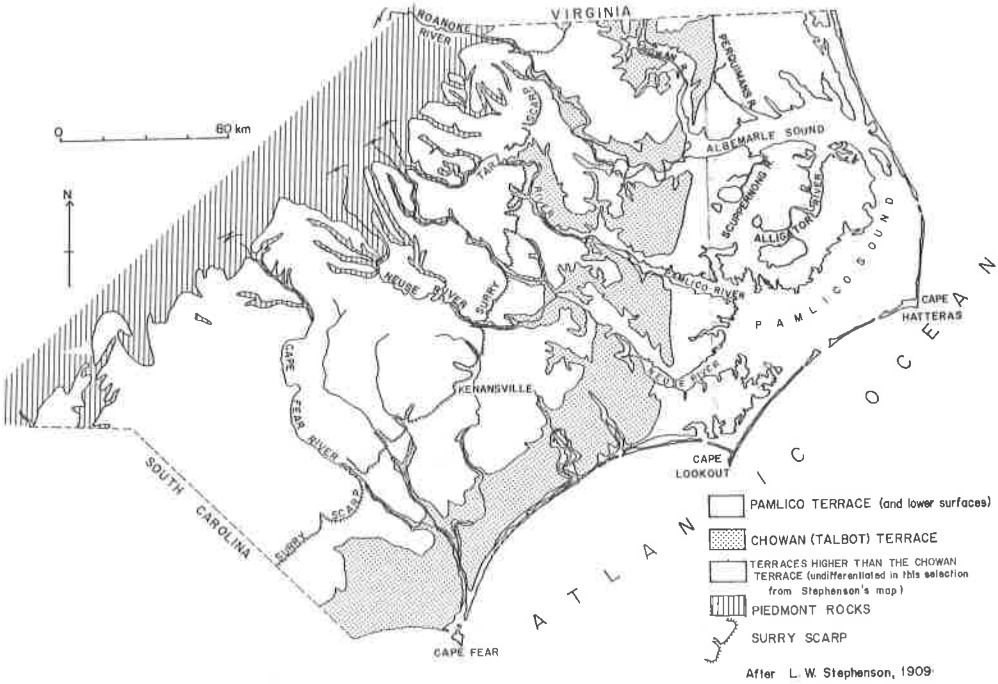


Figure 2. Map showing the Pamlico and Talbot (Chowan) Terraces and the eastern edge of exposed pre-Cretaceous rocks in eastern North Carolina. After Stephenson (1912).

The Talbot and Pamlico Transgressions and the Reestablished Estuaries of Northeastern North Carolina

In southeastern Virginia the Talbot Sea seems to have formed most of the straight and prominent Suffolk Scarp as a shoreline of the open ocean. In adjacent North Carolina, where it encountered a lower land surface, the Talbot Sea transgressed farther landward and had a digitate shoreline of alternating promontories and estuaries. The following Pamlico transgression crested at a level of sea some 3 to 5 meters below that of the Talbot. In southeastern Virginia its oceanic shoreline apparently mimicked that of the Talbot Sea along the base of the Suffolk Scarp. But in adjacent northeastern North Carolina the Pamlico Sea formed its own, new, oceanic shoreline on the well-graded, relict, off-shore slope of the Talbot Sea. This part of the Pamlico shoreline is mostly a southern extension of the Suffolk Scarp of southeastern Virginia with the same elevation of toe but with its crest at a lower level.

These unusually extensive transgressions of the open ocean, which reached a maximum of some 100 kilometers inland from the present barrier, occurred in latitudes where the seaward (eastern) divide of the Susquehanna River was submerged. Thus oceanic surf could attack the interfluves between east-flowing Susquehanna tributaries in northeastern North Carolina and extreme southeastern Virginia. Farther north the eastern divide of the Susquehanna River (the higher parts of the axis of the Delmarva Peninsula) intervened between the open ocean and the east-flowing tributaries of the present Chesapeake Bay. Accordingly there was no broad oceanic transgression by either the Talbot or Pamlico Sea and the surfaces made by those inundations in the Susquehanna Valley are narrow, estuarine valleyside terraces which mimic the shoreline of the present Chesapeake Bay. But seaward from the Suffolk Scarp in northeastern North Carolina and closely adjacent Virginia, the pre-Talbot drainage was disrupted by both Talbot and Pamlico transgressions of the open ocean. And since it was the Pamlico transgression that took these streams out of the meltwater-affected Susquehanna River system, they had little tendency to incise themselves during later glacial episodes of low sea level. Thus their present large estuaries demand special explanation.

It seems improbable that the high energy surf that affected the area seaward of the Suffolk-Pamlico Scarp during the transgressions of the Talbot and Pamlico Seas could have passed over estuaries of the Neuse, Tar (Pamlico) and Roanoke (Albemarle) Rivers without obscuring them by near-shore, shallow-marine erosion and deposition. Apparently they were graded over by both these transgressions and during the ensuing emergence were either relocated or reestablished by subsidence caused by compaction of their buried estuarine muds. Their topographic cross-sections are compatible with this idea. Albemarle Sound (River) and the Pamlico and Neuse Rivers are disproportionately wide in relation to their shallowness. Maximum depths are about 5 meters, whereas both Chesapeake and Delaware Bays, of comparable width but more recently influenced by meltwater, attain depths of some 27 meters. It seems instructive that bridges cross the wide estuaries of northeastern North Carolina on miles of pilings, but great suspension bridges were necessary to span Chesapeake and Delaware Bays. The necessity of suspension bridges probably does not reflect present water depths so much as the lack of coherence and solidarity in diffuse sediment which has been deposited since the last time these rivers carried meltwater. Hack (1957) observed that much of the sediment in Chesapeake Bay is poorly consolidated mud and has a high water content.

Figure 3 (after Oaks and Coch, 1973) shows two cross sections in the Embayed Section of southeastern Virginia between the south end of Chesapeake Bay and the North Carolina state boundary. These show two reestablished valleys with the younger versions nested wholly within the valley walls of the older ones. In each instance both a basal

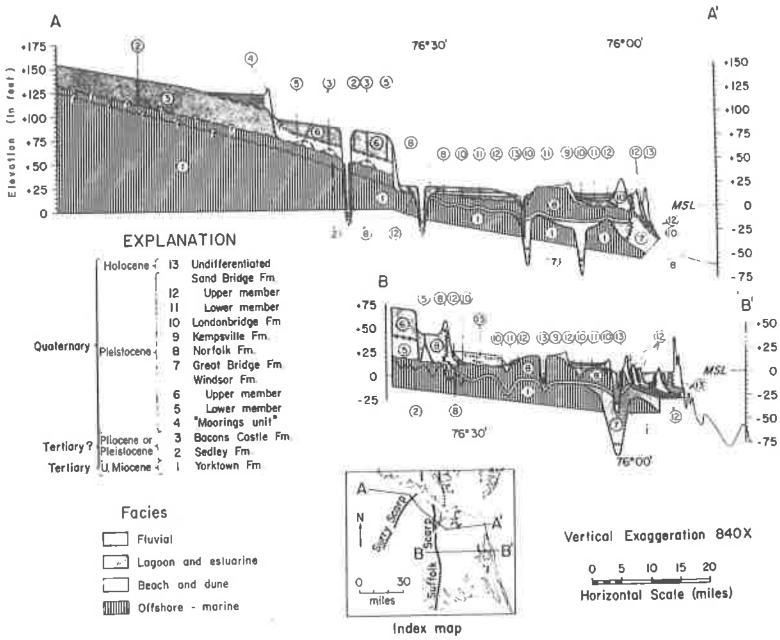


Figure 3. Geologic cross sections in the southeastern part of the Embayed Section of the Atlantic Coastal Plain in southeastern Virginia. After Oaks and Coch (1973).

beach-and-dune facies and an overlying offshore facies of the Norfolk Formation separate the ancestral pre-Norfolk version of the valley from the re-established post-Norfolk version. This makes it difficult to avoid the conclusion that the older, ancestral version of the valley was wholly masked by high-energy shallow marine erosion and deposition during Norfolk time and suggests that the younger version was initiated by subsidence caused by compaction of the buried estuarine sediments in the older one.

Moreover the Norfolk Sea seems to be the one that formed the Suffolk Scarp, which in southeastern Virginia was the shoreline of both Talbot and Pamlico Seas. This suggests that the oldest ancestral versions of the nested valleys were cut in pre-Talbot (pre-Norfolk) time and the youngest versions did not develop until post-Pamlico time.

Since the rivers of northeastern North Carolina are in the Embayed Section and adjacent to the area described by Oaks, it seems plausible to assume that they had a complex history akin to that of the area explored by his drilling. I would expect such complexity to extend as far south as the Neuse River, which is the most southerly stream of the Embayed Section as well as the most southerly of the streams that seem to have been tributary to the meltwater-carrying Susquehanna River.

Former and Reestablished Routes of Streams in Northeastern North Carolina

In the regression of the Pamlico Sea the Susquehanna River apparently failed to find the southern part of its former course, and was shunted seaward farther north in the general latitude of the present mouth of Chesapeake Bay. Hence, after Pamlico time there was no further meltwater-induced dissection south of the present Chesapeake Bay. Unlike the digitate Talbot shoreline, the younger Pamlico shore is rather straight and was mostly a high energy shoreline of the open ocean. It lies along the straight toe of the Suffolk Scarp, and farther south, between the Albemarle (Roanoke) and Neuse Rivers, it built a coastal sand ridge whose relict is variously know locally as Minnesott Ridge, Arapahoe Ridge and Acre Ridge (Suffolk Sand Ridge of Oaks). This suggests that the Pamlico Sea planed off any peninsulas or islands that may initially have risen above it and filled the intervening valleys with off-shore sediment. Pre-Pamlico divides were cut down to grade and pre-Pamlico valleys were sedimented up to grade. Hence the present large estuaries of northeastern North Carolina should be reestablishments of pre-Pamlico valleys without benefit of renewed dissection by glacial meltwater.

Where the Suffolk Scarp truncates the Pennholloway Terrace its crest reaches elevations of some 18 to 24 meters and what seems to have been a Talbot spit and shoal extends southward from this higher part of the scarp. This (Figure 2) deflected the Chowan River out of its southeasterly course into a southerly one and brought it into confluence with the Roanoke River, which was similarly deflected northwards. This new course of the combined Chowan and Roanoke Rivers was incised during the low glacial sea level that intervened between Talbot and Pamlico times. It was graded up to the general off-shore profile of the Pamlico Sea and was not reincised in post-Pamlico episodes of low glacial sea level because the rivers of northeastern North Carolina were severed from the meltwater-carrying Susquehanna River by the Pamlico transgression. The Albemarle River valley was reestablished in its present form as a wide, atypically shallow estuary by compaction of pre-Pamlico estuarine sedimentary fill. Oaks (1965, p. 213) refers to a written communication from W. H. Harris who found a deep buried channel that connects Perquimans River (Figure 2) east of the Suffolk Scarp (Ridge) with the Chowan River west of it. Since the original valley of Perquimans River (the former lower Chowan River Valley) was transgressed by the Pamlico Sea and subjected to a near-shore, high-energy shallow-marine environment, it must have been wholly obscured topographically. Hence the present reappearance of Perguimans River in its pre-Pamlico location supports the idea that the wide, shallow estuaries of northeastern North Carolina are post-Pamlico restorations of pre-Pamlico valleys. Apparently they were reestablished by subsidence that was caused by compaction of estuarine fill.

The other valleys that drain into Albemarle River from its north side are parallel with the Perquimans River. They also share the regional tendency for rather straight southeasterly courses and may well have similar histories of marine submergence, burial and topographic reexpression by subsidence caused by compaction of estuarine muds. On the south side of Albemarle Sound the lower part of the Scuppernong River shares the regional southeasterly drainage direction in reverse in a barbed relation to Albemarle River. Tributaries of the lower part of the Alligator River follow the same trend regardless of their present direction of flow. Those on the west side of the Alligator River have barbed confluences with it, which suggests that they also are reestablishments of relict streams which formerly were integral parts of a regional southeastward drainage that, in pre-Pamlico times, extended across the area now occupied by Albemarle Sound and the land to north and south of it (Figure 2).

The main reach of Alligator River drains an area of thick peat and seems to have no pre-Pamlico history. It has a north-south course at right angles to the plexus of buried channels described by Riggs and O'Connor (1974) which seems to have been cut into the surface from which the Pamlico or a later lower sea level regressed. Several of these buried channels extend beneath the area through which the Alligator River flows.

Figure 4 after Brown et al. (1972), shows structure contours on the top of the Yorktown formation which seems to be the last pre-glacial stratum in this area. These contours depict a buried valley which follows the trend of Albemarle River up to its confluence with Perquimans River whence the buried valley continues up the valley of Perquimans River without change of orientation and Albemarle Sound turns off to the west. Thus the buried valley would be the southeasterly route by which an ancestral Chowan River reached the sea independent of the Roanoke River.

An early route of the lower Roanoke River is suggested by the structure contours as a buried valley which begins below the Pamlico Scarp in line with the Roanoke River Valley upstream from the place where it was deflected northward to join the Chowan. Both this part of the present Roanoke Valley and its buried ancestral lower course share the regional southeasterly trend. This buried, former, lower course of the Roanoke River is now the site of the thicker peat deposits of the Dare Peninsula and its axis seems to have determined the course of the upper estuarine part of the Alligator River near Gum Neck where the Alligator barbs into an acute angle turn from a southeasterly course into a northerly one. Apparently the growth of peat was aided by the slow post-Pamlico reestablishment of the buried valley as compaction of estuarine fill let the surface subside to become a swampy swale. By such slow evolution the reestablishment of the valley and the upward growth of the peat would progress simultaneously and the valley would never hold an open stream channel until peat-destroying conditions

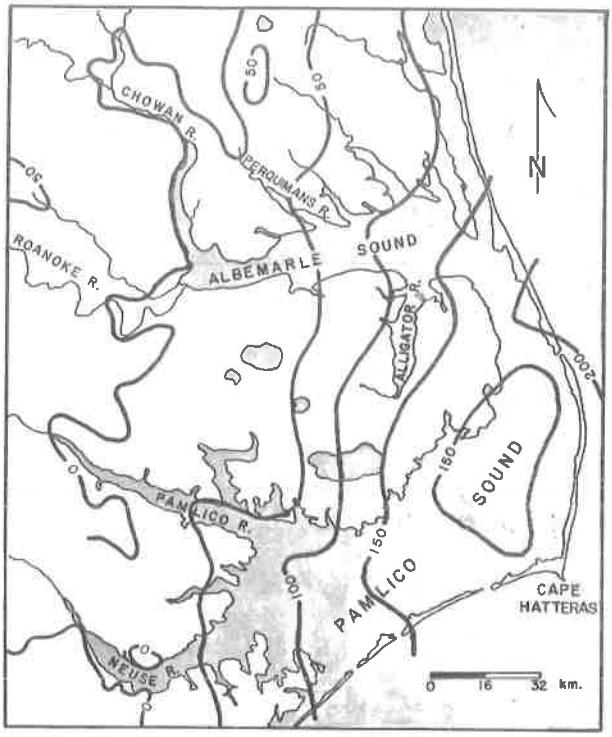


Figure 4. Map of a part of the Embayed Section of the Atlantic Coastal Plain in northeastern North Carolina showing structure contours on the top of the Yorktown formation. After Brown, Miller and Swain (1972).

ensued, as seems to be the case now along the banks of the Alligator River. A similar evolution of the peat of the Dismal Swamp is suggested by its forming first in valleys which followed the regional southeasterly trend away from the toe of the Suffolk Scarp as shown in Figure 5 after Whitehead (1972). At other interglacial times the Roanoke River may have debouched through the disproportionately large estuary of the Pungo River which Welby (1971) shows to be deeply incised in the Yorktown formation.

All the above descriptions suggest that most pre-Talbot stream valleys of northeastern North Carolina were subparallel in a southeasterly direction in common with the regional mode; that they were in large measure filled with sediment in Talbot or Pamlico time and have been re-expressed topographically by subsidence resulting from compaction of estuarine fill.

The Neuse and Pamlico Rivers also seem to have reestablished their pre-Talbot or pre-Pamlico courses by subsidence. The antiquity of their present courses is shown by the buried counterparts of their valleys as seen in the structure contours on the top of the Yorktown Formation (Figure 4). These buried valleys are coaxial with the present estuaries. It is also of note that these two valleys share the regional southeasterly trend.

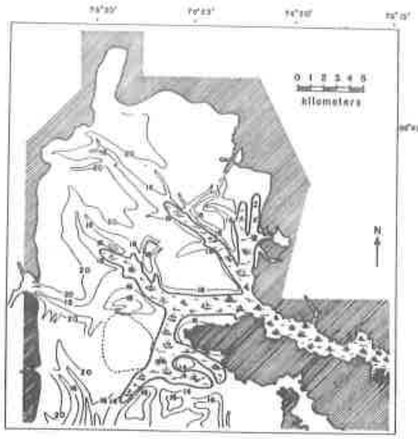
The estuaries of northeastern North Carolina have no doubt been widened by shoreline erosion at present sea level, but the extent of such widening seems to be revealed by shallowly submerged flats adjacent to the eroding shores. Such flats are shown on the bathymetric profiles of Custer and Ingram (1974).

INFLUENCE OF MELTWATER STREAMS IN PREVENTING THE FORMATION OF BEACH RIDGE PLAINS IN MOST OF THE EMBAYED SECTION

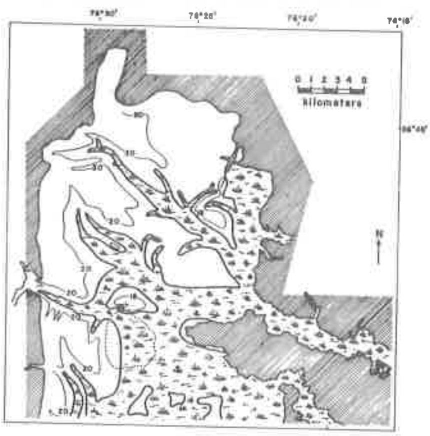
Estuaries of the southern part of the Embayed Section seem to have been made possible initially by meltwater-influenced stream dissection during an early, low sea level prior to the high sea level which in the Sea Island Section produced at once the Surry Scarp as a mainland shore, the Wicomico Terrace as a lagoon, the Walterboro (Dorchester) Scarp as the steeper nearshore part of a shallow-marine offshore slope, and the Pennholloway Terrace as its flatter, more seaward expanse (PWWS for Pennholloway-Walterboro-Wicomico-Surry sea level (White, 1966)).

This PWWS relict barrier-lagoon system can be traced with interruptions for long distances through the Sea Island Section, but it is obscure or absent north of a relict cape near Kenansville, North Carolina, on the divide between the Cape Fear River of the Sea Island Section and the Neuse River of the Embayed Section. This suggests that the PWWS Sea could build a barrier in the Sea Island Section because it transgressed a smooth surface on which there had been little stream dissection; but north of the Neuse River - Cape Fear River divide, in the Embayed Section, it had difficulty building a barrier because it transgressed a landscape which had been deeply dissected by tributaries of a meltwater-carrying Susquehanna River.

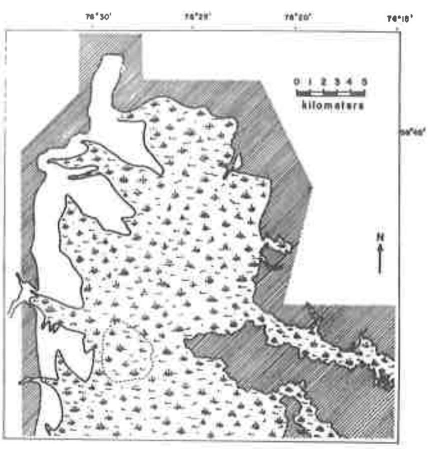
Such a dissected landscape would produce the many headlands and estuaries characteristic of a coastline of submergence, and its modification by shoreline processes would produce beaches that wrap around cliffed headlands, spits and eventually bay mouth bars. And deep, closely-spaced valleys off shore would provide sumps for the reception of drifted sediment and generally forestall the development of a smooth off-shore surface on which a barrier could be built. Thus it is significant that the Surry Scarp (the mainland shore of the PWWS coast) is readily traced northward across North Carolina into Virginia



Topography of Dismal Swamp, ca. 8,300 B.P.



Topography of Dismal Swamp, ca. 6,000 B.P.



Topography of Dismal Swamp, ca. 3,500 B.P.

(Wentworth, 1930; Flint, 1940; Daniels, Gamble and Nettleton, 1966; Oaks and Coch, 1973) but any associated relict barrier is obscure or absent in the Embayed Section.

In Talbot time a similar situation prevailed. In the Sea Island Section south of the Neuse River drainage area the Talbot (Chowan) Terrace as shown on Stephenson's (1912) map (Figure 2) has a generally curvilinear relict shoreline which is concentric with the crescentic oceanic shoreline of the present Onslow Bay between Capes Lookout and Fear. But from the Neuse River northward, in the Embayed Section, the relict shoreline of the Talbot Sea is digitate, as in a shoreline composed of estuaries and peninsulas. This difference of the Talbot shoreline of the Sea Island Section from that of the Embayed Section probably reflects the greater dissection accomplished by the meltwater-affected streams of the Embayed Section which made a shoreline so deeply and broadly embayed that the Talbot Sea was not able to make as much progress toward straightening it as it did in the less dissected Sea Island Section south of the Neuse River.

Just as dissection by streams tributary to the meltwater-carrying Susquehanna River prevented the development of the PWWS barrier-lagoon system north of the Cape Fear River-Neuse River divide, so also did it prevent the development of multiple beach ridges on the Pennholloway and lower terraces in the Embayed Section.

In the Sea Island Section the Pennholloway Terrace is a relict of the

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Figure 5. Sequence of maps of Dismal Swamp showing three stages in the progressive accumulation of peat. After Whitehead (1972).

smooth, gently-sloping, shallow-marine, offshore slope of the PWWS Sea surmounted by a veneer of littoral sediment deposited during later lower levels of sea. Since it had not been appreciably dissected by streams, it could maintain a straight or broadly crescentic oceanic shoreline as progradation or regression caused its gradual emergence-- hence the long succession of parallel or concentric relict beach ridges of the lower Coastal Plain in the Sea Island Section (Winker and Howard, 1977).

In the Embayed Section, by contrast, the meltwater-induced dissection made closely spaced estuaries possible at interglacial sea levels higher than Pamlico. Hence there was neither straight coast line nor gentle, smooth, offshore slope on which oceanic beach ridges could form, except on the seaward slope of the distal part of the Delmarva Peninsula. However, in the southeastern part of the Embayed Section, south of the present Chesapeake Bay, valleys were not reincised after they ceased being tributary to the meltwater-carrying Susquehanna. Apparently, for this reason the Pamlico Sea regressed across a well-graded shallow-marine profile, which may have failed to develop progradational beach ridges because its slope was so gentle that regression was to rapid to let them form. Short lived discontinuous bars may have been thrown up in shoal water far offshore. And later transgressions, of less height above present sea level, were enabled to throw up interrupted barriers between reestablished estuaries.

Daniels, Gamble, Wheeler and Holzhey (1972) noted a change in character of the topography north and south of the Neuse River, and thought it might be related to estuaries. They wrote (p. 17):

> The Talbot surface south of the Neuse estuary is a transitional landscape from the smooth, nearly featureless flats (at) the north... (to) the ridge and swale topography mapped by DuBar (1971) in the Wilmington area (at the south)... the characteristics of the surfaces and commonly the sediments appear to change considerably from north to south across the Neuse. Are these changes somehow related to the fact that the Neuse is the southernmost major estuary and this has somehow influenced past sedimentation?

EFFECTS OF DISSECTION BY MELTWATER STREAMS ON THE PLAN OF THE OUTER COAST LINE OF THE EMBAYED SECTION

In addition to the effects described above, the abnormally great dissection by streams that carried meltwater through the Coastal Plain has been a principal factor in determining the gross plan of the outer coast line of the Embayed Section. This oceanic shoreline is atypical in having broad convexities between estuary mouths (Figure 1), in contrast to the coast line of the Sea Island Section which has great reentrant coastal crescents or arcuate concavities between the cuspate capes Hatteras, Lookout, Fear, Romaine, and Canaveral.

The reentrant coastal crescents of the Sea Island Section are products of erosion and deposition by coastal process unaffected by fluvial dissection, but the obtuse coastal protuberances of the three coastal compartments of the Embayed Section seem to result from fluvial erosion by the Hudson, Delaware and Susquehanna Rivers when their discharge was grossly increased by glacial meltwater. During such times sea level was lower than it is now, and these three rivers apparently extended their courses across an emerged continental shelf following the same pattern of southward deflection as that of the present Delaware and Susquehanna (White, 1966).

Each of the three compartments of the Embayed Section coastline (Cape Hatteras to Cape Henry, Cape Charles to Cape Henlopen, and Cape May to Sandy Hook, at the mouth of New York Harbor) has two essentially straight reaches of coast which meet in an obtuse angle at the most seaward-protuberant part of the compartment. The southerly reach of each such coastal compartment is probably roughly analogous to a contour on the preglacial regional slope where sea level now intersects it. In contrast, the northerly reach of each coastal compartment seems to mark the intersection of sea level with the higher western wall of the valley of a meltwater-carrying stream whose lower eastern valley wall is submerged. Apparently the slopes of such valley walls were too steep to allow barriers to form and for this reason the northern end of each coastal compartment is atypical in having a mainland beach rather than a barrier, thus explaining the repetitive pattern noted by Swift (1975) in these coastal compartments. In each compartment he noted a mainland beach at the north or east end followed to the south or west by a spit and a barrier chain (Figure 6).

The oceanic coast of Long Island seems to have a similar pattern for a partially different reason. There, the high ground of the Ronkonkoma End Moraine caused the mainland beach at the east, and to the west an associated glacial outwash plain simulated the gentle seaward incline of a marine off-shore slope to make spit and barrier possible.

Streams which flow to the northern reaches of the New Jersey and Delmarva coastal compartments (Figure 6) have broad estuaries filled with open water (the Navesink, Shrewsbury, Shark, Manasquan, Metedeconk and Toms Rivers of the northern part of the New Jersey coastal compartment; and Rehoboth Bay, Indian River Bay, Little Assawoman Bay, Dirickson Creek, St. Martin River, Turville Creek and the largely marsh-filled Trappe Creek of the northern part of the Delmarva coastal compartment). Apparently these streams incised their valleys because they were tributary to the meltwater-incised Hudson or Delaware River.

On the other hand most streams that flow to the southern reaches of these coastal compartments have no estuaries, and the few

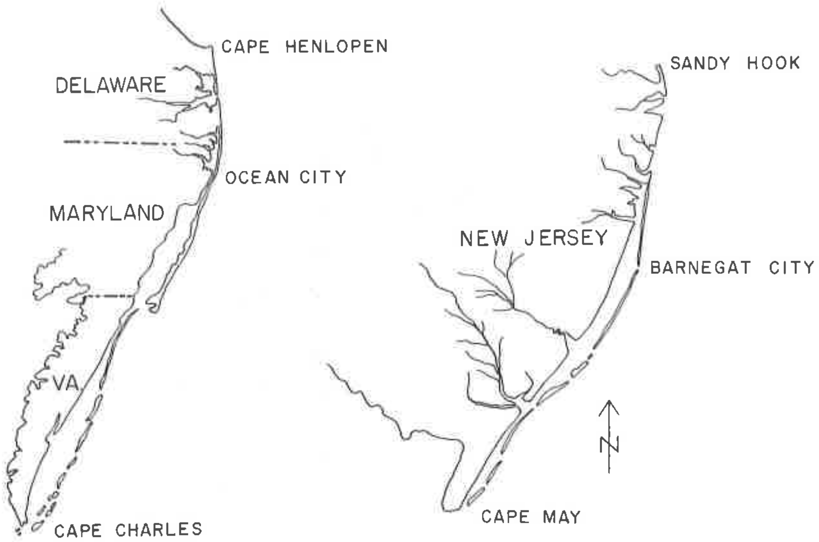

Figure 6. Maps showing the New Jersey and Delmarva coastal compartments.

estuaries that do occur (such as those of Great Egg Harbor and Mullica Rivers of New Jersey) are derelict. They are filled with tidal marsh, and apparently the dissection that cut their valleys occured during some early low glacial sea level and was not refurbished during the low sea level which attended the last glaciation. The estuaries of the northern coastal reaches seem to be the headward parts of the valleys of streams that, like those now tributary to Chesapeake Bay, were incised because they were tributary to the meltwater-carrying Hudson, Delaware and Susquehanna Rivers during times of low glacial sea levels. The landscape through which the lower reaches of these streams formerly flowed is now wholly submerged, and differentially obscured by marine sediment. However, in the case of the Delaware River (Figure 7) the general form of the main shelf valley is fairly well shown by bathymetry and it seems significant that its thalweg follows an extension of the thalweg of the present estuary of the Delaware River to a point some 20 kilometers off shore in the open ocean where, at a depth of 28 meters, it makes an abrupt dextral turn southward into a course parallel with the more northerly of the two straight reaches of the oceanic coast of the Delmarva peninsula between Cape Henlopen and Ocean City, Maryland.

A sub-bottom continuation of this valley was traced by Folger, Knebel and Twichell (1976) from 30 meters water depth to a right-angle juncture with the head of the northeast-trending Wilmington Canyon. This suggests that the ancestral Delaware River followed a course similar to that of the Susquehanna River in that it was repetitively deflected southward (White, 1966).

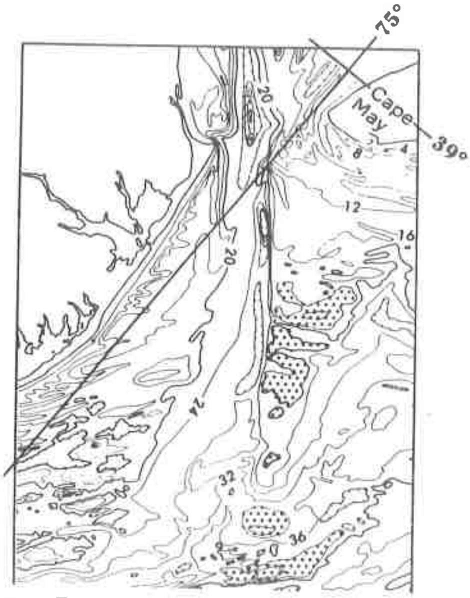

Figure 7. Isobaths in meters showing dextral southward bend in thalweg of Delaware shelf valley. After Uchupi (1970).

Swift observes that the Delaware Shelf Valley is atypical in being rather well preserved. He notes (1973, p. 2745) that most wholly-submerged parts of estuaries "have (been) heavily modified with respect to their earlier counterparts, with the result that shelf valleys cannot always be traced directly into estuaries. The Delaware Shelf Valley.... is a unique exception to this general rule." I think this exceptional preservation results from the late residence of the front of the Laurentide Ice Sheet in the drainage area of the Delaware River, because the southernmost extent of the last ice sheet was in southeastern New York and northern New Jersey. By contrast this glacial front entered the Susquehanna River Valley marginally if at all. Perhaps this is why the latest course of the Susquehanna River across what is now the continental shelf has been obscured by sediment. The original course of the Susquehanna River is not known, but I suspect it originally debouched near the present Cape Hatteras, thus explaining the large estuaries of northeastern North Carolina as its former tributaries and the Hatteras submarine canyon as a product of erosion by turbidity currents formed from the glacial silts it carried (White, 1966).

Seismic reflection profiles of Shideler and others (1972) show a buried valley which parallels the northern reach of the Cape Hatteras to Cape Henry coastal compartment some 10 to 20 kilometers off shore. They project it through a major change of direction to continuity with a surface valley in the outer shelf, but it may be significant that it persists through all their cross sections, and lies wholly in the straight line which extends from the great cusp in the shelf break off Cape Hatteras, through the mouth of Chesapeake Bay, and along the axis of the lower two thirds of the length of Chesapeake Bay.

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MANICRINUS (NOV.), A CLADID EVOLUTIONARY HOMEOMORPH OF THE BOTTOM-DWELLING HYBOCRINUS, BROWNSPORT (SILURIAN: LUDLOW) OF TENNESSEE

By

T. J. Frest
and
H. L. Strimple
Department of Geology
The University of Iowa
Iowa City, Iowa 52242

ABSTRACT

The cladid inadunate crinoid genus Manicrinus (nov.) is characterized by well-developed but imperfect bilateral symmetry through the crinoid plane (A ray - CD interray), greatly offset stem facet, lack of an anal tube, and possession of one divided radial (C ray; superradial-inferradial pair). Most of these features are duplicated by members of the exclusively Ordovician Hybocrinidae, for which a bottom-dwelling habit has been suggested (Strimple, 1975). A similar habit is postulated for Manicrinus. Possession of a large radianal (inferradial) situated directly beneath the C radial (or superradial) is an unexpectedly primitive trait which makes assignment of the genus to existing families unfeasible. Manicrinus is tentatively referred to the Gasterocomacea, constituting the new family Manicrinidae. It is argued that the so-called radianal in at least some crinoids is a basic skeletal element inherited from early (Cambrian) crinoids not readily placed in later subclasses, rather than a migrated C ray inferradial. The single know specimen (Manicrinus hybocriniformis, n. gen., n. sp.) is from the Brownsport Formation (Ludlow; Silurian), Decatur County, Tennessee.

It is postulated that a bottom-dwelling life layer was a persistent component of large Paleozoic crinoid communities, and the interrelations of this stratum to the two better known life layers of Lane (1972) are examined. A tentative evolutionary history of the bottom-dwelling stratum is outlined. Its main features are an initial expansive period in the Ordovician, followed by a long period of domination by calceocrinids. Antecedent to the decline of the Calceocrinidae for unknown reasons in the late Paleozoic the bottom-dwelling niche was reoccupied by flexibles and cladid inadunates. These persisted to the close of the Paleozoic, after which bottom-dwelling stalked forms are rare.

INTRODUCTION

The west Tennessee Silurian has been a rewarding collecting ground for fossil echinoderm specialists since the first half of the nineteenth century. In particular, glades developed in the Brownsport Formation (Amsden, 1949) have provided many thousands of echinoderm specimens, especially of crinoids, to collectors. The Brownsport echinoderms were worked intensively by Springer (1926); the specimens he obtained provided the foundation of his massive tome American Silurian Crinoids. Extensive collecting and quarrying operations financed by Springer eventually yielded ninety-five species of crinoids, as well as a few cystoids and blastoids, making the Brownsport crinoid fauna by far the largest yet discovered in the Silurian. Following Springer research on west Tennessee Silurian crinoids diminished to a trickle. However recent collecting in the classic glades of Decatur County has demonstrated that numerous taxa remain to be described.

The unique specimen described below as Manicrinus hybocriniformis, n. gen., n. sp. was among a lot of Brownsport fossils collected from a Decatur County glade by L. R. Laudon (University of Wisconsin) and donated by him to the University of Iowa. As is the case with virtually all glade collections none of the specimens were found in place; however the provenance of the crinoid can hardly be doubted. The Dixon and Decatur Formations, respectively underlying and overlying the Brownsport, generally are not glade formers and personal experience indicates glades formed from the 100-120 ft. thick Brownsport are rarely contaminated by fossils from other formations. Neither the Dixon nor the Decatur have had a large or abundant crinoid fauna reported from them. Fossils associated with Manicrinus indicate that the specimen came from the Eucalyptocrinus Zone, Beech River Formation of Pate & Bassler (1908). Amsden (1949) considers the Beech River as a faunally, not lithologically, based facies of the Brownsport Formation. According to this author the crinoids are not associated with a dense brachiopod or coral fauna (Bob and Lobelville Formations of Pate and Bassler, 1908) and are most abundant in the lower part of the Brownsport (Amsden, 1949, p. 30). It is therefore quite likely that Manicrinus is from the lower Brownsport.

Age relationships of the formation are not yet settled. Berry and Boucot (1970) regard it as of Ludlow age but Amsden (1971) believes that the Brownsport and Decatur are coeval, thus raising the possibility that the formation extends into the Pridoli. The available age determinations are mostly based on rather sporadic conodont sampling, except that the Pridoli age of the Decatur rests also on the presence of Camarocrinus (Berry & Boucot, 1970, p. 141). Witzke, Frest, & Strimple (1977) question the value of Camarocrinus as a Pridoli age indicator. We accept the Ludlow determination pending detailed study of the conodont fauna of this part the Tennessee Silurian by other workers.

Acknowledgments

Royal H. Mapes (University of Iowa) read an earlier draft of this paper and suggested numerous improvements. We are also indebted to James C. Brower (Syracuse University), who reviewed the final version and made several suggestions that materially improved the paper.

FUNCTIONAL MORPHOLOGY

Some characters of Manicrinus are strikingly reminiscent of Ordovician crinoids of the order Hybocrinida (e. g. Hybocrinus and Hybocystites). The functional morphology of these genera was the subject of a recent paper by Strimple (1975) and so will be reiterated here only sufficiently to facilitate discussion of the similar functional morphology of Manicrinus. The order Hybocrinida is a compact group of monocyclic inadunates, ranging from Lower Ordovician to Lower Silurian and nearly cosmopolitan in distribution. Species of two genera, Hybocrinus and Hybocystites, have cup shapes deviating markedly from the pentameral symmetry that dominates the class Crinoidea. These hybocrinids have subglobose cups with a prounounced bulge in the posterior side, a column facet that is typically very small relative to cup width and displaced toward the anterior side, and unequally-sized basals. The resultant cup shape is decidedly not radially symmetrical. It may best be regarded as imperfectly bilaterally summetrical through the so-called crinoidal plane (A ray - CD interray); but as the two halves defined by this plane are not strict enantimorphs (C radial is often elevated above its D ray counterpart, and anal X is curved toward the C ray) the cup form can be treated with some justification as asymmetric (e. g. Strimple, 1975). In common with more pedestrian hybocrinids, asymmetric members of the order display such unusual features as narrow arm facets, outsized RA (radianal), a curved aboral margin on anal X, unequal-sized radials (C ray R (radial) commonly with area less than one half that of other radials), and an oral surface covered largely by a simple tegmen consisting of five large orals, without an anal tube. All hybocrinids are monocyclic. We illustrate a specimen (SUI 42775) of a representative asymmetric Hybocrinus, H. nitida Sinclair (Middle Ordovician: Bromide Formation, Oklahoma) for comparative purposes (Plate 1g-1, figure 2b). Manicrinus, a dicyclic inadunate thought to be a member of the order Cladida under present classification can only be related to the Hybocrinida distantly, yet shares many of its diagnostic features as well as those unique (in the Hybocrinida) to the "asymmetric" forms. The genus has a proportionately small stem facet, undersized C radial, large RA, and probably lacked an anal tube. As in asymmetric Hybocrinus the longest basal is in the CD interray, the posterior side of the cup is elongate, and the stem facet is canted toward the anterior side. Some differences from asymmetric hybocrinids should also be noted. Aside from the fundamental point of dicyclism vs. monocyclism, the cup sides in Manicrinus are straight rather than rounded and there are faint axial ridges on the cup plates. All asymmetric hybocrinids have rounded cup sides and convex-outward unridged plates. Otherwise the resemblance is complete (Plate 1).

If the noted similarities of appearance and cup plate morphology cannot be interpreted as indicators of close phylogenetic relationship they can reasonably be taken to indicate adaptation to comparable life habits. Few other crinoids have similar features; very likely the involved genera occupied an ecological niche that was unusual for crinoids, and necessitated the acquirement of a highly specialized morphology for successful exploitation. Brower & Veinus (1974, p. 33) have suggested that one species of Hybocrinus (H. punctatus) may have lived with the stem on the substrate. Strimple (1975) postulates a bottom-dwelling habit for all asymmetric Hybocrinus and we hypothesize a nearly identical life habit for Manicrinus. Because complete crowns with intact stem and attachment device, if any, have not yet been found for any crinoid having the cup morphology here considered, functional morphology must be inferred from indirect evidence. An erect habit is implausible for these crinoids because the crown could not easily be held with the plane formed by the arm bases horizontal and would be unwieldly and difficult to balance. The stem-cup junction, a weak point more liable to rupture than more distal columnal-columnal junctions, would be subjected to abnormal and uneven stress due to cup asymmetry and the off-center location of the stem facet. The stem in the presently considered genera was tenuous, judging from the small attachment facet and the rarity of preserved examples still attached to the cup, and hence could better teather or anchor the crown than hold it erect. If the crown lay on or near the bottom, presumably resting on the broad posterior side, which is often nearly flat along the plane of bilateral symmetry, the stem facet would be near the sediment-water interface. Thus a living position on the sea bottom as illustrated (Figure 1) is reasonable. Our ascription of a bottom-dwelling habit to stemmed echinoderms has precedents. A similar mode of life has been suggested for paracrinoids (Durham, in Parsley & Mintz, 1975; Frest & Strimple, 1977), as well as several crinoids. Among inadunates the nearly perfectly bilaterally symmetrical Calceocrinacea have been generally accepted as bottom dwellers (Jaekel, 1918; Brower, 1966; Kesling & Sigler, 1960; Breimer & Webster, 1975); some flexibles are postulated by Lane & Webster (1966) and by Moore & Strimple (1973) to occupy a similar niche. Even some crinoids with completely radially symmetrical cups have modified the stem or arms in ways compatible with such a life style (e. g. Idosocrinus Wright and an undescribed Permian inadunate from Texas, being studied by Strimple, with calceocrinid-type arms).

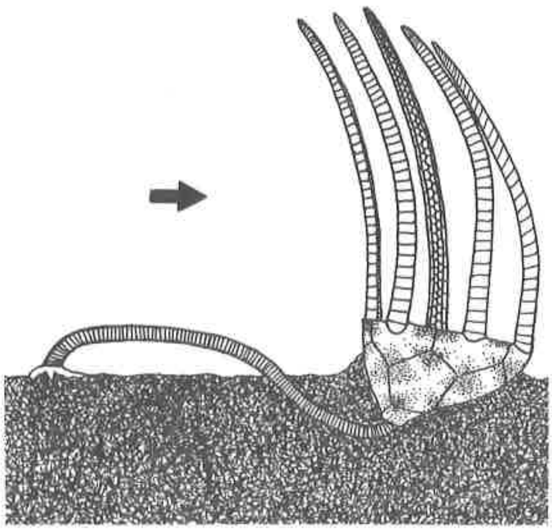

Figure 1. Diagrammatic reconstruction of postulated living position and life habit of Manicrinus hybocriniformis. Current is assumed to move from left to right.

Whether the prone stem functioned like a runner (in the manner favored by Brower, 1966 and Kesling & Sigler, 1969, for calceocrinids) or as an anchor (as Durham, in Parsley & Mintz, 1975, suggests for Platycystites and Strimple, 1975, figure 1, illustrates for Hybocrinus) is difficult to determine. In either case the crinoids were probably able to adjust their position somewhat in response to a changing current regimen--a special case of the "active orientation" of Breimer & Webster, 1975. Both the flexibles studied by Lane & Webster and many calceocrinids have relatively robust columns and are thought to have lived in agitated environments. The Bromide Hybocrinus nitida is a member of the open-shelf community of Longman & Sprinkle (1976). This echinoderm-dominated community occupied the deepest-water habitat available in the Bromide but as the postulated Bromide sea was relatively shallow some agitation is quite likely. Probably strong currents or severe agitation were not typical; however, gentle but persistent currents, and possibly some storm-caused disturbances, are plausible. The tenuous column of H. nitida or the homologous Manicrinus probably could not resist strong currents or abrupt shifts in current direction but would be adequate in a situation where weak or moderate essentially unidirectional currents were prevalent.

It is significant that recorded occurrences of asymmetric Hybocrinida (and the sole occurrence of Manicrinus as well) are from echinoderm dominated communities; this is true of the Battleship Wash flexibles (Lane & Webster, 1966, p. 13-14) and of most calceocrinids as well. The diverse Bromide and Brownsport crinoid faunas contain numerous erect-crown crinoids employing various strategies to effectively exploit the usual "high rise" (Sprinkle, 1973) crinoid habit. We envisage Hybocrinus nitida and Manicrinus as exploiting a different stratum, outside of the intensely competitive high rise stratum occupied by most crinoids, but yet not directly competitive with the normal low rise (near to the substrate) filter-feeding groups such as the brachiopods. Crinoids of this type may, however, be partly dependent on the prior existence of a high density high rise echinoderm community to reduce competition from other near-substrate attached filter-feeding groups. These are often excluded from or much reduced in number in so-called crinoid meadows (echinoderm dominated communities), and our postulated bottom dwellers are almost invariably found only in large and abundant crinoid faunas. Though possibly receiving less waterborne food, the crown of Manicrinus or similar forms with stems prostrate on the sea bottom would be near enough to the bottom to be less effected by possibly damaging surge or strong currents (Lane and Webster, 1966, p. 14). Additionally they might be in a position to use as prey the bacteria and larger free-swimming animals that seldom venture far from the substrate-water interface. A recumbent habitus, while placing the animal more in jeopardy from sediment-dwelling predators, would also make the crown less conspicuous to vagile forms, which would possibly include most crinoid predators. Crinoids with "runners" would also require less energy to maintain themselves in the optimum orientation for feeding from prevailing currents, because the stem need not be held erect and the crown and stem both would have partial support from the underlying sediment. The postulated habit would be efficient only in areas where the density of other low rise groups, which presumably were under normal circumstances more efficient filter-feeders, was unusually low. Thus only under relatively restricted situations was the postulated habit practical, and only a small proportion of the echinoderm taxa present in a given fauna would be capable of utilizing it.

Symmetry relations of the cup are such that an orientation such as that shown in Figure 1 is most plausible. We believe that the cup rested on the broad posterior side with the shorter anterior side facing into the prevailing current. This posture would maximize the area of the cup in contact with the substrate while minimizing exposure. The C ray arms and anal tube would project slightly above the other arms, whose bases form a plane which in life was probably tilted slightly into the current. This would minimize interference of the arms with each other and guarantee that discharged solid wastes would be carried away from the oral surface. The stem could either be entirely or only partly exposed, extending in an upcurrent direction to an attachment device. The resemblance of such a form to an outstretched human arm and hand suggested the name Manicrinus.

Our reconstruction of the life habits of Manicrinus bears some resemblance to the postulated habit of the calceocrinid Halysiocrinus in some middle Mississippian crinoid assemblages (Lane, 1963, 1972, 1973). However, other invertebrates (e. g., brachiopods, pelecypods, and sponges) are more common in the Carboniferous assemblages (Lane, 1973) than is the case in the Brownsport. As interpreted by Lane, these assemblages include two "life layers" of crinoids, distinguished by stem length, at about 25 cm and 75 cm above the bottom (Lane, 1972). While the Brownsport crinoids have not been similarly studied it is quite likely that an analogous or identical stratification is present. We suspect that such a community structure may be ubiquitous in non-reef crinoid "meadows": whether the same sort of layering takes place in reef-associated crinoid assemblages has not been demonstrated.

The wide time and stratigraphic ranges of possible bottom-dwellers suggests to us that a third life layer is also frequently present, minimally in areas with sizeable echinoderm faunas, but no reef development. The uncommoness of bottom dwellers in most large crinoid faunas, for the reasons stated above, was probably the biggest bar to recognition of a third layer in Paleozoic echinoderm assemblages dominated by stalked forms by previous workers. However, the combination of reduced numbers and diversity with analogous occurrences, living habits, and bizarre (though closely comparable) morpholigical features in such distantly related groups as the Hybocrinidae, Manicrinidae, and Calceocrinidae, leads us to postulate a trilevel structure for most large Paleozoic crinoid faunas.

We have argued that numerous filter feeding echinoderm groups at one time or another have attempted to exploit the bottom dwelling habit. One might speculate that the limited scope of such a habit would exacerbate the effects of the competitive exclusion principle, so that only a few species could exploit it in even a very large echinoderm fauna. Numerous forms (e. g. paracrinoids, Columbocystis and related forms, cystoids, and crinoids) seem to have made the necessary adaptations by the Middle Ordovician; but very few of these groups survived into the Silurian. The notable exception is the Calceocrinidae, which, while not uncommon in the Ordovician (3 genera), is particularly successful in younger rocks, especially the Silurian and Devonian (Webster, 1977). These crinoids, with their near perfect bilateral symmetry, highly streamlined crown, and basal-radial hinge, may have effectively displaced many of the earlier groups that were their competitors. For reasons as yet unknown the Calceocrinidae abruptly decreased in numbers and variety near the opening of the Carboniferous (Mississippian), though they survived into the Permian. At about this time another expansion of bottom dwellers occurs, derived from cladid inadunate and flexible stocks rather than from the Disparida. While the cause of the calceocrinids' demise is not certain, some possibilities can be eliminated. Reduction or restriction in area of the preferred habitat was not a factor, as other crinoids managed to occupy it in sizeable numbers, and these groups are fairly widely distributed. It is also unlikely that competition from other crinoid groups attempting to exploit the same habitat was the cause. None of the replacing forms appear as well adapted to bottom dwelling as were even the morphologically most primitive calceocrinids. Cup shape in these forms is usually only slightly modified from radial symmetry and the arm configuration (with few exceptions) is not much different from that of coeval middle and upper layer forms. Compared to the early Paleozoic bottom dwellers that later forms seem much more crude, as if they are evolving into a comparatively new (for them) and underoccupied habitat, rather than usurping the position of the previously dominant group.

We tentatively reconstruct the evolutionary history of the bottom-dwelling stratum as follows; after an initial period in which several echinoderm groups were successful as bottom-dwelling filter feeders the especially well suited calceocrinids displaced most other echinoderms from this habitat. Following a long period of virtually undisputed dominance (among echinoderms) the calceocrinids declined due to unknown factors. Contemporary with or (more probably) slightly after initiation of their decline other inadunates and flexibles began to exploit the now underpopulated niche. While not as spectacularly or completely successful as the calceocrinids these groups persisted to the close of the Paleozoic, after which this habitat became apparently closed to almost all crinoids. The causes of the near extinction of the bottom-dwelling types rather abruptly at the end of the Paleozoic may have been manifold. Increased effectiveness of other bottom-dwelling filter feeders, particularly the pelecypods, may have been a factor, as might structural changes in the supporting echinoderm community. This interpretation will be documented more fully in a later paper.

Plate 1. a-f, holotype of Manicrinus hybocriniformis (SUI 42774). a - oral view, showing edges of radials, elongate cup outline through A-CD (crinoid) plane. b - basal view, to show stem facet, cup asymmetry. c-f, side views of cup; c - centered on A ray, to show plate ridges, arm facet; d - CD interray view, illustrating posterior bulge, large anal X; e - cup as viewed from E ray, note short anterior slope, long posterior slope; f - centered on C ray, to show divided radial, g-l, Hybocrinus nitida Sinclair (SUI 42775), for comparison with Manicrinus. g- top view; h - basal views; i-l, lateral views centered respectively on A ray, (l) interray, E ray, and C ray. All figures x3. 5, coated with ammonium chloride sublimate.

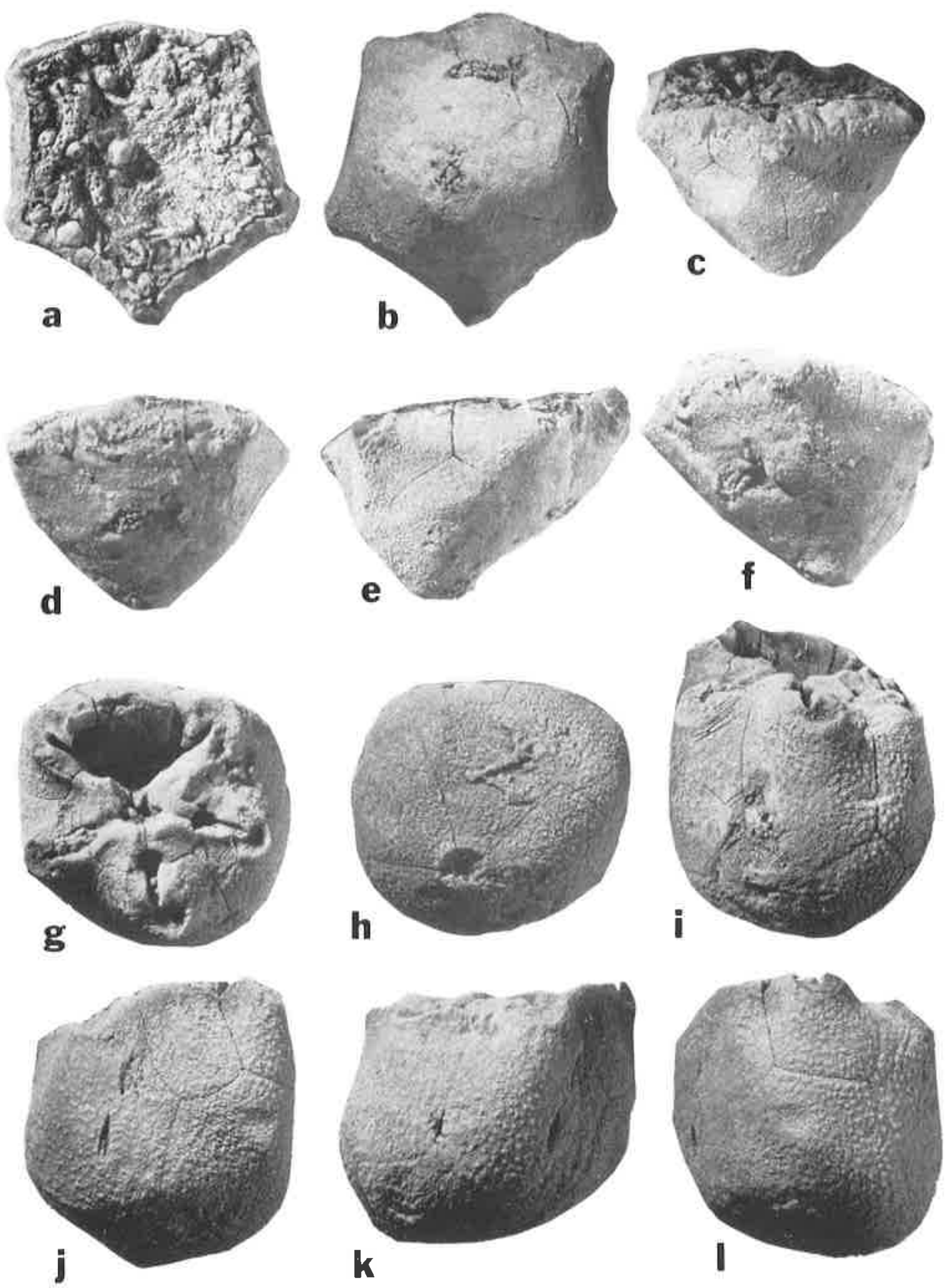

Plate 1.

bowl-shaped cups, reduced anals, and separate axial canals in both the radial arm facets and brachials. The Manicrinidae, as indicated below, are more closely related to the first group.

FAMILY MANICRINIDAE, new family

Definition. - Gasterocomacea with tegminal anal opening, a single prominent anal plate (anal X), and one compound radial in the C ray.

Assigned genus. - Manicrinus, new genus.

Range and distribution. - Silurian (Ludlow), Tennessee.

Remarks. - The very limited available material argues against establishment of a new family, and we are not completely satisfied with our chosen course. However careful consideration leads us to the conclusion that the other alternatives would cause even greater difficulties. Though the tegmen is not preserved the curved proximal margin and lack of faceting at the summit of anal X, plus the folded-over tops of the radials (Plate 1a, Figure 3a) establish the lack of an anal tube, presence of a flat or nearly flat tegmen, and tegminal location of the anal opening. These features, and additionally the cup plate configuration and configuration of the arm facets, clinch the superfamilial assignment. Among the Gasterocomacea retention of decidedly primitive features in cup shape and anal plate arrangement link the Manicrinidae with the families of group one. But even cursory analysis demonstrates the unsuitability of assignment of Manicrinus to any of these families.

Despite its Silurian age and drastic morphologic modifications required for its peculiar life habit the genus is oddly primitive; if it predated the families of group one and had five instead of three infrabasals there would be little argument with the proposition that all three are descended from it. Unlike other "primitive" (or unspecialized) Gasterocomacea, Manicrinus lacks a radianal (RA)--that is, an interradial element below or to the right side of anal X in the CD interray. This condition, as will be argued below, is partly a matter of definitions. Manicrinus does have a divided C ray radial, and if the widely accepted hypothesis that the origin of the RA is from a C ray inferradial is correct, any translation of this plate from its original position directly beneath the C ray superradial liftward would make this plate a RA. Its position in Manicrinus is then extremely primitive. This condition is not known for any other gasterocomacean but is closely approached in the carabocrinid-sphaerocrinid-porocrinid lineages. These three families may be more evolutionarily advanced than the Manicrinidae in one other respect: Ordovician members of all three possess calycinal pore systems, presumably respiratory in function--a feature extremely uncommon in the Crinoidea generally. The unique goniospires of the Porocrinidae were regarded as a diagnostic familial character by Kesling and Paul (1968). The nature of the pore system

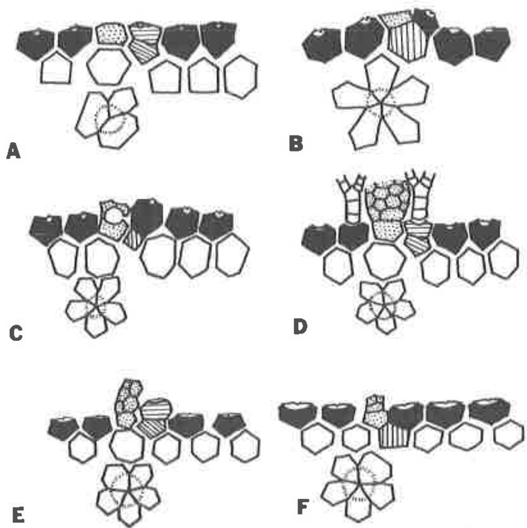

Figure 2. Plate diagrams of primitive inadunate crinoids. a - Manicrinus (Manicrinidae); b - Hybocrinus (Hybocrinidae); c - Paleocrinus (Sphaerocrinidae); d - Dendrocrinus (Dendrocrinidae); e - Cupulocrinus (Cupulocrinidae); f - Thenarocrinus (Thenarocrinidae). All except Hybocrinus (Hybocrinida) are cladids. Infrabasals and basals are white simple radial black; anal x and tube plates strippled; radianal vertically lined; superradial horizontally lined; inferradial obliquely lined. b-f adapted from Moore, 1962.

of Paleocrinus (Sphaerocrinidae) was studied by Brower & Veinus (1974). A pore system has not previously been noted in the Carabocrinidae, except incidentally; however all species examined by us, including the type species of Carabocrinus, C. radiatus Billings, have goniospire-like areas between the radials and tegminals (orals). This feature should evidently be made a part of the generic diagnosis of Carabocrinus; we are currently investigating the morphology of this genus. Later sphaerocrinids (Sphaerocrinus, Thalamocrinus and Dazhucrinus (Mu and Wu, 1974)) lack cup pore systems and may be only distantly related to Ordovician forms. The cup shape of Manicrinus, which is clearly derived from a regular straight-sided cone, is also more primitive than that of the egg-shaped group one genera (Moore & Laudon, 1943). On the other hand possession of three rather than five infrabasals is definitely an advanced character not present in other group one families.

This combination of highly unusual features in Manicrinus

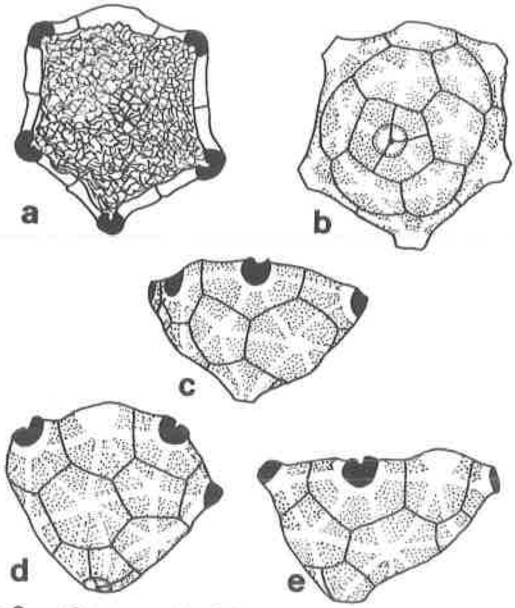

Figure 3. Camera lucida drawings of holotype of Manicrinus hybocriniformis (SUI 42774). a - oral (plan) view; b - basal view; c - lateral view centered on A ray; d - lateral view centered on posterior interray; e - side view centered on E ray.

warrants, we believe, separate familial status. It is worth pointing out that emendation of any of the three existing families to encompass the genus would create so broad and artificial a group that the distinctness of the remaining families would be obliterated--a less desirable and more unnatural situation, in our opinion, than that fostered by placement of Manicrinus in its own family.

GENUS MANICRINUS, new genus

Type species. - Manicrinus hybocriniformis, n. sp.

Definition. - Manicrinid with Hybocrinus-like cup shape and plate arrangement; dorsal cup made up of three infrabasals, five basals, five radials, and a single anal, anal X (Figure 2a). Infrabasals (IBB) not all equal; small IB in CD interray. Radials (RR) unequal; four simple, C ray R compound, both members of pair about equal in area.

Derivation of name. - Combining manus (Latin; hand) with crinus, in allusion to the genus' resemblance in presumed living position to an outstretched hand.

Range and distribution. - Same as for family.

MANICRINUS HYBOCRINIFORMIS, new species

Figures 1, 2a, 3, Plate la-e

Diagnosis. - Manicrinus with imperfectly bilaterally symmetrical cup resembling non-conical Hybocrinus species; plate configuration as given for genus.

Derivation of name. - Combining formis (Latin, suffix meaning like or resembling with Hybocrinus: the reference is to the shape of the crinoid's cup.

Material. - One specimen, the holotype, SUI 42774, now in the Repository, Department of Geology, The University of Iowa; collected by L. R. Laudon, University of Wisconsin.

Occurrence. - Hillside glade, Brownsport Formation (? lower), south of Perryville, Decatur County, Tennessee, Perryville 7 1/2' quadrangle, Tennessee Coordinate System 1,389,900 E, 446,250 N.

Description. - Cup a depressed asymmetric cone elongated along the crinoidal (anteroposterior) plane. Outline in top view imperfectly pentagonal with side formed by anal X curved; distance between C and D R arm facets greater than distance between other adjacent pairs. Width of cup greatest along plane bisecting A ray and CD interray (11.9 mm); least as measured between B and E R arm facets (11.0 mm). Height of cup (from stem facet through a point normal to plane formed by A, B, D, & E arm facets) 7.3 mm. Length from stem facet to top of cup 7.5 mm on anterior side, 10.4 mm on posterior side. Diameter of stem facet 1.7 mm, about one seventh maximum cup width. All cup plates thin, with faint ridges through plate sides connecting plate centers, dividing cup into numerous triangular areas, spaces between ridges not depresssed; intracirclet ridges fainter than intercirclet ones. Infrabasals three, unequal, upflared, together forming uninterrupted off-centered cone, with A ray length (along side) slightly less than that of CD interray. IBB centered in EA and BC interrays pentagonal, nearly equal, wider than high. CD interray IB four-sided, taller than wide. Upper margins of IBB forming crude pentagon. Basals (BB) five, with varying areas and shapes, together forming irregular but closed circlet; three BB (AB, BC, DE) five-sided, remaining BB hexagonal. AB and BC BB about equal in area, small; BC and ED BB also roughtly equal in area, largest plates of circlet; EA B area intermediate. Radial circlet disrupted by intrusion of large anal X; A, D, and E ray RR simple, pentagonal, wide; A ray R smallest, 5.2 mm in width and 3.6 mm in height; D & E ray RR larger, subequal in size. B ray R simple, hexagonal; extra side occurs where plate borders divided C ray R. Paired C ray radials (superradial, sR; inferradial, iR) equal in area and width but sR lower, roughly quadrangular while iR proportionately taller, pentagonal. Combined area of pair slightly greater than that of non-compound RR. sR projecting above arm plane defined by tops of simple RR, iR directly beneath sR. Arm facets narrow (angustary), equidimensional in all rays, horseshoe-shaped, with no separate axial canal, inclined obliquely outward (declivate). Greatest height and width of facets about 1. 6 mm. Anal X large (width 4. 1 mm; height 4. 6 mm), projecting above level of simple RR. Edge of anal X at top of cup sinuate as viewed from above. Anal X evaginated from cup to form convex bulge in posterior interray. Arms and tegmen not preserved; possibly very like those of Hybrocrinus (i. e. atomous arms; simple flat tegmen).

Remarks. - Phylogenetic relationships and paleoecology have been discussed at length above and need not be reiterated here. The morphologic convergence of asymmetric Hybocrinus and Manicrinus emphasized in the previous sections of this paper even extends to the configuration of the posterior interray; in both forms the upper suture of anal X is arcuate and a pouch-like bulge distorts the cup symmetry in oral view. The function of this bulge is problematic: in Hybocrinus the anal area resembles a cystoid periproct; it is unusually large and partly roofed over by numerous small plates, some possibly imbricating slightly. These plates were very likely embedded in a tough flexible integumen (Springer, 1911), so that they are seldom retained. Conceivably the posterior bulge was related to an anal pumping mechanism that served to supplement the crinoid's arms as respiratory devices. If the crinoid lived in the manner reconstructed, its simple arms and bottom-hugging habits might have placed it at a disadvantage both in obtaining oxygen from and discharging (by diffusion) waste products into surrounding seawater, as compared to its high rise associates. However such an arrangement could have been advantageous to Hybocrinus in that coeval crinoid genera homeomorphic with it (i. e. Carabocrinus Paleocrinus, and Porocrinus) had calycinal pore systems which may have fulfilled similar functions. Its utility in the Silurian, by which crinoids with pore-systems have almost vanished, is not clear.

The anomalously primitive C ray-CD interray plate arrangement is a peculiar feature of Manicrinus. Using the broad definition of radianal employed by Moore (1952), the possession of a single compound radial (invariably the C ray) is not especially unusual. However, Moore's definitions are controversial (see Philip 1964, 1965) and Moore himself several times modified his scheme (Moore & Laudon, 1943; Moore, 1950; Moore, 1952; Moore, 1962). Even as defined broadly very few crinoids with one compound R have the "radianal" (C ray iR) directly beneath the sR; this is characteristic, though, in two primitive cladid families, the Cupulocrinidae (Cupulocrinus; Figure 2e) and Dendrocrinidae (Dendrocrinus, Figure 2d). As noted by Philip (1965) Moore's usage sometimes blurred the distinction between a full-fledged RA and a C ray iR. Relying on Moore's latest treatment of the problem (Moore, 1962) and discussion of this paper by Philip (1965) it is probably reasonable to state that the disputed plate is an iR if it remains in "normal" position beneath the C ray sR but becomes an anal functionally if it intrudes to any degree, or moves into, the CD interray.

The dispute over homologies of crinoid anal plates has been contentious and a consensus has never emerged. The one point on which all previous investigators have agreed since the evolutionary hypothesis was originally propounded by Bather (1890, p. 329), according to Moore (1962) and Philip (1965), is that the RA is not an independent (i. e., basic) skeletal element, but rather has its origin as the C ray iR, which may be shifted laterally into the posterior interradius and migrate either upward or downward in the cup. It is largely in line with this argument that we considered the anal plate arrangement in Manicrinus as primitive, although retention of the divided radial without positional change can also be so considered.

An alternative evolutionary hypothesis explaining the origin of the RA is that the plate is a basic skeletal element, and not radial in origin. As far as we know this has not been proposed previously for the subclasses Inadunata and Flexibilia. However, it is more in accord, we believe, with observations on skeletal development in the larvae of modern crinoids (Articulata); evidence cited in support of a similar argument by Clark (1912, 1915) needs to be reexamined. Part of the reluctance to accept independent origin of the RA is certainly due to the widely held but seldom explicitly stated notion that plate configuration in the two cited Paleozoic subclasses became stabilized at two or three five-plate circlets very soon after their divergence from non-crinoid ancestors. In this view there were few or no interradial elements, and perhaps only one anal, in the crinoids which gave rise to the Inadunata and Flexibilia. The lack of agreement as to the homologies of anal plates in these crinoids belies such an argument. Several long-known genera, all of which are discussed in Moore's 1962 paper or in Philip's more recent contributions (1964, 1965), pose difficulties for any scheme based on acceptance of Bather's hypothesis. Several other forms described in the last decade have compounded the difficulty, but perhaps not insurmountably. Be that as it may, we will endeavor to suggest an alternate hypothesis that is more in line with the results of recent work on primitive echinoderm morphology and evolution. We cheerfully admit that our evidence is not compelling and we do not at present advocate abandonment of the scheme championed by Bather and Moore.

Such obviously primitive crinoids as the Lower Ordovician cladid inadunate Aethocrinus (Ubaghs, 1969) and the inadunate-like Cambrian Echmatocrinus (Sprinkle, 1973; to be placed in a separate subclass in the forthcoming crinoid volume of the Treatise on Invertebrate Paleontology, according to Sprinkle, 1976) have in common a high conical cup made up of numerous rather irregularly arranged plates (Ubaghs, 1975), including a large number of clearly interradial elements, although identification of thecal plates in such forms has sparked a spirited debate (e. g. Ubaghs, 1969; Philip and Strimple, 1971; and Ubaghs, 1972 on Aethocrinus). Whatever the precise identification of these plates, it is conceivable that one or more situated in the CD interray is the precursor of the RA of later forms. These primitive genera suggest that the Crinoidea evolved from a multiplated ancestor lacking both regularly arranged plate circlets and clear distinctions between radial and interradial elements. Very likely crinoids, as well as many other echinoderm classes with better Cambrian records, underwent their major initial radiation into a poorly-filled Cambrian ecosystem, as postulated by Sprinkle (1976). These early crinoids, embracing a number of morphologically and ecologically divergent, short-lived experimental "prototypes," would have achieved extensive design improvements by the end of the Cambrian. This would allow a second major radiation in the early Ordovician, which gave rise to the more familiar forms that dominated the rest of the Paleozoic. Thus Ordovician forms with "radianals" minimally could include forms with "extra" basic skeletal elements as well as forms in which migration of an iR produced an additional anal plate; radianals could be "polyphyletic"! Aside from the foregoing there is one additional indirect line of evidence supporting our suggestion. Members of the other Paleozoic subclass, the Camerata, which also appears like Hera out of the head of Zeus near the base of the Ordovician, appear to lack an RA and many may also lack anal X. The CD interradius in primitive (many-plated) camerates is distinguished chiefly by greater width or the presence of extra plates, although commonly an extra plate is intruded into the radial circlet. At the very least it is clear that anal plates may have different origins among subclasses.

It is tempting to speculate as to the functional significance of simple, regular plate circlets, especially among the Inadunata, and of additional plates in the CD interray in all subclasses. In the former case it is likely that, aside from the advantages gained by strengthening the cup mechanically, adaptation to a filter-feeding habit and acquisition of a radial feeding system, as suggested by Sprinkle (1973), provided the impetus for reduction in number and increased regularity of cup plates. The conversion from an irregular holdfast to a regular, flexible column, believed to have occurred in the Crinoidea in the lower Ordovician (Sprinkle, 1973, 1976), may have been an added factor. Regularization and simplification of extra-calicinal appendages may have stimulated regular organization within the cup itself. Addition of extra plates to the posterior interradius very likely was related to an increase in volume of the digestive tract, which approaches the cup wall in this area; the functional "goal" would presumably be greater efficiency in digestion. This could have been necessitated by a decrease in the volume of available food, related either to competition from other rapidly evolving filter-feeding phyla or perhaps to fluctuations in the abundance of microplankton due to physical or chemical factors.

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LITHOFACIES ANALYSIS OF WAYNE GROUP ROCKS

(MIDDLE SILURIAN), NORTH CENTRAL TENNESSEE

By

David N. Lumsden
and
Tong C. Haw
Department of Geology
Memphis State University
Memphis, Tennessee 38152

ABSTRACT

The five formations of the Wayne Group (in ascending order Osgood, Laurel, Waldron, Lego, Dixon) were investigated at six locations distributed approximately perpendicular to the presumed depositional strike. Lithofacies are entirely carbonate consisting of 57 percent fossiliferous wackestones, 30 percent lime or dolomite mudstone and 13 percent packstone; grainstones are rare. The Wayne is largely dolostone to the northeast and limestone to the southwest; however the proportion of dolomite varies from bed to bed and is present only as micrite or microspar. Fossils are the only framework components and are never dolomitized. Except for very uniform bedding, sedimentary structures are absent. We postulate an environment of deposition with very shallow water and widely varying salinity in the northeast deepening into shallow normal marine waters to the southwest.

INTRODUCTION

No petrologic study of Wayne Group rocks in Tennessee has been published. This is surprising in view of the fact that correlative rocks are oil and gas productive in Illinois and Indiana. To determine the possibility of similar facies development in the Wayne Group in West Tennessee we have investigated its fabric and mineralogy at six outcrops. This study gives only a brief glimpse into the overall problem and we hope future work will verify some of our speculations.

The sample localities used in this investigation are located along the Silurian outcrop belt at the base of the inner northwest edge of the Highland Rim (Figure 1). The Highland Rim is a low relief, topographic plateau capped by Mississippian cherts which encloses a topographic low, the Central Basin, that is floored by Ordovician limestones. This breached positive structure is known as the Nashville Dome. The locations were selected primarily for completeness of stratigraphic section; fortunately they are also distributed approximately perpendicular to the

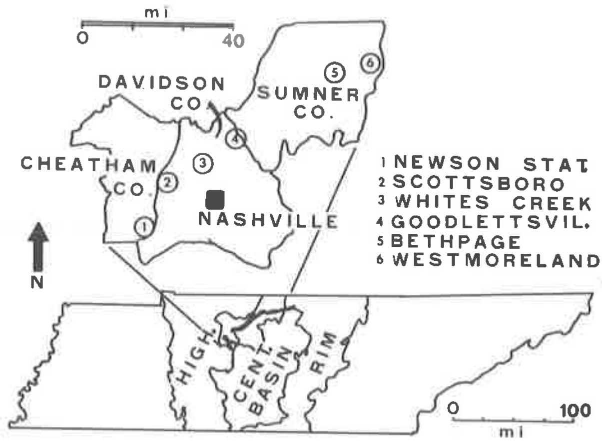


Figure 1. Location Map showing the state of Tennessee with the Central Basin and surrounding Highland Rim. The black shading represents the Silurian-Devonian outcrop belt. Sample locations are detailed in Haw, 1974.

presumed depositional strike. Detailed locations of measured sections can be found in Haw (1974).

Wayne Group rocks are Middle Silurian (Niagaran) in age (Wilson, 1949). They are time equivalents to the reef bearing St. Clair Limestone of the Illinois area and with the Clinton Group and lower Lockport Group of the classic Niagra Gorge sequence (Berry and Boucot, 1970). The Wayne Group comprises five formations including, in ascending order, the Osgood, Laurel, Waldron, Lego and Dixon (Figure 2). This terminology has been widely accepted since originally proposed by Wilson (1949). Where observed, the lower contact with the Brassfield Limestone (Medinan) is sharp and possibly disconformable. At the Newson Station location the upper contact with the overlying Beech River Formation is conformable. At the other 5 locations the Chattanooga Shale overlies the Wayne and pre-Chattanooga erosion has removed an unknown thickness of the upper Wayne forming an erosional disconformity. This makes isopachous maps of the group of little value in the study of Wayne paleogeography. Contacts within the Wayne Group are conformable. The Osgood-Laurel and Lego-Dixon contacts are gradational and frequently difficult to define.

Over the western Highland Rim the Wayne thins slightly to the east (data in Wilson, 1949); however, the absence of Wayne Group rocks in the Nashville Dome area is due to erosion, not non-deposition. Both Wilson (1949) and Freeman (1951) indicated that the Nashville Dome barred sediments from the east. Wilson believed some sediments washed over during Waldron deposition. In any event the Nashville

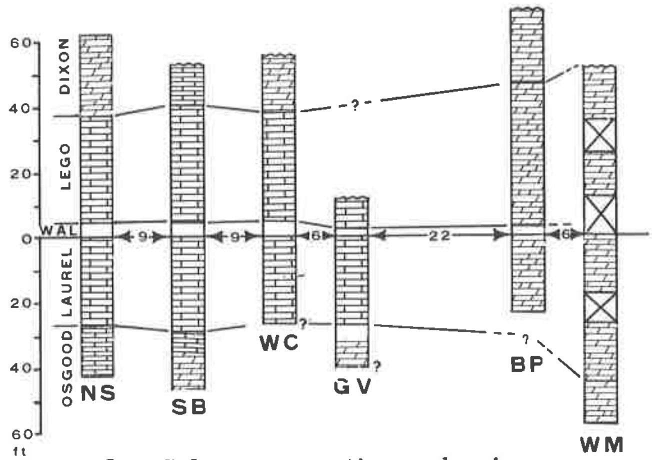


Figure 2. Columnar sections showing gross lithology and thickness relations. Datum is the base of the Waldron Formation. Vertical scale is in feet. The horizontal distance between locations is in miles. Locations are in Figure 1.

Dome-Cincinnati Arch feature appears to have exerted significant control on depositional patterns within the Wayne Group sediments.

Acknowledgments

Field work was supported by the Tennessee Division of Geology, Robert Hershey, Director. Consultation with Division geologists and access to Division documents greatly aided this research. C. W. Wilson, Vanderbilt University generously guided early field work. A Memphis State University Grant for Faculty Research initiated this study.

METHODS OF STUDY

A total of 540 hand specimens were collected, at an average spacing of 1 foot. Spacing was adjusted to include every visible change in lithology. Where beds were thick and of uniform lithology, several evenly spaced specimens were collected.

Thin sections were prepared from each sample and partially or completely stained with Alizarin Red S to facilitate recognition of dolomite. Samples were then examined with the petrographic microscope to determine fabric and dolomite content. The proportions of various components were determined by visual estimates, by comparison with standards prepared after the manner of Terry and Chilingar (1955).

These visual estimates were spot checked by point counts and agreement between the methods was excellent.

Random samples were analyzed for their insoluble residue content by dissolving them in 10% HCl. A complete insoluble residue was not conducted as such data previously have been compiled by Hardeman (1941).

Several samples were analyzed by X-ray diffraction. Only calcite and dolomite peaks were observed. X-ray analysis of the insoluble residues revealed only illite and quartz.

RESULTS

Stratigraphy

The Wayne Group is remarkably homogeneous. Color is uniform, varying from light olive gray to dark greenish gray, with some mottled beds. Identification of individual formations requires good stratigraphic control usually the presence of the readily recognizable Chattanooga Shale or Waldron Shale. The Lego and Laurel are very similar, both have a small insoluble content (< 5%) and consist largely of fine-grained fossiliferous wackestone. The Osgood and Dixon are more argillaceous (< 30% insoluble residue) but in hand specimen they resemble the Lego and Laurel. The Waldron is a very argillaceous dolostone or limestone. Thickness variations (excluding the effects of pre-Chattanooga erosion and covered contacts) are slight (Figure 2).

Sedimentary structures are notably absent. Bedding is uniform and bed thicknesses generally range from 2-20 cm. Individual beds can be traced along outcrop without apparent variation in lithology or thickness.

Petrography

Framework Grains. The only framework grains observed were fossils (no pellets, ooliths, or intraclasts). Echinoderms are dominant with pelmatozoan fragments averaging 20 percent per thin section. Ostracode, trilobite, brachiopods, and bryozoan fragments averaged close to 1 percent each and in some specimens exceed echinoderms. Corals and pelecypods are locally abundant. Sorting is usually poor as the robust crinoid fragments remain whole whereas other fossils are commonly splintered into sometimes unidentifiable laths. Fragments are unworn and, excluding cylindrical crinoid columnal fragments, are sharply angular in most samples.

Matrix. As used here this term covers a wide size range of calcite and dolomite including micrite (1-4 microns) forming a subvisible cloudy brown mass, microspar (4 to 30 microns), barely visible in thin section at 40X, and pseudospar (30 to 70 microns) visibly crystalline

(Folk, 1965). This wide range is grouped together because we suspect they have a common primary origin as fine aragonite and high Magnesium calcite mud that later recrystallized to produce the wide size variation. In general the coarser the crystal size, the more abundant the dolomite.

Spar. As used here this term refers to void filling calcite, a fabric not common in the Wayne. It most often takes the form of rim cement on crinoid fragments although lesser quantities of granular cement were observed.

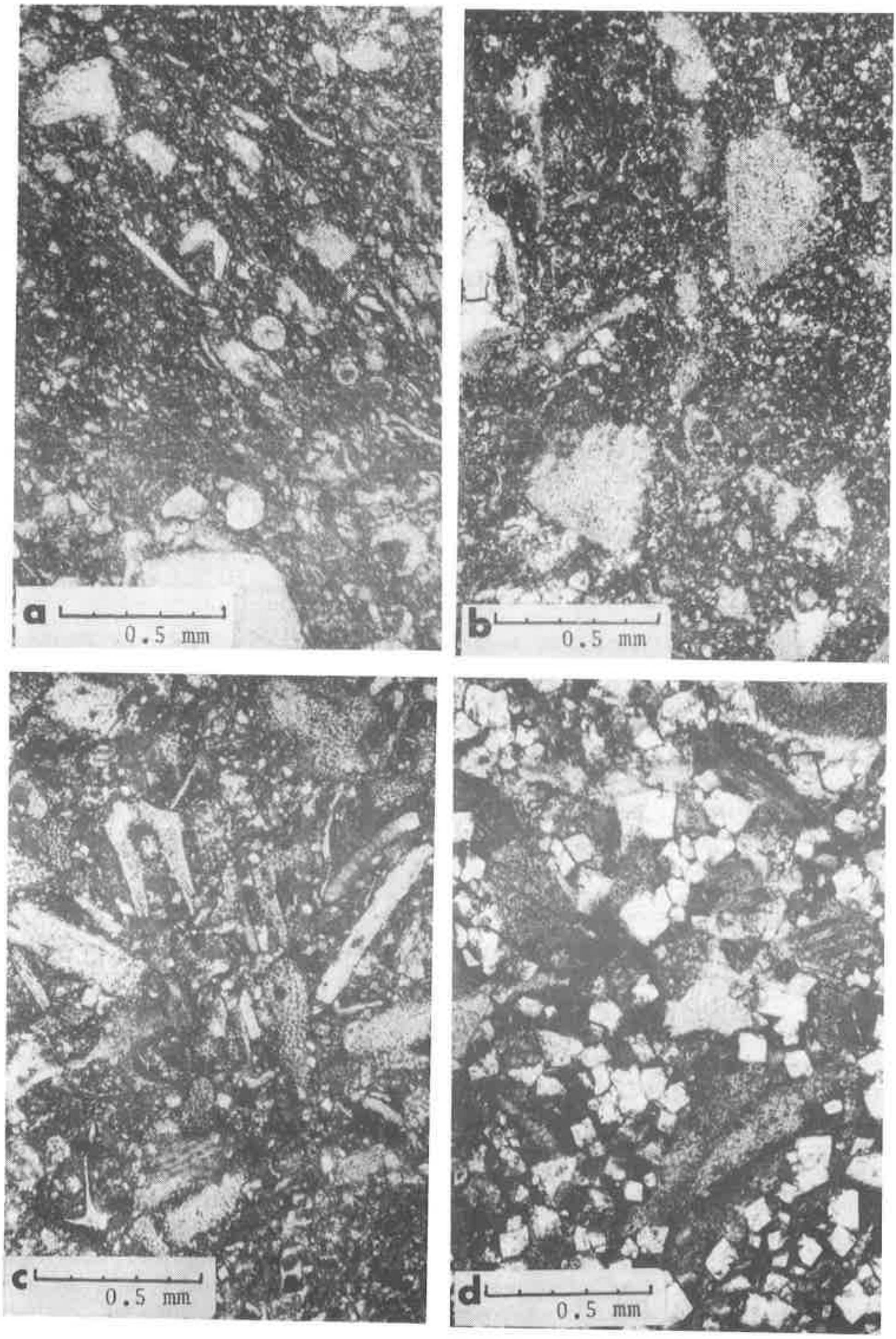
Non Carbonate. Glauconite, as elliptical to somewhat lobate pellets, averages 9.1 percent in the Dixon and Lego (Upper Wayne) and is found in scattered samples from the Waldron, Laurel and Osgood. Pyrite is common and uniformly distributed averaging approximately one percent within each sample. In a few cases pyrite crystals are large enough to be seen in hand specimen. Fine silt-sized quartz is also widely distributed, but seldom exceeds one percent of a sample. Quartz is more abundant in the Dixon than in other units and appears to increase in abundance toward the top of the Wayne. Clays (illite?) are only rarely visible in thin sections.

Facies Types and Significance

The classification of facies types used here follows Dunham (1962). In this usage only three primary facies groups are present in the Wayne although these were refined somewhat in the original analysis, principally on the basis of the amount of dolomite present (Haw, 1974).

Lime Mudstone. Thirty percent of all samples fell into this group. These rocks consist of micrite to microspar with a fossil content of as much as 10 percent. Dolomite is present in most samples, particularly those found in the northeast portion of the study area. In such cases the matrix is sometimes a pseudospar. The initial deposition of the primary lime mud requires a quiet environment and although this could occur in deep water below wave base the presence of normal marine fossil fragments indicates shallow water conditions in which wave and current energy was diminished.

Fossiliferous Wackestone. This rock type constitutes 57 percent of all samples examined (Figure 3-A), consisting of a matrix of micrite to microspar in which fossils range from 10 percent to 40 percent. Dunham (1962) placed the maximum amount of grains at the point where the grains form a three dimensional self supporting framework, noting however, that the percentage varies with grain shape. For consistency, 40 percent was chosen as the upper limit because this value approximates a self supporting framework where shell fragments are abundant. The fossils are poorly sorted with the shell fragments occurring as sharply angular finely comminuted laths. Although burrows were not observed the fossils appear chewed and splintered by scavangers rather than by physical breakdown (Figure 3-A). Dolomite is common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but occurs only in interstices replacing micrite sized calcite (Figure 3-B). In some cases the dolomite cuts into fossil grain boundaries. The dolomite occurs most often as microspar but commonly is a pseudospar.

Fossiliferous Packstone. This lithology forms 13.0 percent of all samples examined (Figure 3-C). Here fossil grains form a three dimensional network in which the interstices are filled with micrite, microspar and sometimes pseudospar. Some samples have cement spar and, although quantitatively insignificant, they are found more commonly to the northeast and in the Lego and Laurel. Presumably they formed during brief spells of unusually high energy (for the Wayne).

Packstone represents higher energy conditions than wackestone as indicated by occasional patches of cement spar, the greater abundance of normal marine fossil fragments and by the somewhat better sorting of the fossil grains. In particular there are fewer fine shell splinters and in the case of samples with spar cement the shell fragments are large and robust with no fine fragments. The lack of sedimentary structures, uniform bedding, the abundance of normal marine fossils, and micrite or micrite derived matrix indicates shallow open marine environment in which wave and current energy was very low.

Dolomite. A plot of the proportion of samples versus percent dolomite in ten percent increments is presented in Figure 4. Note that most of the samples fall in the extreme ranges; i.e. are nearly pure limestone or pure dolostone. This pattern seems to be characteristic of partially dolomitized sequences (e.g. Ronov, 1956, Schmidt, 1965) and implies that the process of dolomitization, once begun, tends to go

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Figure 3. Photomicrographs of selected samples. A. Fossiliferous Wackestone. Micrite supported fossil fragments many of which have been splintered into silt size, unidentifiable fragments. Lego Formation at McCory Lane (31A). No dolomite, 22% fossils, unstained, uncrossed nicols. B. Partially dolomitized Fossiliferous Wackestone. Fossil fragments, dominantly echinoderm, embedded in a micrite mass. Nichols are uncrossed and the slide is stained hence the light colored flecks and rhombs in the micrite are dolomite. Laurel Formation at Scottsboro (11A), 20% dolomite. C. Fossiliferous Packstone. An unordered framework of splintered and angular fossil fragments with the intersticies filled with micrite. Echinoderms dominate bryozoan, ostracod and brachiopod fragments. Scattered silt size quartz is also visible. Dixon Formation at Newson Station (9A). Uncrossed nicols 50% fossils, 0% dolomite, stained. D. Partially dolomitized Fossiliferous Packstone. Large clear unzoned dolomite rhombs are growing at the expense of interstial micrite and have cut into fossil fragments. Laurel Formation at Scottsboro (11B). Uncrossed nicols, stained, 35% dolomite, 47% fossils.

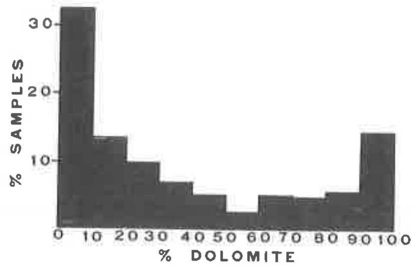

Figure 4. Histogram of the proportion of samples versus abundance of dolomite. Note the bimodal nature with the bulk of samples appearing in the extreme groups.

to completion. The dolomitic limestones, i. e. samples containing from 10 to 90 percent dolomite, are clearly altered from limestone (Figure 3). There is a clear inverse relation between fossil content and dolomite is confined to the matrix portion of the fabric and rarely alters fossils (Figure 3-D). In some cases the dolomite is clearly secondary with euhedral rhombs that are large enough to be visibly zoned but in other cases the dolomite is a blur of micrite and microspar and can only be recognized with the aid of strains of x-ray diffraction.

Facies Variation

Limestone Facies. In view of the fact that only two fabric components make up virtually 100 percent of all Wayne samples (fossils and micrite) facies variation can be effectively illustrated by plotting only one component. Figure 5 presents a bar graph of percent fossils in each formation at each location on a sample by sample basis. It can be seen that the percentage of fossils within each formation at each location is fairly uniform and variation is apparently random. However, there is an overall trend in fossil content in the Wayne; fewer fossils (i. e. lower energy facies) toward the top, the bottom and to the northeast. In addition spar becomes more common in fossiliferous packstone samples to the northeast. This is accompanied by an increase in grain size related to an increase in relative abundance of robust shell fragments; probably the result of the removal of finely splintered material. This combination of generally low energy facies and abundant fossils with patches of relatively high energy fabric suggests very shallow water conditions with scattered storm generated high energy situations.

Dolomite Variation. Figure 6 presents the variation in the dolomite content of the micrite portion samples from each formation at each location. Note that the dolomite pattern is a reversal of the fossil pattern. There is an increase in dolomite content toward the top and

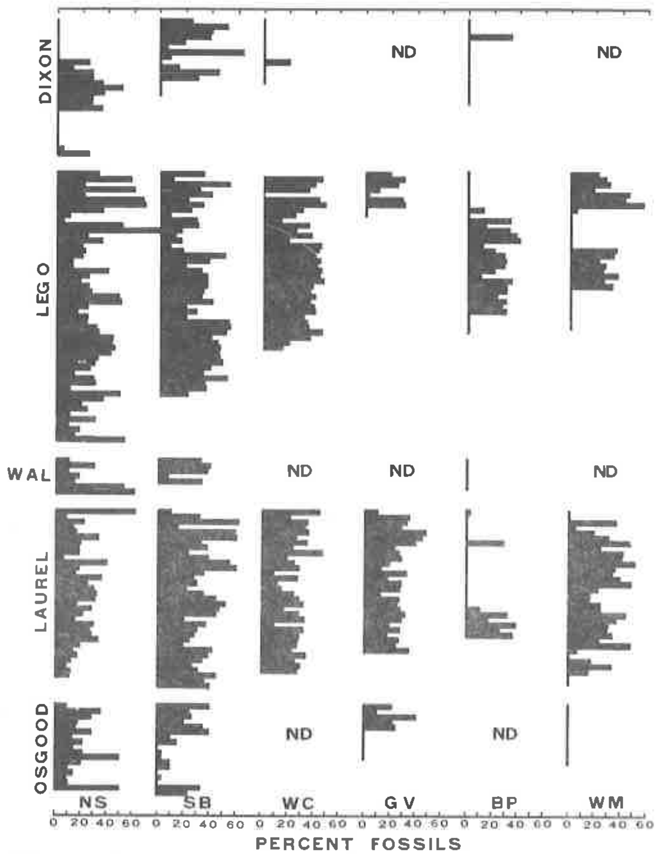

Figure 5. Bar graph of the proportion of fossils in each sample in each formation at each location. ND indicates no data. Although the data are on a sample by sample basis the vertical length the graph is proportional to the thickness of the formation.

bottom of the Wayne and an increase toward the northeast outcrop locations. This implies that the facies in the top and bottom formations (Dixon and Osgood) formed in the same environment as facies deposited in the Middle Wayne (Lego and Laurel) to the northeast. The Waldron facies seem to parallel the Lego and Laurel but there are too many gaps to be certain.

There is also an apparent increase in the size of dolomite crystals toward the northeast. This was not evaluated quantitatively owing to the difference in the dolomite character. To the southwest it is dominantly clearly visible rhombs whereas to the northeast it is dominantly a blur of interlocking grains.

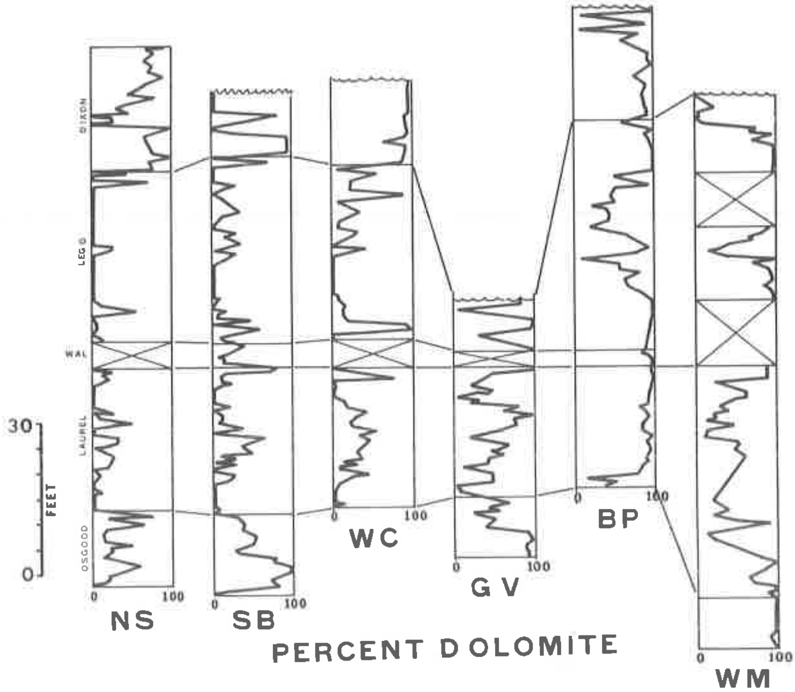

Figure 6. Graph of the proportion of dolomite in the matrix fraction of each sample in each formation at each location. Note that although the dolomite proportion varies randomly within each formation there is a noticeable trend to more dolomite to the northeast (right) and toward the top and bottom units.

Figure 7 illustrates the abrupt nature of the increase in the overall dolomite content in the Lego and Laurel Formations.

DISCUSSION

A comparison with the correlative St. Clair Limestone, a reef bearing, oil productive formation of the Illinois area is instructive (Lowenstam, 1949). Like the Wayne the St. Clair has a high dolomite content and some units are dolostones. The reef belt averages 15-20 percent clastic content, i. e. similar to the Wayne. The thicknesses in the Illinois Basin are greater, 100-600 ft., but reefs, although less common, are found in the thin portions as well as the thick. As in the Wayne, glauconite is present and chert is absent. Projection of the Illinois Basin reef trends into Tennessee is not possible due to lack of

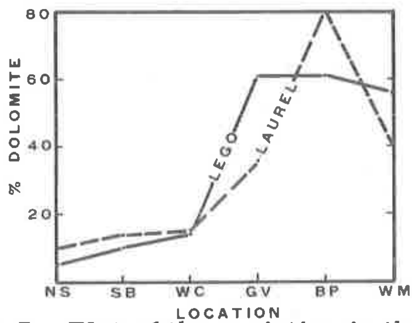

Figure 7. Plot of the variation in the dolomite proportion of the Lego and Laurel formation as a function of location.

sufficient subsurface data in the intervening area. It is apparent that there are similarities between the two areas and presumably the Wayne of Tennessee may have similar porous facies.

The potential for such porous facies in the Wayne cannot be proven with the small number of sections so far studied but there is such a possibility. The question in where to look for such development, to the west or to the east? The choice depends largely on the selection of the appropriate model for Wayne Group deposition, the carbonate ramp (Ahr, 1973) or the carbonate shelf (many authors including Ginsburg, 1957). In the ramp model the high energy reef facies is found down dip at the shelf edge. The limited geographic area of this study precludes a definite answer; however we slightly favor the ramp model for the Wayne. This is supported by the observation of normal marine fossiliferous micrite to the west that rapidly grades into dolomitic micrite to the east (Figure 7). High energy facies may occur to the northeast. One cannot preclude the presence of a reef zone along a shelf edge somewhere to the west of the Tennessee River where the Wayne is covered by the Cretaceous coastal plain overlap. Further study is needed.

CONCLUSIONS

The Wayne Group area studied here is dominated by low energy micrite-charged facies, 57 percent fossiliferous wackestone, 30 percent lime and dolomite mudstone and 13 percent fossiliferous packstone. There is an overall tendency toward lower energy facies in the upper and lower Wayne (Dixon and Osgood) and toward the northeast.

The absence of any sedimentary structures, the uniformity of bed thickness, unabraded fossil and low energy facies all point to quiet water deposition. The normal marine fossils indicate shallow water.

The abundance of dolomite toward the northeast implies a very shallow, possibly hypersaline environment in that direction.

Dolomite is present exclusively in the micritic portions of samples and some specimens are classified as a dolostone. The proportion of dolomite increases toward the top and bottom of the Wayne and toward the northeast. This may be interpreted as the result of a single transgressive-regressive phase in which the Osgood (lower Wayne) represents the nearshore transgressive phase and the Dixon (upper Wayne) represents a nearshore regressive phase.

The area of the Wayne Group studied here shows marked similarities to age equivalent rocks in the Illinois area, however, the Wayne has lower energy facies and lacks known reef buildups. High energy porous facies may exist to the southwest at a possible shelf edge zone or less possibly to the northeast at a shore zone.

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MORPHOLOGY OF THE MIDDLE ATLANTIC U. S. CONTINENTAL SLOPE AND RISE

By

Bonnie A. McGregor
Atlantic Oceanographic and Meteorological Laboratories*
National Oceanic and Atmospheric Administration
Miami, Florida 33149

ABSTRACT

The continental margin off the Delaware and Maryland coast between Baltimore and Washington Canyons has a different morphology from that of adjacent regions of the U. S. east coast continental margin. A series of ridges extends down the continental slope to the rise, perpendicular to the margin. Seismic reflection profiles parallel to the margin were obtained to determine the internal structure of the ridges, and the processes that may have been active in their formation. A 600-800 m thick sequence of stratified sediment is present on the slope with many unconformities. Numerous periods of deposition and erosion are believed to have been responsible for forming the morphology of this area. Levee or large submarine slide origin, though implied by the morphology, are not supported by the seismic reflection profiles.

INTRODUCTION

The U. S. east coast continental margin off the Delaware-Maryland coast and seaward of the Baltimore Canyon Trough between Washington and Baltimore Canyons displays a different morphology and a varied depositional environment when compared with other slope regions from Georges Bank to Cape Hatteras. A series of broad ridges extends down the continental slope to the upper rise (Figure 1). The continuation of profile 3 (Figure 1) along the slope from south of Hudson Canyon to south of Norfolk Canyon shows the change in morphology between Washington and Baltimore Canyons (Figure 2). Adjacent portions of the slope, north of Baltimore Canyon and south of Washington Canyon, have a dissected morphology with many small, closely spaced valleys. Between Washington and Baltimore Canyons large, broad ridges are present on the slope.

Using the NOAA ship RESEARCHER, five seismic reflection

*Present address: Department of Oceanography
Texas A&M University, College Station, TX 77843

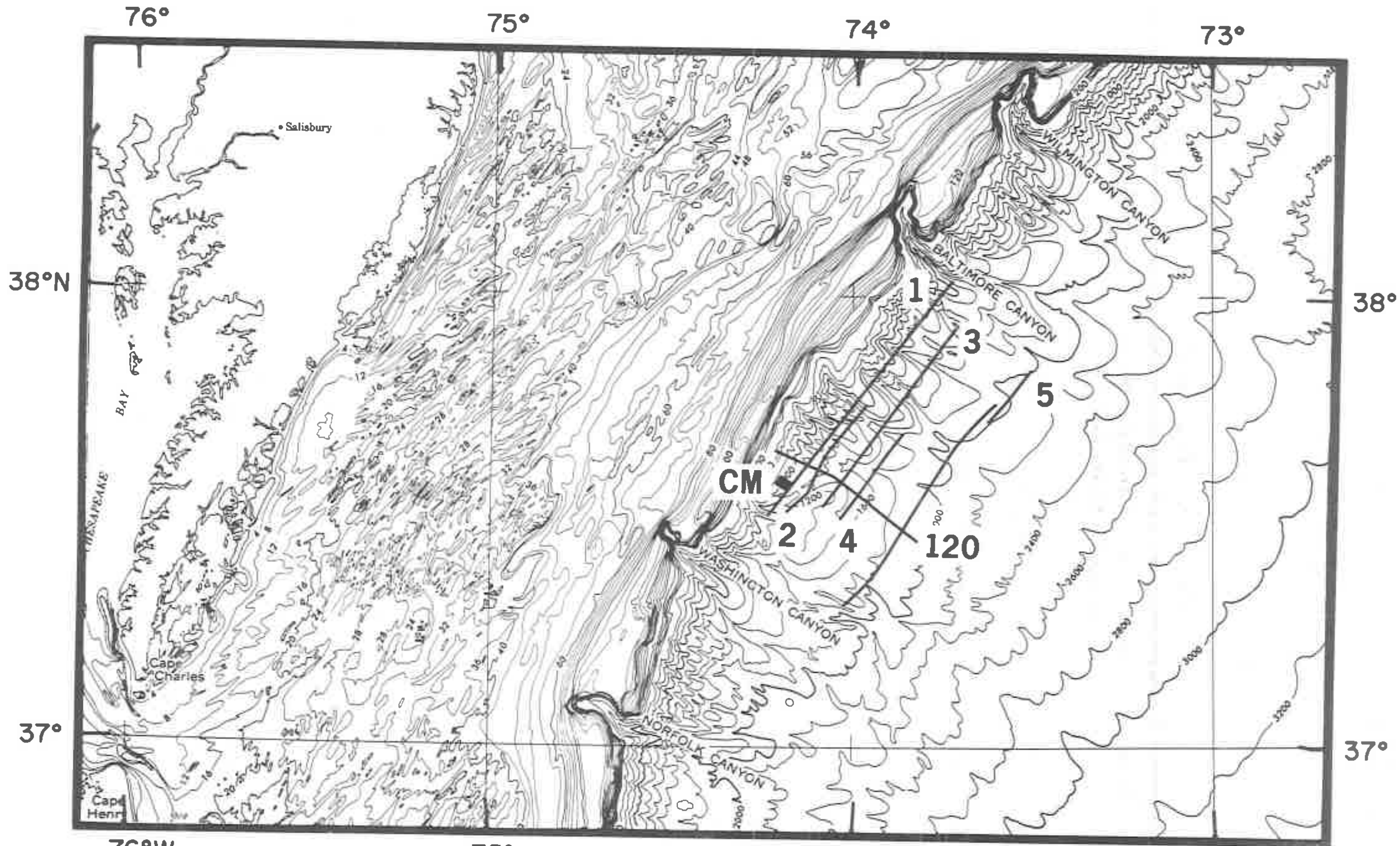

Figure 1. Bathymetric map after Uchupi (1970) with location of seismic reflection profiles. Numbers are profile designations for Figures 2 through 8. CM is current meter location.

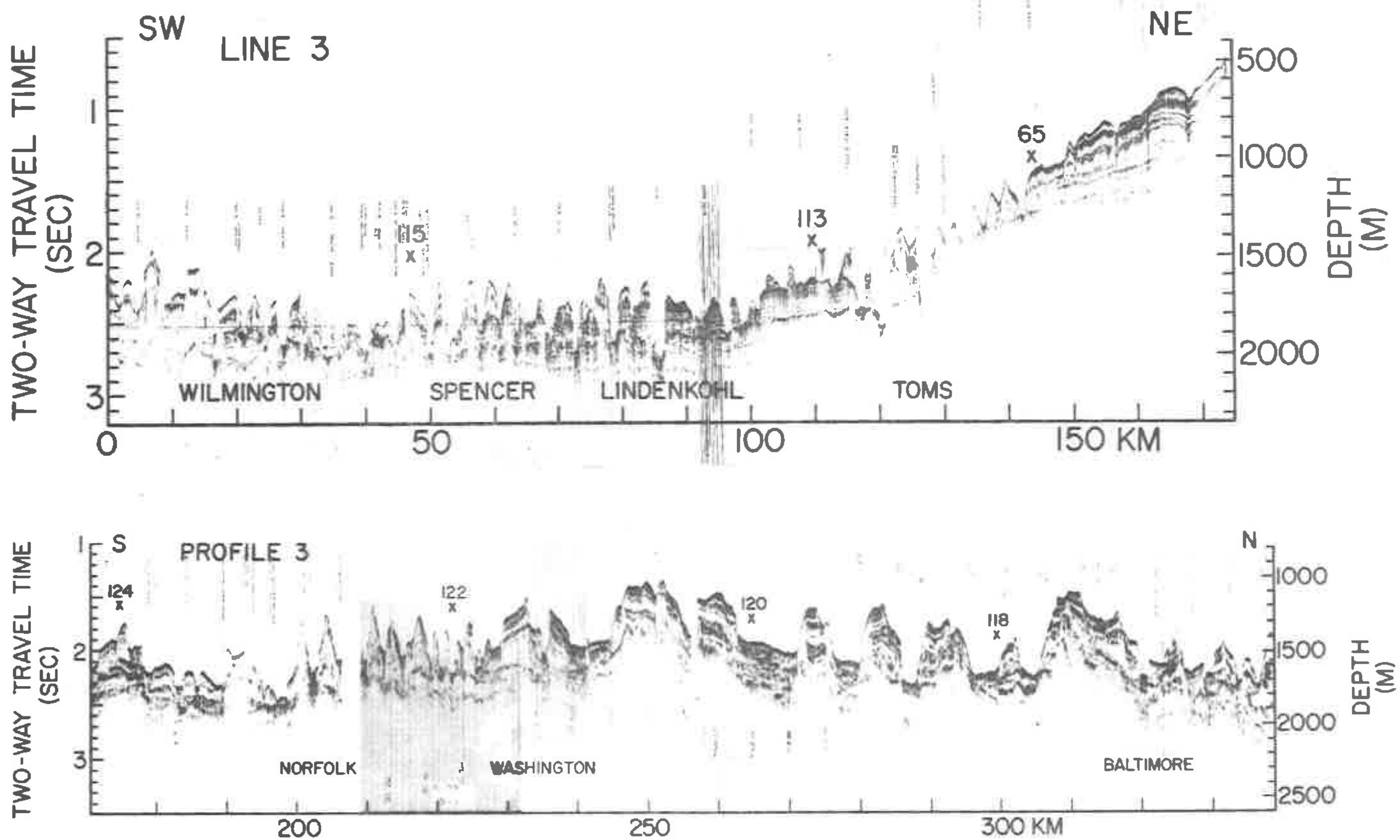

Figure 2. Seismic reflection profile parallel to the continental margin from just south of Hudson Canyon to south of Norfolk Canyon. The track is an extension of line 3, Figure 1. X's and numbers refer to crossing profiles of Uchupi and Emery (1967).

profiles were run parallel to the margin along the slope and rise (Figure 1) to determine the internal structure of the ridges that trend perpendicular to the margin and to characterize their origin and the processes that have been active during their formation. The seismic system used as sound sources 160 cc (10 in^3), 640 cc (40 in^3), and/or 1920 cc (120 in^3) air guns depending on water depth. The firing rate was approximately seven seconds with 1800-2000 psi air pressure in the guns. A 50-element hydrophone was used as a receiving unit, and a recorder displayed the data. The return signal was filtered at 140-430 Hz except for profiles 2 and 4 which were filtered at 63-160 Hz. Photographs of the original records are shown in Figure 3 through 7.

A Savonius rotor current meter was planted on the slope 3 m above the bottom in 910 m of water (Figures 1 and 3) and obtained records for a 14 day period, September 3-17, 1975.

Acknowledgments

I wish to thank George H. Keller and Richard H. Bennett for assisting in the data collection and for reviewing the manuscript. I am grateful to John W. Kofoed for also reviewing the manuscript. Thanks also to the officers and crew of the NOAA ship RESEARCHER for their assistance in gathering the data during March, April, and September, 1975. This work was supported by the National Oceanic and Atmospheric Administration.

SEISMIC REFLECTION PROFILES

The morphology and sedimentary framework of the continental slope changes with water depth. The ridges are well developed between the depths of 1200 and 1500 m (Figures 3-4). Maximum subbottom penetration is approximately 800 m assuming the same sound velocity as in water. The sedimentary section is well stratified with many unconformities throughout. Few reflecting horizons are shown within the upper 400 m of the sea floor on profile 1 (Figure 3), because multiples and width and character of the outgoing signal mask the return from any horizons present. At depth the reflecting horizons on the upper slope (profile 1) appear to be rather continuous. Crossing profiles 120 and 118 of Uchupi and Emery (1967) can be used to approximately line up the profiles.

Profile 2 (Figure 4), located about 3. 5 km seaward of profile 1, shows a thick sequence (700 m) of stratified sediment with many unconformities. The width of the ridges and intervening valleys has increased. The slope is smoother in surface expression south of profile 120 with a decrease in relief from 150 m to 50 m. In general the slope is not dissected by as many valleys as on profile 1. Small scale slumping has occurred on the north side of the ridges. The stratified sequence

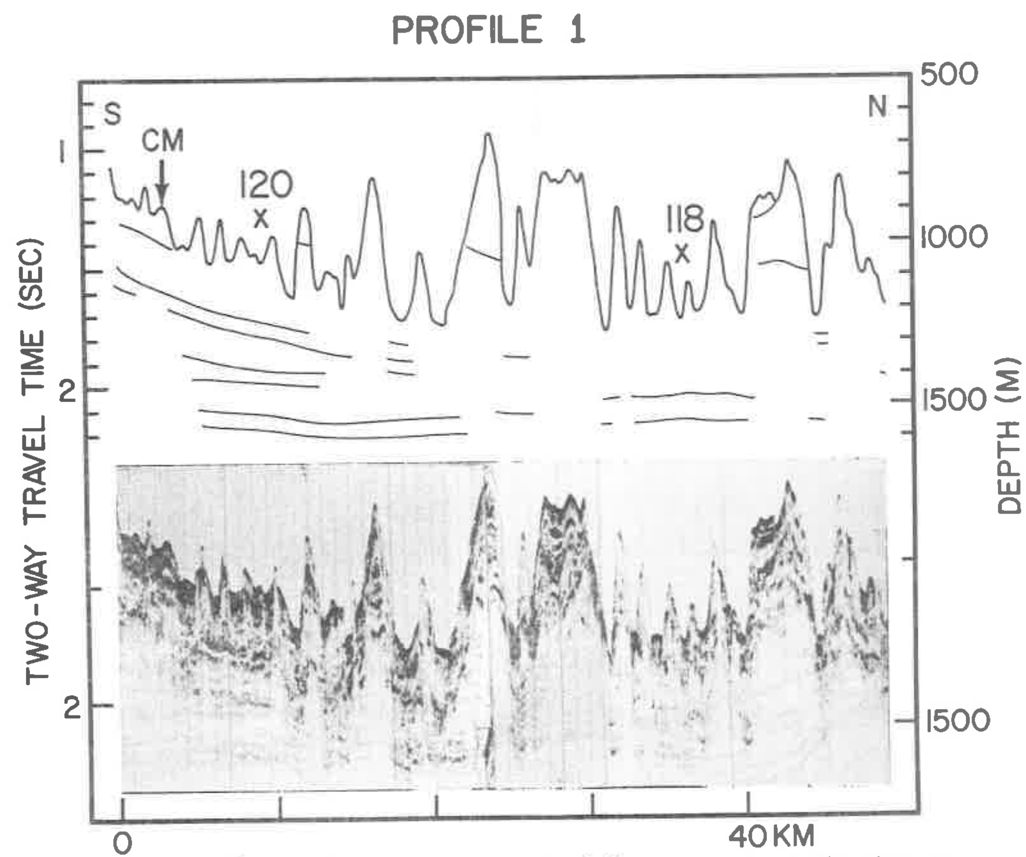

Figure 3. Line drawings and photographs of original seismic reflection records for profile 1. Both 10 and 120 in^3 air guns were used as the sound source. See Figure 1 for location. CM indicates current meter location. "X"s and numbers refer to location of crossing profiles of Uchupi and Emery (1967).

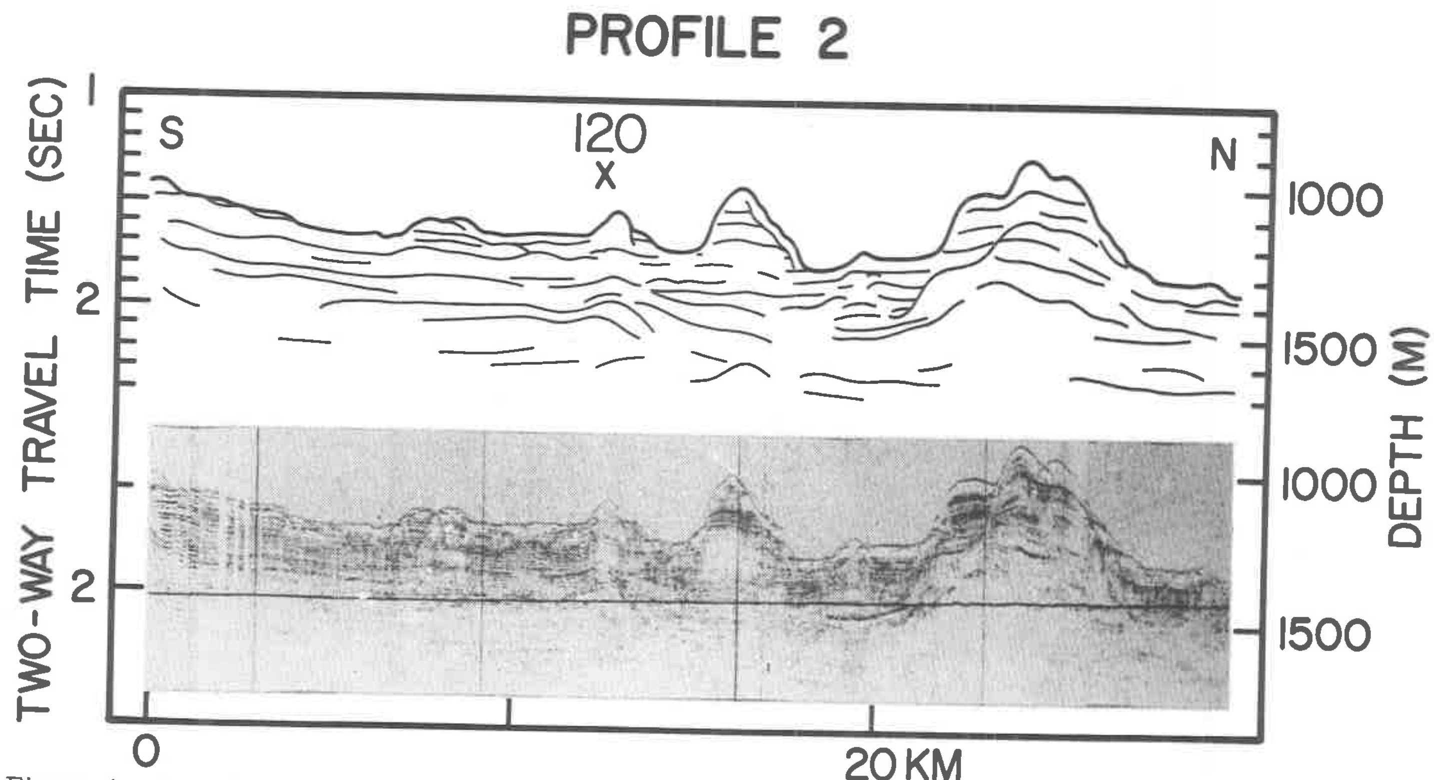

Figure 4. Line drawings and photographs of original seismic reflection records for profile 2. A 40 in^3 air gun was used as a sound source. See Figure 1 for location. "X"s and numbers refer to location of crossing profiles of Uchupi and Emery (1967).

of reflectors 100 m below the surface in the ridge at kilometer 16 appears to correlate with the sequence 100 m below the surface in the ridge at kilometer 23 based on the nature of the reflecting horizon and its subsurface level. Except for this example, the reflecting horizons within the ridges are not correlatable between the ridges. At approximately 500 m beneath the ridges reflecting horizons are much more continuous.

Uchupi and Emery's profile 120 (Figure 8), transverse to the slope, crosses the topography obliquely (Figure 1) (along a ridge on the upper slope, across a valley on the mid-slope, and across the end of a ridge on the lower slope). The reflecting horizons are continuous normal to the margin.

Farther down slope the ridges are more clearly developed on profile 3 (Figures 2 and 5). A thick sequence of stratified sediment with unconformities is present in the ridges. The ridges appear asymmetric in shape with a smoother side on the south and slumping on the north side making the slope more irregular. Reflecting horizons cannot be correlated between the ridges, however, depositional and erosional events must be coincident over such a small area.

On the lower slope and upper rise the ridges have subdued relief (profiles 4 and 5, Figures 6 and 7), however, stratified sediments are still present. The morphology of the continental margin changes as one goes seaward down the continental slope to the rise from a dissected upper slope with many small valleys, to a pronounced ridge and valley sequence, to an irregular but subdued rise. Little hint of this morphology change is shown on profile 120 (Figure 8), however, erosion is indicated by truncation of horizons at the sea floor.

Records of the shallow sediment pattern were also made using a 3.5 kHz sound source along profiles 2 and 4. Stratification shown in profile 4 (Figure 6) can be extended to the upper 70 m of sediment along much of the profile with some thinning of layers on the north side of the feature near crossing profile 120. On profile 2, buried irregular surfaces are present in the upper 70 m of sediment in the topographic lows. Truncation of internal reflectors at the sea floor on the south side of the ridges at km 16 and 21 (Figure 4) is confirmed on the 3.5 kHz record, indicating erosion or lack of sediment accumulation on the south facing slopes. The north slope of both ridges has an irregular surface and is suggestive of small scale slumping.

The age of the sediments shown in the profiles can only be inferred from correlation with drill hole data. Data from DSDP site 108 (Hollister et al., 1972) on the continental slope 170 km to the north, 4 km southeast of crossing profile 113 (Figure 2) dated the strong reflector at 2.5 s as Eocene and the continuous horizon at 2.8 s is believed to be late Cretaceous. Kelling and Stanley (1970) and Uchupi and Emery (1967) believe the continental margin in this area is composed of Tertiary sediments, with canyon erosion in the vicinity of Baltimore Canyon occurring during the Tertiary. A major unconformity shown

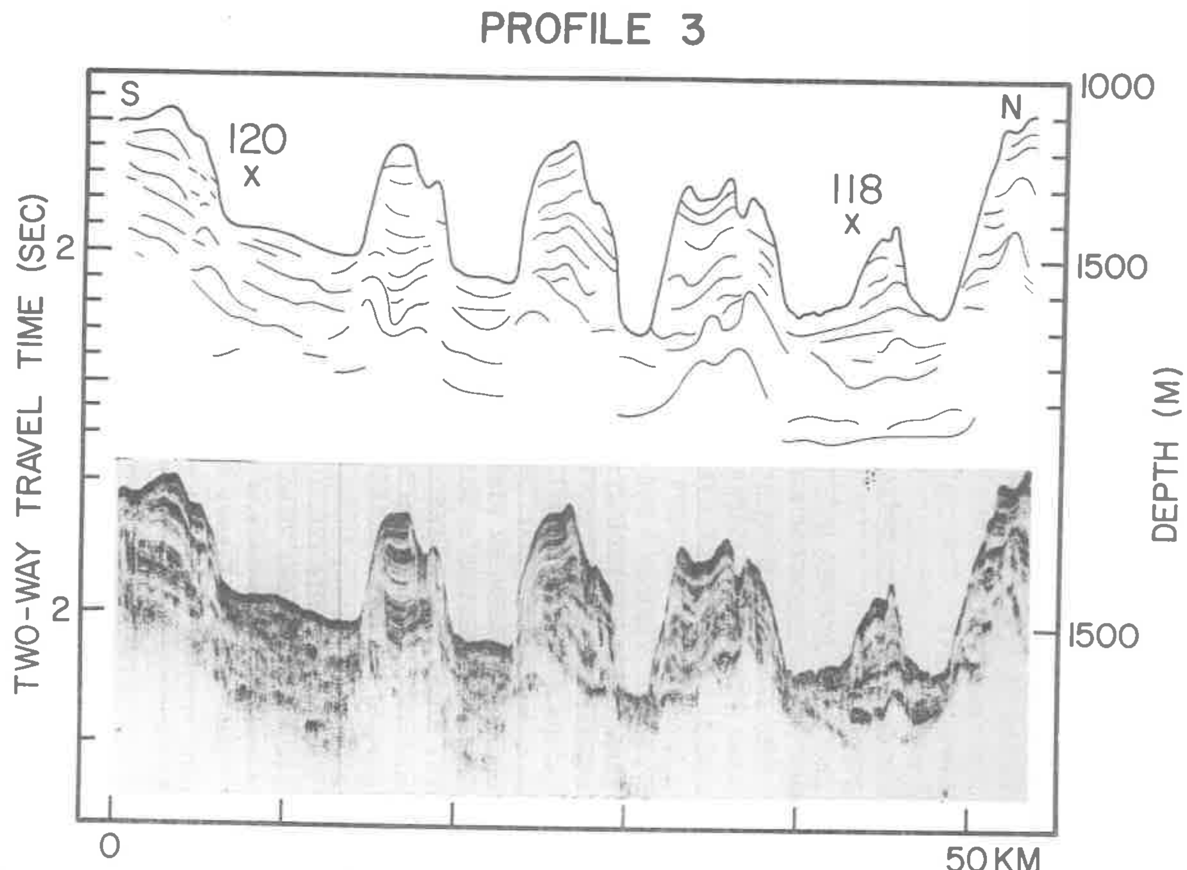

Figure 5. Line drawings and photographs of original seismic reflection records for profile 3. Both 10 and 120 in^3 air guns were used as the sound source. See Figure 1 for location. "X"'s and numbers refer to location of crossing profiles of Uchupi and Emery (1967).

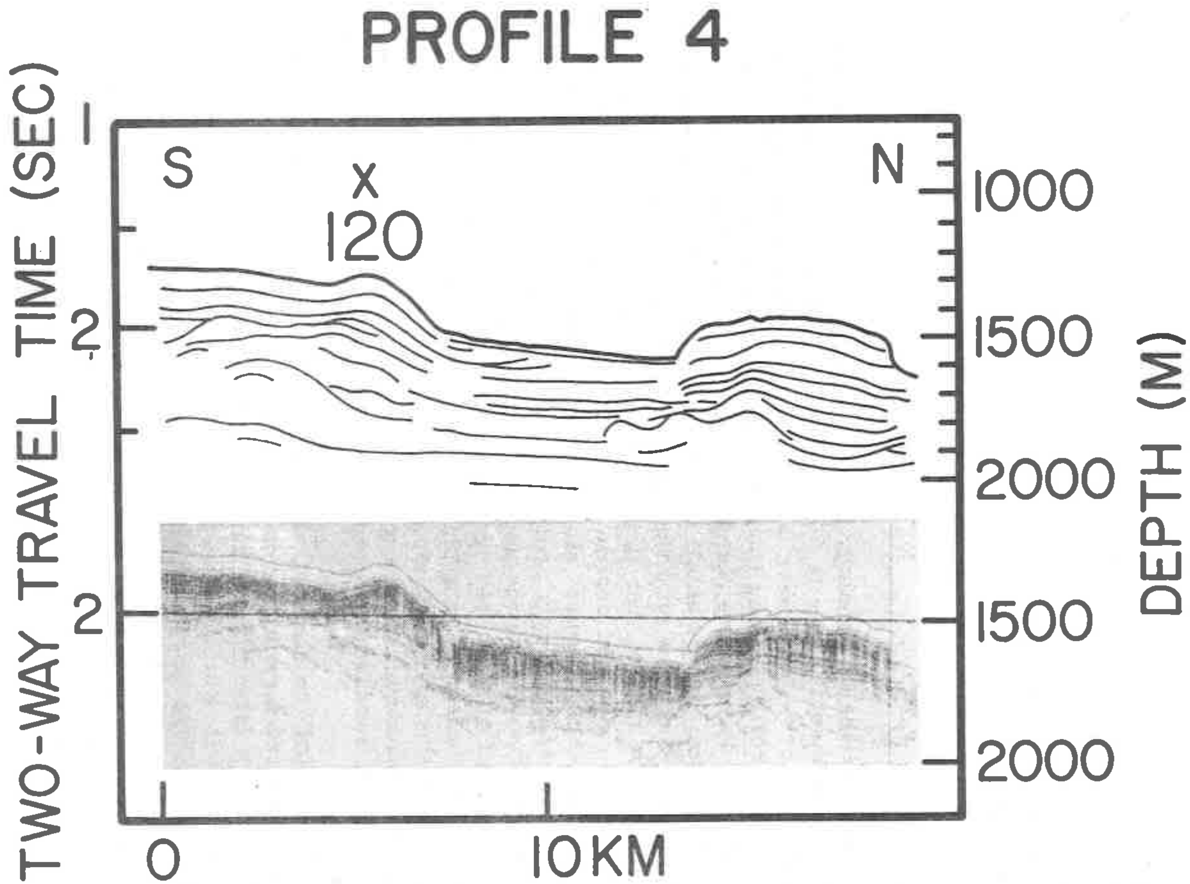

Figure 6. Line drawings and photographs of original seismic reflection records for profile 4. A 40 in^3 air gun was used as a sound source. See Figure 1 for location. "X"s and numbers refer to location of crossing profiles of Uchupi and Emery (1967).

on profile 120 is reported by Uchupi and Emery (1967) to be within the Tertiary followed by renewed deposition and subsequent erosion (Figure 8). To the north on the slope near Wilmington Canyon a 200 m thick sediment accumulation is believed to be Pleistocene in age (McGregor and Bennett, 1977). Because the ridges are composed of sediment over 500 m thick, it is inferred that some of this sediment must be Tertiary in age. However, if the sediments are younger than Tertiary, then this region has had a significantly different sediment accumulation pattern from the Pleistocene to recent than adjacent portions of the continental slope.

DISCUSSION

Because the morphology of the Delmarva portion of the middle and lower continental slope is different from adjacent slope areas (Figure 2) the processes that have been and are active in shaping it are of interest. On profile 1 along the upper slope, the morphology is similar to that found in other areas along the Atlantic continental margin with dissection of the slope by small valleys. In most areas this morphology continues down the slope onto the upper rise. Some stratification may be present in the ridges, but it cannot be resolved. The frequency of the valleys and ridges on profile 1 is greater than on profile 3 (Figures 3 and 5) indicating the upper slope is more dissected than the mid-slope. Uchupi and Emery's profile 120 (Figure 8) also shows that erosion is more extensive on the upper slope. Profiles 2 and 3 show broad ridges composed of stratified sediment. The ridges have remained in approximately the same location with only slight migration and just built upward with time. Farther offshore (profiles 4 and 5) the morphology and internal structure are again similar to that found on the rise off other areas; subdued topography and continuity of horizons parallel to the margin.

Comparing the slope off the Delmarva coast with other areas shows similar and dissimilar characteristics. The Nova Scotian slope seaward of Sable Island Bank has a scalloped topography (Stanley and Silverberg, (1969) which is similar in appearance on contour maps to the continental slope between Baltimore and Washington Canyons. The valleys which trend down slope are rounded rather than V-shaped (Stanley and Silverberg, 1969), which is the same characteristic of the Delmarva slope except for profile 1 (Figure 3) where the valleys are V-shaped. The topography of the Nova Scotia slope is attributed to mass gravity processes (Stanley and Silverberg, 1969) because sub-bottom profiles reveal large slide blocks on the lower slope and rise. In the Delmarva area the sub-bottom profiles (Figures 3-7) show unconformities within and beneath the ridges. No strong continuous reflector is present to indicate the slip surface, as was the case of a submarine slide on the slope northeast of Wilmington Canyon (McGregor and

Bennett, 1977). Massive gravity sliding does not seem to be a major process which has been active in this area. Small scale slumping, however, is present on the ridges as shown on the seismic records.

The seaward extensions on the rise of most of the U. S. east coast canyons have large levees (Pratt, 1967). Figure 2 shows the levees associated with some of the major submarine canyons, such as those of Washington and Baltimore Canyons. Both canyons are flanked by stratified sediment masses containing many unconformities. The levees are asymmetric in cross section with the steeper side facing the canyon which is V-shaped, and the larger, higher levee is on the right as one looks down slope. The right side looking down slope of the U. S. east coast canyons usually has the larger levee and the valleys tend to migrate and hook to the left, because of the Coriolis effect (Menard, 1955; Komar, 1969; Stanley et al., 1971). The ridges on the Delmarva slope have some characteristics in common with levees. The trend normal to the slope and are composed of stratified sediments with many unconformities. Their cross-section is asymmetric. The valleys between the ridges tend to bend slightly to the left looking down slope, implying down slope flow (Figure 1 and Veatch and Smith, 1939). The major leveed canyons have shelf valleys and are or were part of major drainage systems (Swift and Sears, 1974). No evidence of a major drainage system is present on the shelf adjacent to the slope between Baltimore and Washington Canyons, however, the Delaware valley and associated mid-shelf delta are present near the northern part of this portion of slope (Swift and Sears, 1974), and Twichell et al. (1977) have traced the Delaware River valley across the shelf to Wilmington Canyon. Arkosic sediments present on the slope are believed to have been deposited by the Delaware River during the last Pleistocene low stand of sea level (Milliman et al., 1972). A large levee-like ridge is present on the south side of Baltimore Canyon between kilometer 310-320 (Figure 2), and although larger is similar to the ridges on the slope further south between kilometer 250-300. The unconformities in the ridges (Figures 3-7) show they have migrated slightly while building upward similar to what one would expect in a levee. The ridges die out on the rise (profiles 4 and 5; Figures 6 and 7) sooner than the levees of adjacent submarine canyons (Stanley et al., 1971). Although the morphology has some similarity to canyons and levees, it also is dissimilar. The canyon valleys of Baltimore and Washington between the levees are narrow and V-shaped (Figure 2), whereas the valleys between the ridges on the slope between these two canyons are broad and U-shaped. From the number of ridges, five valleys are inferred, yet none of the ridges looks like a levee pair except possibly the ridges at kilometer 285 and 290 (Figure 2). A levee-like ridge adjacent to Wilmington Canyon called the Nyckel Ridge (Stanley and Kelling, 1970) is similar in morphology and internal structure to the ridges discussed here. Stanley and Kelling (1970) believe the Nyckel Ridge is not a levee, although similar in morphology, but rather is structural in origin

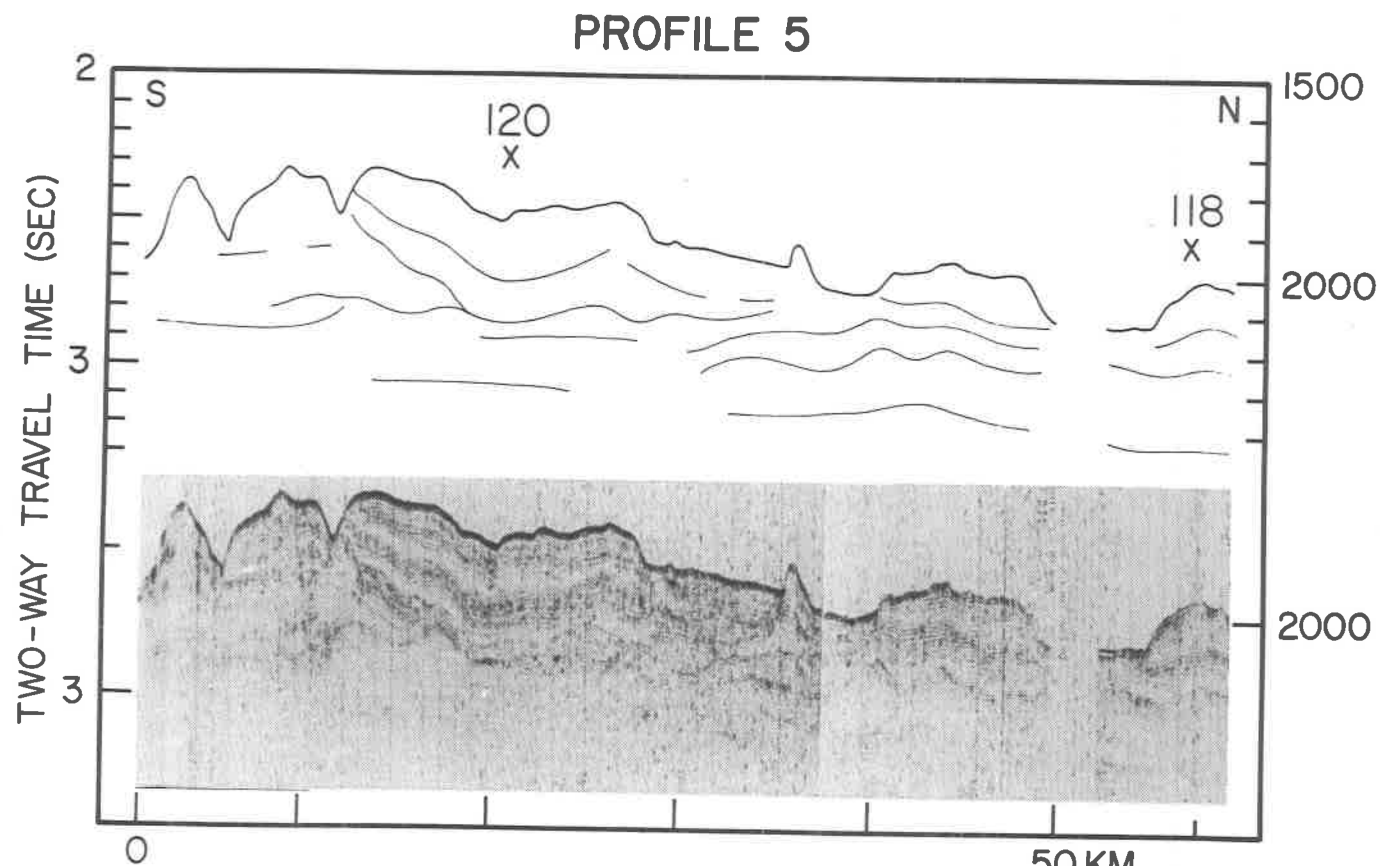

Figure 7. Line drawings and photographs of original seismic reflection records for profile 5. Both 10 and 120 in^3 air guns were used as sound source. See Figure 1 for location. "X"s and numbers refer to location of crossing profiles of Uchupi and Emery (1967).

PROFILE 120

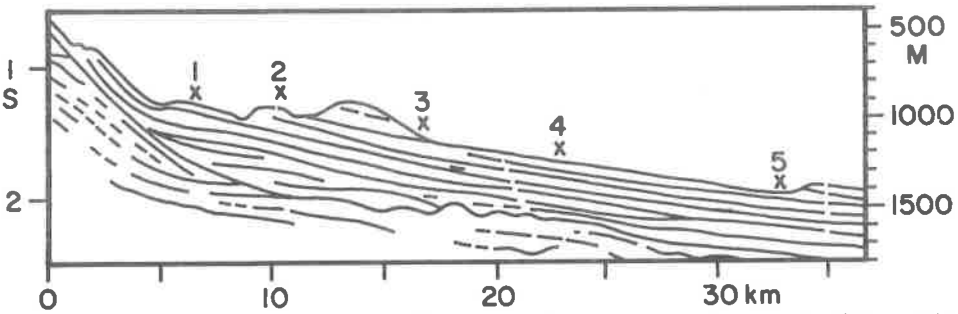

Figure 8. Portion of profile 120 from Uchupi and Emery (1967). X's show crossing locations of profiles in Figures 3 through 7.

composed of faulted pre-Quaternary consolidated rock. Their seismic reflection profiles over the Nyckel Ridge are similar in appearance to the ridges in profile 1 (Figure 3).

Bottom current activity is a process responsible for many bedforms such as the morphology of the rise (Zimmerman, 1971; Heezen et al., 1966; Schneider et al., 1967). Currents have been found just south of this area off Cape Hatteras having both a northward and southward flow along the margin at the intersection of the slope and upper rise (Richardson and Knauss, 1971; Barrett, 1965). These currents have been found by Betzer et al. (1974) to also be transporting relatively large quantities of suspended matter. The current meter data for September 3-17, 1975 (see Figures 1 and 3 for meter location), showed very low velocities with a maximum of 10 cm/sec. Flow was primarily tidal with up and down slope motion. Such a short duration record does not adequately predict the velocity or flow direction one might expect on the slope in this area.

SUMMARY

From seismic reflection data, a varied sedimentation history has characterized the continental margin seaward of the Delmarva area which is different in morphology than adjacent portions of the middle and lower continental slope. Neither large submarine slides nor levees are able to account for the morphology and stratigraphic framework of this area. A large volume of sediment from the Delaware and possibly Chesapeake Bay drainage systems has been deposited on the continental margin in this area under the influence of varied bottom processes since reflecting horizons are not flat nor can they be traced laterally over any distance. Alternating periods of erosion and deposition have occurred with the buildup of the ridges in approximately the same

location through time. Erosional processes including slumping, bottom currents, and possibly turbidity currents must have been active in shaping the morphology of the slope. More extensive study and measurements are necessary to determine if and at what rate these processes are occurring on the margin today and if not active today what environment in the past was conducive to the formation of this morphology.

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