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Abstract

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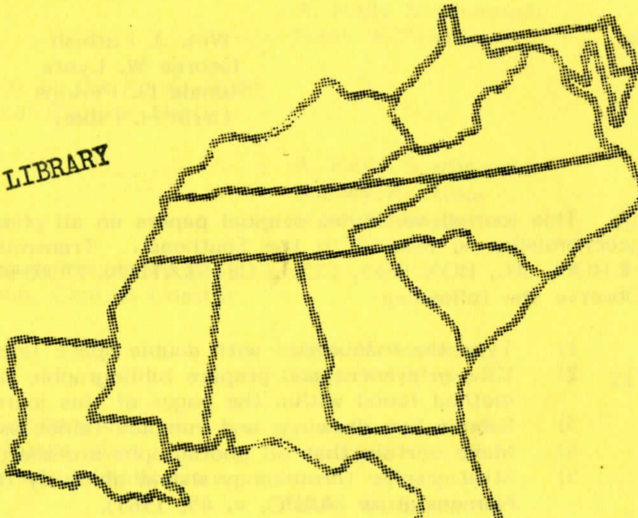

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SOUTHEASTERN GEOLOGY

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CYCLIC DEPOSITION OF NEOGENE PHOSPHORITES IN THE AURORA AREA, NORTH CAROLINA, AND THEIR POSSIBLE RELATIONSHIP TO GLOBAL SEA-LEVEL FLUCTUATIONS

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ABSTRACT

The Neogene phosphorites in the Aurora Area occur within the Miocene Pungo River Formation (units A, B, C, and D) and the Pliocene Yorktown Formation (lower and upper units). These units are characterized by the following patterns of sedimentation. 1) Three major erosional unconformities and four minor unconformable surfaces or hiatuses mark the boundaries between consecutive units and the under- and overlying formations. 2) Indurated carbonate sediments, which usually contain either a weathered fossil assemblage or are completely moldic, cap each unit. The carbonate surfaces locally contain a rock-boring infauna and are often phosphatized. 3) Phosphate sedimentation began in unit A and increased to a maximum through unit C, was negligible in unit D, was reinitiated in the lower Yorktown, and was nonexistent in the upper Yorktown. 4) Phosphate concentration generally increases upward within each unit until carbonate sediments become important, then the phosphate decreases. 5) The dominant carbonate within each unit is as follows: units A and B, dolosilt; unit C, calcitic micrite; unit D, dolosilt with abundant calcite shell material; and both Yorktown units, calcitic micrite with abundant calcite shells.

This sequence of upper Tertiary sediment units suggests a cyclical pattern controlled by global eustatic sea-level fluctuations. Each depositional unit, its carbonate cap, and the associated unconformable surfaces may correlate with established third-order sea-level cycles of Vail and others (1977 and 1979). Units A, B, and C appear to represent the maximum transgressive portion of the second-order Miocene supercycle. Phosphate sedimentation was coincident with each of the third-order transgressions, which culminated in carbonate sedimentation at the apex of each transgressive cycle. The magnitude of phosphate deposition in the Aurora Area increased with each third-order cycle to a maximum during the transgression forming

the apex of the second-order supercycle. Unit D was deposited only over the eastern portion of the area as a regressive facies of the Miocene supercycle. The Pliocene Yorktown sediments were deposited during the next supercycle. The lower Yorktown phosphorites coincided with the transgression while the nonphosphatic upper Yorktown was deposited during the subsequent regressive phase.

INTRODUCTION

The Aurora Area is a 130-km^2 peninsula located in the northern portion of the Aurora 7.5 minute quadrangle map. The area is bounded on three sides by Durham Creek, Pamlico River, and South Creek and extends south to the town of Aurora (Fig. 1). The area includes the North Carolina phosphate mining district. A major open-pit phosphate mine has been in operation since 1964-65; a second open-pit mine is being prepared to begin production in the near future. Detailed stratigraphic and sedimentologic analyses of many sections in the active mine and hundreds of core holes drilled by three companies supply the data base for this paper.

Morphologically, the Aurora Area is situated on the Pleistocene Pamlico Terrace, east of the Suffolk Scarp on the Outer Coastal Plain Province of North Carolina. Structurally, the area is situated about mid-slope in the west-central portion of the Aurora Embayment (Fig. 1). The Aurora Embayment is a north-south-trending Miocene depositional basin which extends from the Cape Lookout High on the south (Scarborough and others, 1982; S. W. P. Snyder and others, 1982), northward to Albemarle Sound, North Carolina. The western updip limit of the embayment is a regional north-south structure or hinge zone (Brown and others, 1972) and defines the western limit of the Pungo River Formation (Miller, 1971).

Most previous workers have adequately described the basic lithologies of the Pungo River phosphorites and recognized the cyclical pattern of sedimentation. However, they have not 1) described the interrelationships of the various lithologies which define the repetitive sediment sequences, 2) described the associated sedimentary structures, and 3) recognized the significance of the cyclical environmental changes within the depositional basin. These are the objectives of this paper.

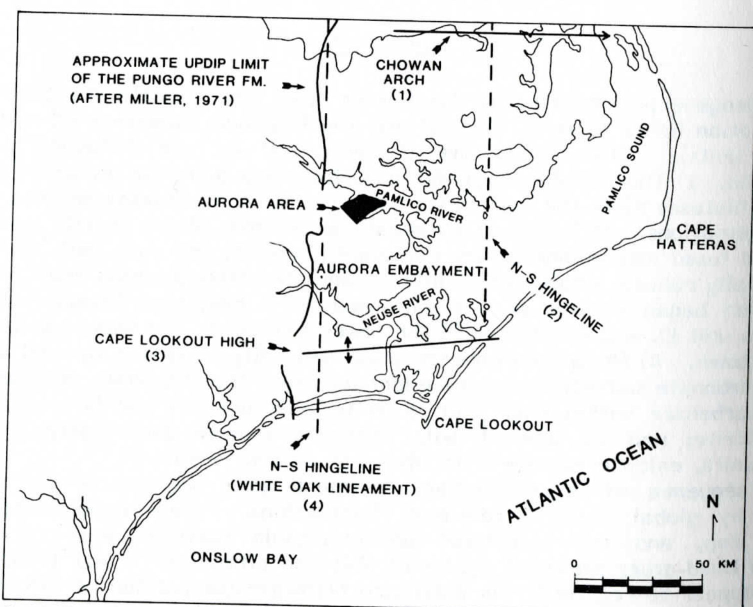

Figure 1. Location map of the Aurora Area, North Carolina. The Aurora Embayment is enclosed by structures 1-4 which are from the following sources: 1. Miller (1971); 2 and 4. Brown and others (1972), Miller (1971); 3. Scarborough and others (1982); S. W. P. Snyder and others (1982).

PREVIOUS WORK

The lithostratigraphy of the Pungo River Formation in central Aurora Embayment has been adequately and uniformly described by numerous workers since the deposit was first discovered in 1952 and first described by Brown in 1958. Brown generated an idealized section for Beaufort County in which he described four phosphatic sand units with four "intercalated calcitic and dolomitic shell limestones" (Table 1). The intercalated carbonates were described as highly competent, ranging in thickness from 6 inches to several feet, and generally becoming thicker towards the base of the phosphorite section. Coarse phosphate pebbles were occasionally found on top of the uppermost limestone layer, which was nearly always present. He interpreted "the cyclical depositional pattern observed in the phosphorite section" as an occasional breaching of a barrier by normal marine circulation conditions producing the intercalated shell limestones in an otherwise "closed or limited-access basin." He concluded that "the often-recognized association of phosphorites and underlying limestones is not merely fortuitous; there is a primary genetic association in many cases."

Kimrey (1964) proposed the name Pungo River Formation for the subsurface phosphorite units in Beaufort County, North Carolina. A core hole on the Pungo River near Belhaven was designated to be the type section. He described the 52-foot-thick unit, occuring 224 feet below the surface, as a sequence of interbedded phosphatic sands, silts, and clays; diatomaceous clays; and phosphatic limestones. In 1965 Kimrey subdivided the Pungo River into five zones based upon gross lithologies and P_2O_5 content with many minor variations in lithology; four of these zones occur in the Aurora quadrangle (Table 1).

In 1967 Gibson published a section of the initial open-pit at the Lee Creek Mine which included the upper 43.5 feet of exposed Pungo River and 66 feet of overlying fossiliferous sands and clayey sands. Seven lithic units which began some distance above the base of the formation were described in the Pungo River (Table 1), and nine units were recognized in the Yorktown Formation. He did not differentiate the upper shell sequences (units 8 and 9), which have subsequently been identified as the Pleistocene Croatan Formation (Gibson, in press; Snyder and others, in press).

Miller (1971) studied the lithology and distribution of the Pungo River Formation throughout the Aurora Embayment. In his description he said that "the phosphatic sands are repeated vertically in the section, and are interbedded with diatomaceous clays, calcareous clays, dolomites, and dolomitic limestones." He described three phosphatic sand units in the Aurora Area: one at the base of the Pungo River, the second roughly one-third of the way up the section, and the third unit at or just below the top of the formation. He found a general increase in phosphate content in each phosphorite unit upward in the section. The lower phosphorites are interbedded with dolomites while bryozoan limestone or coquina occurs in the uppermost part of the Pungo River. Miller believed that the complex interbedding of these rock types reflected fluctuations in depth within the basin caused by a series of minor transgressions and regressions.

STRATIGRAPHY

Five major stratigraphic formations constitute the Neogene section in the Aurora Area; these are summarized in Table 2. Each formation represents a distinct sequence of sediments which can be further subdivided into sediment units with well-defined characteristics and regional continuity.

Pre-Pungo River Sediments

A unit generally referred to as the Eocene Castle Hayne Limestone underlies the Pungo River Formation in the Aurora Area with a sharp disconformable contact. The surface of the Castle Hayne is commonly phosphatized, is extensively bored by hard-rock infauna, and contains remnants of a population of sessile benthos. In portions of the Aurora Embayment, outside of the Aurora Area and in Onslow Bay, Oligocene (Belgrade and New Bern Formations) and lower Miocene sediments (Silverdale

Table 1. Lithologic correlation chart of the phosphatic sediment sequence in the Aurora Area, North Carolina. All boundaries are the authors' interpretations.

BROWN, 1958 — BEAUFORT COUNTY

YORKTOWN FM.	INTERBEDDED SHELL BEDS, MARL, SAND, & CLAY
YORKTOWN FM.	REWORKED PHOSPHATE
PUNGO RIVER FM.	DOLOMITIC SHELL LIMESTONE
PUNGO RIVER FM.	PHOSPHATIC SAND & DOLOMITIC SHELL LIMESTONE
PUNGO RIVER FM.	PHOSPHATIC SAND
PUNGO RIVER FM.	DOLOMITIC SHELL LIMESTONE
PUNGO RIVER FM.	PHOSPHATIC SAND
PUNGO RIVER FM.	DOLOMITIC SHELL LIMESTONE
PUNGO RIVER FM.	PHOSPHATIC SAND
CASTLE HAYNE LIMESTONE	

KIMREY, 1965 — AURORA QUADRANGLE

YORKTOWN FM.		SHELL MARLS, UNCONSOLIDATED TO INDURATED SANDY SHELL BEDS, MASSIVE CLAYS & INTERBEDDED SAND
YORKTOWN FM.		REWORKED PHOSPHATE
PUNGO RIVER FM.	ZONE 1	COQUINA
PUNGO RIVER FM.	ZONE 2	HIGH GRADE PHOSPHORITE
PUNGO RIVER FM.	ZONE 4	LOWER GRADE CLAYEY PHOSPHATIC SAND
PUNGO RIVER FM.	ZONE 5	PHOSPHATIC CLAY
CASTLE HAYNE LIMESTONE		

ROONEY & KERR, 1967 — LEE CREEK MINE

UPPER YORKTOWN FM.	MARL
UPPER YORKTOWN FM.	CALCAREOUS SANDSTONE
UPPER YORKTOWN FM.	MARL
LOWER YORKTOWN FM.	MARL
CALVERT FM.	PHOSPHORITE
CALVERT FM.	COQUINA
CALVERT FM.	PHOSPHORITE & COQUINA
PUNGO RIVER FM.	PHOSPHORITE
PUNGO RIVER FM.	DOLOMITIC LIMESTONE
PUNGO RIVER FM.	PHOSPHORITE
PUNGO RIVER FM.	DOLOMITIC LIMESTONE
PUNGO RIVER FM.	PHOSPHORITE
CASTLE HAYNE LIMESTONE	

GIBSON, 1967 — LEE CREEK MINE

YORKTOWN FM.	UNITS 7-9	VERY FOSSILIFEROUS CLAYEY SAND
YORKTOWN FM.	UNITS 3-6	FOSSILIFEROUS CLAYEY SAND
YORKTOWN FM.	UNIT 2	PHOSPHATIC CLAYEY SAND
YORKTOWN FM.	UNIT 1	CLAYEY SAND & PHOSPHATE PEBBLES
PUNGO RIVER FM.	UNIT 7	YELLOW GREEN SAND & BRYAZOAN HASH
PUNGO RIVER FM.	UNIT 6	YELLOW GREEN SAND & HYDROZOAN HASH
PUNGO RIVER FM.	UNIT 5	MOLDIC LIMESTONE
PUNGO RIVER FM.	UNIT 4	ALTERNATING LIMESTONE & PHOSPHATE
PUNGO RIVER FM.	UNIT 3	PHOSPHATIC SAND
PUNGO RIVER FM.	UNIT 2	DIATOMACEOUS CLAY
PUNGO RIVER FM.	UNIT 1	PHOSPHATIC SANDS BOTTOM OF PIT

RIGGS et al., THIS PAPER — AURORA AREA

CROATAN FM.		
UPPER YORKTOWN FM.		
LOWER YORKTOWN FM.		
PUNGO RIVER FM.	UNIT D	SHELLY DOLOSILT
PUNGO RIVER FM.	UNIT C	MOLDIC LIMESTONE
PUNGO RIVER FM.	UNIT C	INTERBEDDED
PUNGO RIVER FM.	UNIT C	PHOSPHORITE SAND
PUNGO RIVER FM.	UNIT B	BURROWED DOLOSILT
PUNGO RIVER FM.	UNIT B	MUDDY PHOSPHORITE SAND
PUNGO RIVER FM.	UNIT A	BURROWED DOLOSILT
PUNGO RIVER FM.	UNIT A	MUDDY PHOSPHORITE SAND
CASTLE HAYNE FM.		

Table 2. Stratigraphic section for the Aurora Area, N.C. Wavy lines indicate major unconformities; dashed lines indicate minor unconformities or hiatuses.

AGE	FORMATION	THICKNESS(AVE.)	LITHOLOGY
PLEISTOCENE	POST-CROATAN SEQUENCE	3-15m	Quartz sands; quartz sandy clays; muds; & peats
	CROATAN	1-25m	Quartz sandy & clayey shell beds; shelly quartz sands; & quartz sands
PLIOCENE	UPPER YORKTOWN	2-20m	Shelly & clayey quartz silts & sands
	LOWER YORKTOWN	2-4m	Clayey & shelly phosphorite quartz sands
MIOCENE	PUNGO RIVER	20-25M	Shelly dolomites; clayey & dolomitic phosphorite & quartz sands; phosphatic sandy dolomites; & phosphatic & quartz sandy moldic limestones
EOCENE	CASTLE HAYNE		Quartz sandy moldic limestones

Formation) directly underlie the Pungo River Formation (Scarborough and others, 1982; Riggs and others, 1982). The Castle Hayne is a gray, highly fossiliferous, moldic, very sandy limestone or calcareous sandstone.

Pungo River Formation

The lower to middle Miocene Pungo River Formation ranges from 20 to 25 meters in thickness in the Aurora Area and is subdivided into four major sediment units which reflect cyclic patterns of deposition. These units are recognizable throughout the Aurora Embayment with some important lateral changes in lithofacies (Scarborough and others, 1982; Katrosh and others, 1982). The chemical sediment components of the Pungo River (including the phosphate, dolomite, and calcite minerals) were not deposited uniformly through time. Rather, their concentration reflects a cyclical pattern which is the major subject of this paper. Table 3 summarize a composite section for the Aurora Area.

Yorktown Formation

The bottom surface of the Yorktown Formation is relatively planar while the upper surface has considerable topography due to erosional channels and channel deposits of the Croatan Formation; locally the channels have completely eroded away the Yorktown. Hazel (1971), Akers (1972), and Snyder and others (in press) have established the age of the Yorktown to be Pliocene. The Yorktown is divided into upper and lower lithologic units, both of which are very uniform lithologically and represent sedimentation in an open-marine continental-shelf environment (Mauger, 1979).

The lower Yorktown is a persistent 2- to 4-meter unit that occurs throughout the Aurora Area. This unit is a dark olive green, poorly sorted, shelly, muddy, fine to medium phosphorite quartz sand. The phosphate concentration ranges from 5 to 20 percent, becoming finer and decreasing in concentration upward in the unit. The unit commonly contains shelly interbeds of calcareous articulated invertebrates. Abundant quartz granules, phosphate granules to pebbles, bone fragments, and robust shells occur in the basal sediments. These are in sharp contact with the underlying Pungo River, which contains a burrowed and bored phosphorite pavement (microsphorite) on the surface.

Table 3. Composite section describing the sediment units of the Pungo River Formation in the Aurora Area, N.C. Wavy lines indicate major unconformities; dashed lines indicate minor unconformities or hiatuses.

UNIT		THICKNESS(AVE.)		LITHOLOGY
LOWER YORKTOWN		2-4m		Clayey & shelly phosphorite quartz sand
PUNGO RIVER	D	0-4M		Yellowish-green, slightly phosphatic and quartz sandy, bioclastic-rich (barnacles, annelids, & bryazoans) dolosilt
	C	5-8m	3-5m	Cream colored, nonindurated to indurated, very fossiliferous & moldic, phosphatic calcareous mud or limestone interbeds which decrease downward. Interbedded, very dark greenish gray, slightly shelly, quartz phosphorite sand which becomes more massive downward.
			2-4m	Very dark greenish gray, massive, highly burrowed to mottled, clayey phosphorite quartz sand with only minor shell material.
	B	8-10m	2-4m	Light olive green, semi-indurated to indurated, highly burrowed & locally silicified, slightly fossiliferous & moldic, phosphatic sandy, dolomite mud. Moderate olive green, highly burrowed to mottled, dolomite muddy, phosphorite quartz sand.
			5-9m	Dark olive green, massive and mottled, clayey, phosphorite quartz sand which is locally gravelly (phosphorite granules) near the base.
	A	3-5m		Light olive green, non-indurated to indurated, highly burrowed and locally silicified, slightly fossiliferous & moldic, phosphatic sandy dolomite mud. Moderate olive green, burrowed to mottled, muddy, phosphorite quartz sand.
CASTLE HAYNE				Gray, indurated, very fossiliferous & moldic, quartz sandy limestone.

The upper Yorktown contains two subunits. A lower 12- to 15-meter sequence of light greenish gray, shelly, very muddy, fine to medium calcareous and quartz sand was deposited. The fossils in some facies of this subunit are dominated by echinoid fragments. This subunit grades upward into a 1- to 2-meter bed of greenish gray to cream-colored, moldic, calcareous muddy, fine to medium quartz sand which is often lithified. The fossils are generally highly weathered and leached and are often dominated by turritellid gastropods and occasionally by oysters. This latter subunit is only preserved locally where the Yorktown is topographically higher and this facies has not been eroded away.

Croatan Formation

The Croatan sediments represent a complex sequence of very shelly sands deposited in an early Pleistocene coastal system associated with barrier islands, tidal-inlet channels, and extensive shallow nearshore marine shelf environments. The transitional coastal environments truncated and locally dissected the underlying Yorktown Formation producing a surface with considerable relief. The highly variable thickness of the Croatan sediments is a direct result of the filling of this irregular topography. Specific lithofacies, their lateral and vertical relationships, and their geometries are a direct result of differing energy regimes associated with the subenvironments of the coastal system. In the Aurora Area, this formation consists of

four major sediment units.
1) Blue-gray, muddy, shelly sand; shells up to 25 percent of the sediment; generally not bedded; 1 to 8 meters thick.
2) Light-gray, slightly muddy, very sandy shell gravel; shells exceed 25 percent and commonly 50 percent of the sediment; shells large robust forms (corals, *Mercenaria*, pectinids, etc.); generally highly bedded or steeply cross-bedded with channel geometries; 0 to 8 meters thick.
3) Light-gray, clean to slightly muddy, slightly shelly fine quartz sand; shells generally less than 10 percent of the sediment; fragile and delicate shell forms (*Ensis*, etc.) in life position, as lag laminae, or as disseminated fine angular hash; poorly bedded and usually highly burrowed; 0 to 3 meters thick.
4) Light-gray, slightly muddy, shelly fine to coarse quartz sand; poorly sorted with general decrease in grain size upward; shell content varies from a few to 40 percent; 0 to 15 meters thick.

Post-Croatan Sediments

The post-Croaton sediments consist of two distinct lithic sequences. A lower sequence of interbedded fluvial sands, clays, and organic channel deposits is overlain by estuarine muddy sands and clays with minor shell beds containing *Ostrea*, *Rangia*, *Mulinia*, etc. The upper sequence consists of nearshore marine burrowed and cross-bedded sands with a well-developed soil profile and a zone of weathering superimposed upon it. The post-Croatan sediments are mainly late Pleistocene in age; however their geometry is being greatly modified by Holocene to modern streams and their associated channel fills and soil profiles.

CYCLIC PATTERNS OF SEDIMENTATION

Depositional Sequences and Unconformities

Vail and others (1977) defined depositional sequences as stratigraphic units composed of a relatively conformable succession of genetically related strata which are bounded at the top and the base by unconformities or their correlative conformities. They believe that these depositional sequences 1) represent predictable successions of rocks deposited during regional or third-order cycles of relative sea-level change, 2) are the basic stratigraphic units, and 3) are separated by *minor* interregional unconformities or hiatuses (i.e., stratigraphic surfaces which represent nonmeasurable periods of geologic time). A set of depositional sequences resulting from a series of third-order cycles will usually form a higher order sediment unit or depositional supersequence which is the product of a second-order cycle (Vail and others, 1977). They describe supersequences as distinct groups of superposed third-order depositional sequences which are separated by *major* interregional unconformities (i.e., stratigraphic surfaces which represent measurable periods of geologic time).

Detailed lithofacies studies of the phosphorites and associated sediments in the Aurora Area have led to the interpretation of Pungo River and Yorktown sediments as depositional supersequences which are bounded by three major unconformable surfaces (Tables 2 and 3). In the Aurora Area, these surfaces occur between 1) the Eocene Castle Hayne Limestone and the lower Miocene Pungo River unit A, 2) the middle Miocene Pungo River units C or D and the Pliocene lower Yorktown, and 3) the Pliocene upper Yorktown and Pleistocene Croatan Formation. Each of these three surfaces is associated with major periods of erosion during measurable periods of geologic time and they separate major sediment supersequences. The regional erosion associated with each of these surfaces has produced topography on top of the underlying sediment units and thereby has, in part, determined the final occurrence and distribution of underlying lithofacies.

The basic characteristics of the three major unconformities in the Aurora Area are summarized below.

1) Eocene Castle Hayne Limestone--lower Miocene Pungo River Formation.

a) This is a fairly regular surface which dips generally east, has about 25 meters of slope across the Aurora Area, and contains only minor topographic undulations (Fig. 2).

b) The surface on the indurated moldic limestone hardgrounds was generally modified by phosphate deposition with minor sulfide or manganese staining. This occurs either as a black surface stain which decreases downward 25 centimeters or so, or it accumulated on the surface as a microsphorite pavement.

c) The hardgrounds surface supported an extensive hard-rock boring infauna and a population of sessile benthic epifauna.

d) Some minor pebbles occur in the basal section of the Pungo River unit A.

2) Middle Miocene Pungo River Formation--Pliocene lower Yorktown Formation.

a) This is a fairly regular surface which dips generally east with about 15 meters of slope across the Aurora Area (Fig. 2).

b) The surface contains only minor topographic undulations; however, local scour holes up to 1 meter deep are common.

c) A microsphorite pavement or hardgrounds developed on the sediment bypass surface. The microsphorite pavement consists of alternately and repeatedly deposited phosphorite mud which was subsequently burrowed, indurated, bored, and torn up to produce extensive phosphorite intraclast pebbles and cobbles.

d) A gravel lag consisting of phosphate pebble intraclasts, quartz pebbles, abraded and black-stained vertebrate bones and teeth, and coarse shell material occurs on the surface.

e) The surface on top of the underlying indurated carbonate units contains an infauna of hard-rock borers.

f) The Pungo River sediments, which were deposited as a marine onlap sequence to the west, have been severely truncated by an extensive erosional episode. The resulting major unconformity produced the apparent stratigraphic offlap pattern described by Scarborough and others (1982).

g) This surface occurs on top of Pungo River unit C in the western part of the area and on unit D in the eastern portion. The present distribution and variable thickness of unit D is a direct product of this erosional event.

3) Pliocene upper Yorktown Formation--early Pleistocene Croatan Formation.

a) Topographic relief exceeds 15 meters and is superimposed upon a regional easterly dip; the surface is an erosional truncation of the upper Yorktown lithofacies.

b) The erosional lows are often associated with modern drainage systems.

c) Lithofacies of the upper Yorktown moldic turritellid limestones and differentially calcite-cemented fossiliferous sandstones are preserved on Yorktown topographic highs.

d) Local pebble and boulder zones of calcareous cemented sandstones, moldic limestones, and occasional solution cavities occur in sediments immediately above the surface in the topographic lows.

Thus, each of the three major unconformities separates distinctive supersequences of marine sediments. The two central supersequences, the Pungo River and Yorktown Formations, both contain phosphorites and are composed of a series of smaller sediment units or depositional sequences. In the Aurora Area the Pungo River consists of four sequences separated by three minor unconformities (Fig. 2), and the Yorktown consists of two sequences separated by a minor unconformity. These minor unconformities or hiatuses separate units which are conformable, rarely show evidence of significant amounts of erosion, and mark major and abrupt changes in lithology. The underlying unit is commonly a highly burrowed and fossiliferous carbonate which shows the following paragenesis:

1) The cessation of active deposition.
2) Exposure of the unit as a submarine surface during a period of sediment.
3) Semi-induration to induration of the carbonate.
4) Weathering of the shells which were often completely leached out leaving a dominantly undeformed moldic carbonate unit.
5) The local establishment of a hard-rock boring infauna on the surface.

Pungo River Depositional Sequences

Each of the four Pungo River depositional sequences is characterized by similar

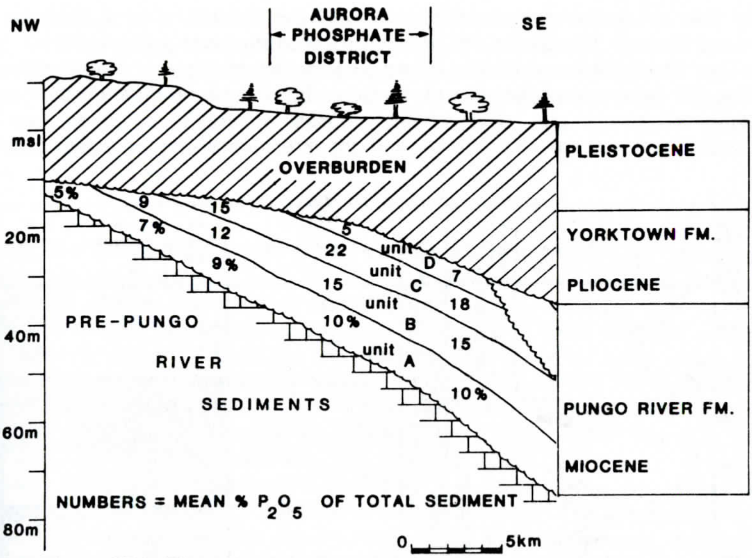

Figure 2. Idealized NW-SE geologic cross section through the Aurora phosphate district showing a) the mean P_2O_5 for each of the depositional units in the Pungo River and b) the changing phosphate concentrations vertically up the section and laterally down the slope of the basin.

vertical sediment patterns. Figure 3 shows the detailed variation in the three main components (phosphate, carbonate, and terrigenous sediments) vertically through a composite section of two core holes. Figure 4 is a composite of seven core holes which eliminates the subtle variations in lithofacies within each of the depositional units. An inverse association exists between the terrigenous and phosphate components, both of which are inversely related to the carbonate component. The main portions of units A, B, and C are mixed terrigenous sediments and phosphorites with a minor and restricted fossil component which probably reflects cold-water and somewhat toxic conditions at the sediment-water interface (Riggs, 1979b and 1980). Each of these units grades upward, either gradually or with increasing interbeds, into a carbonate cap-rock which contains minor terrigenous and phosphate sediment. The carbonates often contain large populations of a more diverse fauna, probably representing a more normal open-marine environment of deposition with decreased amounts of terrigenous input.

Excluding the carbonate caps within each unit, there is a general decrease in terrigenous sediment and an increase in phosphate upward from the base of unit A to the top of unit C (Fig. 4). Average phosphate concentrations are 5 percent to 20 percent in unit A, 10 percent to 40 percent in unit B, and culminate in unit C with concentrations in discrete beds between the carbonate interbeds reaching 60 percent to 75 percent of the total sediment (Fig. 2). The phosphate concentration decreases to a minimum within the carbonate sediment of the cap-rock within each unit (Figs. 3 and 4). However, the carbonate portions of each unit, particularly units A and B, often contain significant phosphate concentrations as clean, well-sorted phosphorite quartz sands filling burrows. The sands were deposited on the unconformable surface and subsequently backfilled the extensive underlying burrow system developed during the deposition of the carbonate units. The basic sediment patterns within each of units A, B, and C and the overall vertical patterns between units A, B, and C are generally persistent throughout the Aurora Area. However, minor lateral lithologic variations in the phosphate, clay, and carbonate content do occur within each unit (Fig. 2), and the number and character of the carbonate interbeds in the upper portions of each unit is variable.

Unit D represents a major change in the depositional regime as phosphate sedimentation declined to a minimum. Generally, there is a thin and minor basal sediment that contains up to 5 percent to 10 percent phosphate. This grades rapidly upward into the dominant very fossiliferous calcite biorudite in a dolosilt matrix with no phosphate. Unit D occurs in the down-basin or eastern portion of the Aurora Area (Fig. 2). The distribution pattern along the feather-edge of the unit is somewhat irregular due to subsequent erosional truncation of the entire updip portion of the Pungo River.

The cyclic pattern of deposition and interrelationships of each of the sediment

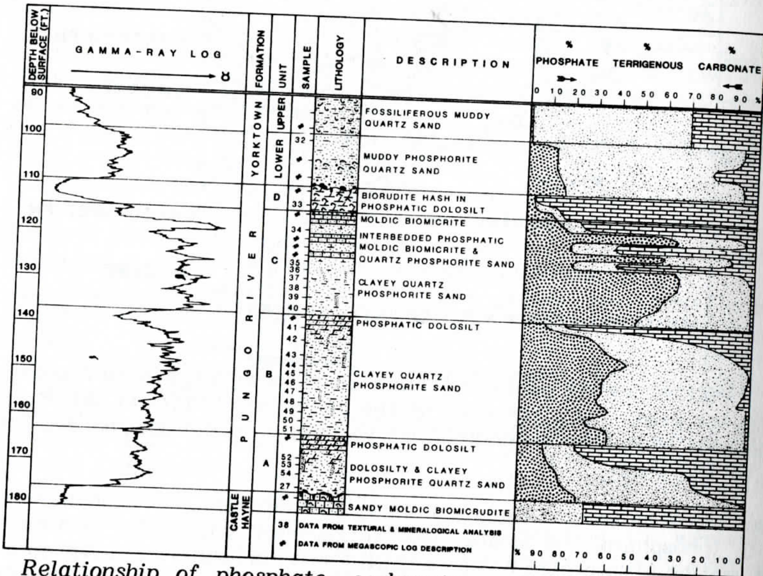

Figure 3. Relationship of phosphate, carbonate, and terrigenous sediment to the stratigraphic units and the gamma-ray log of the phosphorite section in the Aurora Area, N.C. (North Carolina Phosphate Corp. core holes H10 and GH8.5).

FORMATION AND UNIT		AVE. THICKNESS (M)	AVE. % PHOSPHATE	AVE. % CARBONATE
UPPER YORKTOWN		15	0	30
LOWER YORKTOWN		3	10	3
PUNGO RIVER	D	2	2	98
			4	96
	C	2	9	81
			interbedded	sequence
	C	5	62	6
			49	0
	B	3	11	71
			33	41
	B	7	39	0
			36	0
	A	4	8	80
			21	40
CASTLE HAYNE			0	60

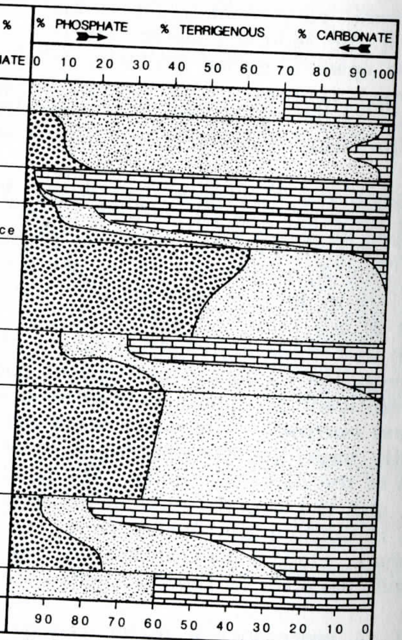

Figure 4. Composite averages of total phosphate, carbonate, and terrigenous sediments from textural and mineralogical analyses of core holes in the Aurora Area, N.C.

components produce a very distinctive and recognizable signature on the gamma-ray logs (Fig. 3). Occasionally, the carbonate portions of units A, B, and C are not readily picked up on the logs due to rich phosphorite sand which has backfilled the burrows in the carbonate sediments. The general gamma-ray signature for the Pungo River has been known and used for years in exploration, but it has not been correlated to depositional sequences.

Yorktown Depositional Sequences

The Yorktown Formation consists of two depositional sequences referred to as the lower and upper units (Tables 2 and 3). Both sequences are distinct lithologic units; the lower unit is a clayey phosphorite quartz sand facies, whereas the upper unit is a very fossiliferous, clayey and calcareous, very fine quartz sand without any phosphate. Snyder and others (in press) identified the microfaunal suite of both units as being of definite Pliocene age. This formation is very uniform and occurs throughout the Aurora Area, except locally where Pleistocene drainages have eroded into and occasional through the units, and is almost ubiquitous throughout the Aurora Embayment (Scarborough and others, 1982; Katrosh and others, 1982).

The lower Yorktown contains significant concentrations of phosphate which averages between 10 percent to 25 percent of the sediment. The phosphate is generally most abundant and coarsest at the base where there is a significant concentration of gravel. The phosphate becomes much finer grained upward with a complete loss of pebbles and a gradual decrease in total abundance. The coarse gravels have been interpreted in the past to be "obviously reworked" from the underlying Pungo River Formation (Brown, 1958; Gibson, 1967; Miller, 1971). However, similar types of phosphate have not been found to occur within the Pungo River except locally in the basal portion immediately above the Castle Hayne-Pungo River major unconformity. We believe that the phosphate gravel is related to the development of a microsphorite pavement on top of the "hardground" formed by the uppermost carbonates in the Pungo River; this makes it an unconformity type phosphate as described by Riggs (1980). The phosphate pavements and the resulting coarse intraclasts were formed on the Pungo River-Yorktown major unconformity surface during the initial stages of the Pliocene transgression and, thus, represent primary phosphorite sedimentation at that time. In addition, preliminary petrographic work within the lower Yorktown suggests that all of the phosphate may represent primary deposition during a Pliocene phosphogenic episode.

The top of the lower Yorktown is marked by a major change in lithology and color. Locally, the surface is marked by a poorly developed and variable zone of calcite-cemented, partially indurated, and moldic sediment. Mauger (1979) described a similar zone in the Lee Creek Mine. The major change in composition at this poorly developed weathering profile between the lower and upper units suggests a major change in the depositional regime at this time.

STRATIGRAPHIC RELATIONSHIP TO GLOBAL SEA-LEVEL CURVES

Vail and others (1977) define three orders of cycles of relative sea-level change. First-order or "global cycles" are records of worldwide sea-level responses to major, large-scale geotectonic processes which have durations of 100 to 300 million years. The second- and third-order cycles have durations of 10 to 80 million years and 1 to 10 million years, respectively (Fig. 5). Vail and others believe that some second-order cycles may be of sufficient duration and magnitude that they may also be a response to geotectonic mechanisms. However, they believe that glaciation and deglaciation may account for some second-order and many third-order cycles, especially in the Neogene. They also recognize that there may be other yet unidentified causes working "in combination with geotectonics and/or glaciation to accentuate or diminish the changes." For example, Pitman (1978) proposed the idea that abrupt changes in rates of sea-floor spreading could cause sea-level fluctuations while the resulting sediment patterns along continental shelves are dependent upon the rate of sea-level change and sediment flux (Pitman, 1979).

Based on their global sea-level curves, Vail and others (1977) have delineated a

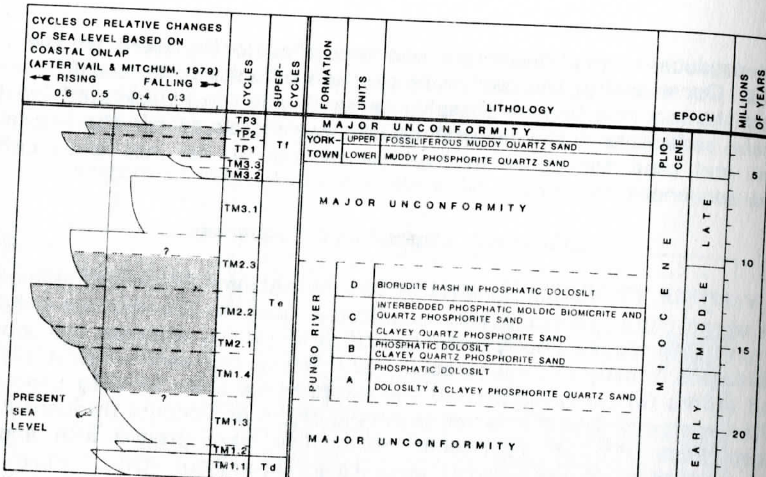

Figure 5. Proposed relationship of the upper Tertiary stratigraphic units to global sea level curves.

series of global highstands and lowstands of the sea. Global highstands are when sea level is above the shelf edge in most regions of the world and, consequently, are characterized by widespread marine sediments on the shelves and adjacent coastal plains. Global lowstands are when sea level is below the shelf edge and are characterized by erosion and nondeposition producing major interregional unconformities. Vail and others (1977) identify major highstands at about 13 million years ago in the middle Miocene and about 4.5 million years ago in the early to middle Pliocene. Major lowstands occurred at about 6.75 million years ago in the late Miocene and at 2.9 million years ago in the late Pliocene to early Pleistocene. Each of these second-order global highstands and lowstands of the sea are shown on Figure 5 and appear to have controlled the cyclical sedimentation patterns represented in Neogene sediments in the Aurora Area. Thus, the sediments which are lower to middle Miocene, Pliocene, and Pleistocene in age (Table 2), and which are separated by major unconformities, appear to fit entirely within the two second-order, or Te and Tf, supercycles of Vail and Mitchum (1979).

The major foraminiferal age-dating for the Pungo River Formation has been done by Gibson (in press). He has found planktonic foraminifera indicating zone N.8 (Blow, 1969) widely distributed in the area extending from south of the Neuse River in North Carolina, northward to the Norfolk area in Virginia. Gibson found strata containing planktonic assemblages equivalent to zone N.11 (Blow, 1969) in the central and northern parts of the Albemarle Embayment in North Carolina. These planktonic zones correspond to late early to early middle Miocene for the time of deposition for these Pungo River sediments. Katrosh and Snyder (1982) and Snyder and others (1982) have demonstrated that the lower lithofacies (units A and B) and the uppermost lithofacies (unit D) of the Pungo River Formation in the Aurora Area have an extreme paucity of planktonic forms, the foraminiferal preservation is generally poor, the abundance is extremely variable, and the distribution patterns are not clear either regionally or vertically through the units. Consequently, most published ages for the Pungo River are from the upper lithofacies (particularly unit C) and do not represent the age limits of the formation. Recent work by S. W. Snyder and V. J. Waters (pers. comm., 1982) has documented Pungo River lithofacies in Onslow Bay which contain good planktonic foram assemblages which fit into zone N.6 (Blow, 1969); this places the older lithofacies into the middle early Miocene. Recent drilling by R. A. Crowson (pers. comm., 1982) suggests that older lithofacies may occur below unit A in the downdip portion of the Aurora Embayment. Brown (1958) concluded that the foraminifera in the top few feet of the phosphorite section could be dated middle Miocene; due to poor foraminiferal preservation and control, the remainder of the phosphorite section could be considerably older--the base could possibly even be as old as late Oligocene. Gibson (1967) concurred, stating that some of the poorly preserved molluscan molds suggest greater affinities to Oligocene than Miocene species. As can be seen in Figure 5, these age assignments place the Pungo River at least into the TM1.4, TM2.1, and TM2.2 third-order cycles of Vail and Mitchum (1979), which approximately coincides with the maximum stand of sea level of the second-order Te supercycle.

The Yorktown Formation, which unconformably overlies the Pungo River Formation, has been dated by Hazel (1971), Akers (1972), and Snyder and others (in press) using planktonic foraminifera. Their age assignment ranged from just below the base of zone N.19 to the middle of zone N.20 of Blow (1969) and from the early part of zone PL1 to the middle part of zone PL3 of Berggren (1973). This places the Yorktown into the early to early late Pliocene, or between 4.8 to 3.1 million years ago (Berggren, 1973). Thus, the Yorktown falls into the Tf supercycle of Vail and Mitchum (1979) and represents the third-order cycles TP1, TP2, and TP3 (Fig. 5).

Thus, by defining the basic lithostratigraphic depositional sequences and using established faunal age assignments, periods of major and minor sea-level highstands and lowstands have been identified for the Aurora Area. These Neogene cyclical patterns seem to compare moderately well with the established coastal onlap curves of Vail and others (1977 and 1979).

HYPOTHESIS FOR CYCLIC DEPOSITION IN THE AURORA AREA

The hypothesis is based upon the interpretation of detailed lithostratigraphic data and superimposed biostratigraphic data for age assignments as follows: 1) vertical lithologic changes within each depositional sequence; 2) vertical lithologic changes through the depositional supersequences; 3) recognition and location of major and minor unconformities; 4) lateral lithic continuity of both the depositional sequences and supersequences through the Aurora Area; 5) regional stratigraphic continuity and geometry as developed by Scarborough and others (1982); and 6) the known foraminiferal data. Figure 5 presents a preliminary interpretation of the relationship of the Neogene section in the Aurora Area to the global sea-level curves of Vail and Mitchum (1979).

1) A lowstand of the sea during the earliest Miocene produced a major unconformity on top of the pre-Pungo River sediments. During this period of exposure, nondeposition, and erosion, these sediments were first indurated and then leached producing undeformed moldic limestones and sandstones. This rock surface formed hardgrounds which were phosphatized and populated by benthic boring infauna and sessile epifauna during the initial phases of the subsequent transgression.

2) The deposition of the Pungo River supersequence began in the middle lower Miocene and continued through the middle Miocene. These sediments represent the highstand of the sea during the second-order or Te supercycle (Vail and Mitchum, 1979).

a) Units A, B, and C represent depositional sequences of marine onlap which were deposited in response to a progressively rising sea level.

b) Units A, B, and C are depositional sequences which may represent third-order cycles deposited in response to relative rises in sea level associated with cycles TM1.4, TM2.1, and perhaps a portion of TM2.2, respectively (Vail and Mitchum, 1979).

c) Units A, B, and C are dominantly terrigenous sediments and phosphorites containing a limited and restricted, cold-water fauna; each unit culminated in carbonate sedimentation containing a rich, subtropical fauna.

d) The top of each unit is marked by a minor unconformity. These disconformable surfaces of nondeposition represent brief periods of relative falling sea levels associated with third- or higher-order cycles (Vail and others, 1977).

e) Unit D follows the same depositional pattern as units A, B, and C. Unit D is dominated by carbonate with only minor terrigenous and phosphate sediment at the base. The foraminifera suggest more open-marine conditions than units A and B (Katrosh and Snyder, 1982). Thus, the unit still represents a highstand of the sea; however, the regional distribution, geometry, and changing depositional regime suggest that unit D was deposited on the first part of the regressive phase of supercycle Te (Vail and Mitchum, 1979). This unit may coincide with the initial portion of third-order cycle TM2.3.

3) Relative sea level continued to drop producing a major lowstand during the late Miocene, which coincides with the third-order cycles TM3.1, TM3.2, and TM3.3 (Vail

and Mitchum, 1979). This period of nondeposition and erosion truncated the updip portions of the Pungo River depositional sequences, producing the apparent offlap pattern described by Scarborough and others (1982) and the major unconformity between the Pungo River and the Yorktown Formations.

4) The Yorktown depositional supersequence, which includes both the lower and upper sequences, was deposited in response to the highstand of the sea associated with the second-order or Tf supercycle (Vail and Mitchum, 1979).

a) The end of the late Miocene erosion period is marked by an extensive development of unconformity type phosphorite (Riggs, 1980). The leading edge of the third-order cycle of relative sea-level rise (TPl of Vail and Mitchum, 1979) deposited repeated laminae of microsphorite mud (Riggs, 1979a) which was sequentially burrowed, indurated, bored, broken into intraclastic phosphorite gravels, and deposited in the basal sediments of the lower Yorktown sequence along with a coarse quartz sand and granule component.

b) The lower Yorktown terrigenous and phosphorite sediments were deposited in response to the transgression coincident with the third-order TP1 cycle (Vail and Mitchum, 1979) which culminated in a sea-level maximum about 4 million years ago. The lower Yorktown contains a significant concentration of intraclastic phosphorite sand which appears to increase in concentration to the east and south of the Aurora Area.

c) A minor unconformity, characterized by a moderate weathering zone (Mauger, 1979), separated the two depositional sequences and marks a major change in lithology and depositional regimes. This hiatus appears to be coincident with, or immediately following, the sea-level maximum of the second-order global Tf cycle of Vail and Mitchum (1979).

d) The upper Yorktown is characterized by a normal marine, very fossiliferous, clayey and calcareous, fine quartz sand with essentially no phosphate. This depositional sequence was deposited during the slightly lower stand of relative sea level coincident with the regression of the second-order Tf supercycle and the third-order Tp2 cycle of Vail and Mitchum (1979).

5) A major lowstand of the sea between 3 and 4 million years ago terminated the Yorktown depositional supersequence. This lowstand is coincident with at least the third-order TP3 cycle and possibly extends into the early Pleistocene Q supercycle of Vail and Mitchum (1979). The surface sediments of the upper Yorktown were weathered, indurated, and the fossils dissolved producing moldic limestones and calcareous sandstones. The distribution of these sediments was then severely modified by erosion of the superimposed drainage system.

6) Subsequent Pleistocene transgressions first deposited the complex facies of nearshore marine and coastal shell beds of the Croatan Formation on the irregular upper Yorktown surface.

7) Another Pleistocene transgression, following a major lowstand of the sea, produced the depositional sequence of fluvial, estuarine, and coastal terrigenous post-Croatan sediments.

8) The Holocene-Recent weathering and erosional surface, the resulting unconformity, and the associated depositional sequence of fluvial and estuarine terrigenous sediments are presently being superimposed upon the similar post-Croatan sediment sequence.

It is self-evident that the Neogene sediments were only deposited and preserved in the Aurora Area during major highstands of the sea. It is expected that some younger and older deposits associated with the lowstands do exist in the seaward and deeper portions of the Aurora Embayment and out onto the continental shelf (Riggs and others, 1982).

In the past, the phosphorites of the lower Yorktown have been interpreted as reworked from the erosion of the underlying Pungo River sediments (Table 1). However, recent stratigraphic and petrographic work at East Carolina University suggests that the lower Yorktown phosphorites may represent primary phosphate sedimentation. Could this portion of the Pliocene (TP1) represent a phosphogenic period? If this is the case, the formation and deposition of phosphorite in both the Pungo River units A, B, and C and in the lower Yorktown in the coastal plain appear to be intimately tied to the transgressive portions of supercycles Te and Tf of Vail and Mitchum (1979). Also, phosphate sedimentation in the Aurora Area appears to increase with the transgression, culminating in optimum deposition just prior to the global sea-level maximum, when carbonate sedimentation occurs.

Riggs (1980) proposed a close and integral relationship between the formation of major sedimentary phosphorites, their anomalous sediment components, and periods of major and increasing tectonism. Pitman (1977) proposed that the highs in the global sea-level curves could be products of major tectonism and high rates of sea-floor spreading. Comparison of the cyclical sediment sequences and their associated phosphate components to the global sea-level curves suggests that there is a very strong correlation of phosphorite formation and the associated sediment patterns to major oceanic events and the relative position and movement of sea level.

ACKNOWLEDGMENTS

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STRATIGRAPHY AND PETROLOGY OF THE PUNGO RIVER FORMATION, CENTRAL COASTAL PLAIN OF NORTH CAROLINA

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ABSTRACT

Up to 30 m of phosphatic sediments of early and middle Miocene Pungo River Formation were deposited in the north-south-trending Aurora Embayment of North Carolina. These sediments thin to approximately 10 to 15 m over the Cape Lookout High, a pre-Miocene feature which forms the southern boundary of the Aurora Embayment. The western and updip limit of the formation parallels a regional north-south structural hingeline or White Oak Lineament. The formation thins to a feather-edge at this lineament and thickens rapidly to the east and southeast. Deposition of the Pungo River Formation extended some unknown distance to the west of the White Oak Lineament, the present updip erosional limit.

The Pungo River Formation consists of the four major sediment sequences in the Aurora Area (units A, B, C, and D as described by Riggs and others, 1982b) and three lateral facies (units BB, CC, and DD). Phosphate sedimentation was concentrated in units A, B, and C which are laterally correlative throughout most of the study area. However, the muddy phosphorite quartz sands of unit B and possibly the phosphorite quartz sands and carbonate sediments of unit C grade downdip to the southeast into an 11-m-thick diatomaceous facies (unit BB). Units A, B, and C grade into a slightly phosphatic, calcareous, quartz sand facies (unit CC) to the south, in the area of the Cape Lookout High, which probably represents a shoaling environment. Dolomitic unit D, of the northern and eastern portions of the Aurora Embayment, grades laterally into calcareous unit DD in the central portion of the embayment.

Allochemical phosphate grains of the intraclastic variety dominate all sediment units in the formation. However, unit A contains abundant pelletal phosphate in the fine to very fine sand-size fraction. The highest phosphate concentrations occur along the upper shelflike basin margin in the west-central portion of the Aurora Embayment. Updip to the west, the phosphate concentration decreases within each unit which also thins due to subsequent erosion. Major facies changes within the sediment units have resulted in decreased phosphate contents downdip to the east and south within the Aurora Embayment.

Within the Aurora Area, units A through C of the Pungo River Formation are generally characterized by cyclic deposition consisting of decreasing terrigenous and increasing phosphate sedimentation upward through the units; the deposition of each unit culminated with the formation of a carbonate cap-rock. The depositional pattern of these regionally persistent and cyclical lithologies suggests that units A through C were deposited during a major transgression. The overlying unit D was deposited during the early stages of a subsequent regressive phase. Truncation of the units by erosion took place prior to the deposition of the Pliocene Yorktown Formation. Thus, this extensive erosion has produced an apparent offlap configuration of the Pungo River units that actually represents a major transgressive or onlap sediment sequence and an early stage regressive sequence.

The phosphorites and phosphatic sediments of the Pungo River Formation in the central Coastal Plain of North Carolina were orginally described by Brown (1958) and correlated with the middle Miocene Calvert Formation of Maryland and Virginia on the basis of benthic foraminifera. Subsequent work utilizing mollusks and benthonic and planktonic foraminifera has demonstrated that the Pungo River ranges in age from at least middle early Miocene and extends well into the middle Miocene (Gibson, 1967, in press; Katrosh and Snyder, 1982; Riggs and others, 1982a, 1982b). The Pungo River Formation is also equivalent to portions of the Hawthorn Group of Florida, Georgia, and South Carolina (Gibson, 1967; Riggs, 1979b).

The Pungo River Formation is found only in the subsurface of eastern North Carolina. Its westward updip boundary coincides with and parallels a major north-south structural hingeline recognized by Miller (1971). This hingeline is called the White Oak Lineament by S. W. P. Snyder and others (1982). Miller (1971) recognized several erosional outliers west of the White Oak Lineament which indicates that the formation extended beyond its present updip limit. The formation dips and thickens to the east. Miller (1971) has mapped the formation northward to Virginia, and eastward and southward to the coastline (Fig. 1). The northern and eastern extent of the formation is unknown. To the south, phosphatic sediments of the Pungo River have been recovered from holes drilled on Bogue Banks, Carteret County (Steele, 1980), and from vibracores across the continental shelf in Onslow Bay (Riggs and others, 1982a).

The study area is located in the east-central portion of the North Carolina Coastal Plain, covering the southern half of the Aurora Embayment (Figs. 1 and 2). The Pungo River Formation, within the study area, unconformably overlies either the 1) Eocene Castle Hayne Limestone (Brown and others, 1972; Miller, 1971); 2) Oligocene Trent Formation (Baum and others, 1978) or the River Bend Formation (Ward and others, 1978); or 3) the lower Miocene Silverdale Formation or the Haywood Landing Member of the Belgrade Formation (Baum and others, 1978; Ward and others, 1978) depending upon the location and one's choice of stratigraphic terminology. For the purposes of this paper, the underlying units will be designated only as *pre-Pungo River*

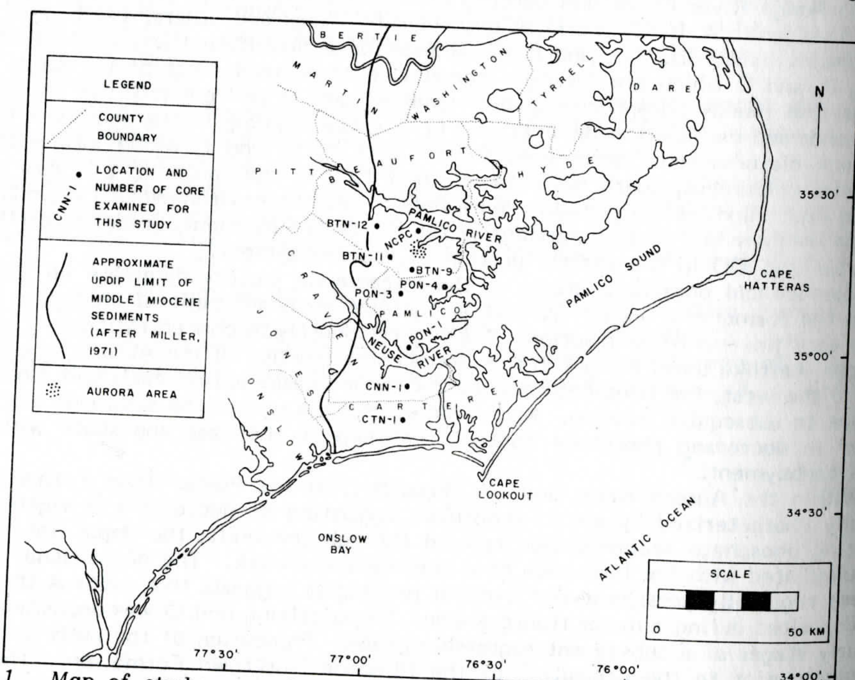

Figure 1. Map of study area showing core hole locations and western updip limit of the early to middle Miocene Pungo River Formation (from Miller, 1971).

sediments. The Pungo River Formation is unconformably overlain by the fossiliferous, gravelly, muddy, phosphatic, quartz sands of the Pliocene Yorktown Formation throughout most of the Aurora Embayment.

Core samples of the Pungo River Formation (Fig. 1) were gathered from two sources: eight cores drilled by International Minerals and Chemical Corporation in 1966 (Riggs, 1967) and several cores drilled in 1979 and 1980 by North Carolina Phosphate Corporation (NCPC) (Riggs and others, 1980). All samples were examined with a binocular microscrope to determine the mineralogy and texture, to assign lithologic names, and to identify the megascopic phosphate grain types. Thin sections from selected phosphate-rich intervals were examined to aid in the identification of phosphate grain types and to supplement mineralogic determinations. Textural analyses, performed on all samples, further characterized the interrelations of mineralogy, grain size, and phosphate grain types.

The major objective of this paper is to describe the lithostratigraphy of the Pungo River Formation within that portion of the Aurora Embayment extending from the Aurora Area, southward and westward to the embayment margins (Fig. 2). More specifically, the objectives are to 1) describe the lateral and vertical facies relationships within the formation and correlate the lithologic units and subunits throughout the study area, and 2) describe the phosphate petrology within the major phosphorite units.

STRUCTURAL CONTROLS

Miller (1971, p. 40) stated that "the location of economic or potentially economic phosphate deposits . . . shows that structural conditions in the basin of deposition played a prominent, perhaps dominant, role in deposition and concentration of the phosphate." The close relationship of structural elements to phosphate sedimentation and accumulation has been discussed by Freas and Riggs (1964), Riggs (1967, 1979b, and 1980a), and Miller (1971).

The structural features which have traditionally been recognized as controlling Tertiary sedimentation in the Coastal Plain of North Carolina are the Norfolk and Cape

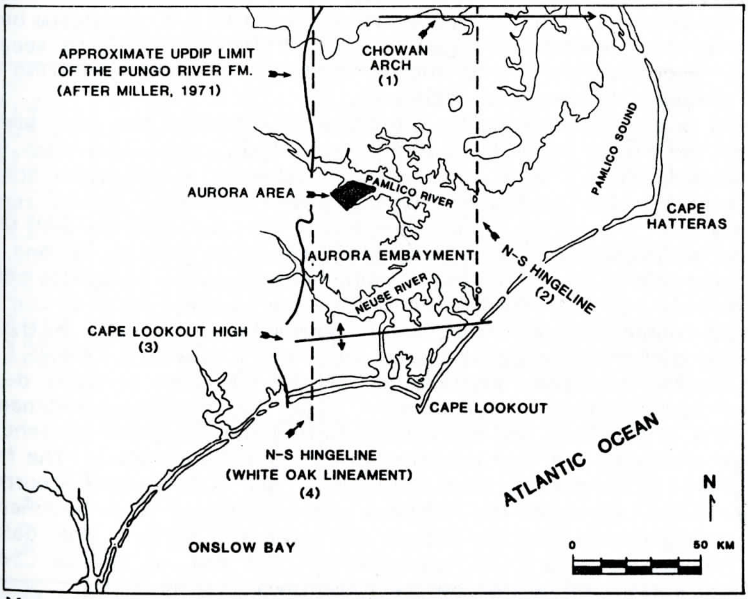

Figure 2. Map showing the north-south oriented Aurora Embayment which is defined by the structures from the following papers: 1) Miller, 1971; Riggs, 1967; 2) Brown and others, 1972; Miller, 1971; 3) Miller, 1971; Riggs, 1967; S. W. P. Snyder and others, 1982; 4) Brown and others, 1972; Miller, 1971; S. W. P. Snyder and others, 1982.

Fear Arches, with an associated intervening basinal area called the Albemarle Embayment (Gibson, 1967; Miller, 1971; Brown and others, 1972; Mauger, 1979). The thickest sequence of Tertiary sediments was deposited in this basin with the sediments thinning or absent over the positive features.

The Pungo River sediments were deposited in the Aurora Embayment, a smaller depositional basin contained within the Albemarle Embayment. The Aurora Embayment is delineated by four structural elements as shown in Figure 2. The western and eastern margins are delineated by north-south-trending hingelines defined by Miller (1971) and Brown and others (1972). The western hingeline is called the White Oak Lineament by S. W. P. Snyder and others (1982). The northern margin is delineated by the east-west-trending Chowan Arch of Riggs (1967), which is located just south of the Albemarle Sound (Fig. 2). The southern margin is defined by a positive feature located south of the Neuse River which has been recognized by many workers (Riggs, 1967; Gibson, 1967; Miller, 1971; Brown and others, 1972; S. W. P. Snyder and others, 1982). This east-west-trending topographic high, called the Cape Lookout High by S. W. P. Snyder and others (1982), has affected the deposition of the Pungo River Formation and younger sediments in the southern portion of the study area (holes PON-1, CNN-1, and CTN-1 in Fig. 4). Miller (1971) believes these four structural features created a restricted "Pungo River basin" or Aurora Embayment in which phosphate was precipitated and concentrated, primarily along and just to the west of the easternmost hingeline.

LITHOSTRATIGRAPHY

Within the Aurora Embayment, the Pungo River Formation consists of seven major sediment units (Fig. 3). Four of the sediment units (units A, B, C, and D) have been described from the Aurora Area by Riggs and others (1982b). These four units have persistent mineralogical and textural characteristics and are laterally correlative throughout most of the study area. Units BB and CC (Fig. 3) are lithologically distinct from units A through D, are restricted in occurrence, and are lateral facies of units A, B, and C (Figs. 4 and 5). Unit DD (Fig. 3) occurs in the central portion of the study area and is a lateral facies of unit D (Figs. 4 and 5). The facies change from unit D to unit DD consists primarily of a change in matrix composition. Unit D is a bioclastic-rich sediment with a dolomite matrix; unit DD is a calcareous bioclastic-rich sediment (Fig. 3). Miller (1971) attributes this facies change to secondary dolomitization of a primary calcite or micrite matrix by magnesium-bearing groundwater movement through the bioclastic sediments.

Figure 4 is a north-south geologic cross section through the study area. Units A, B, and C of the Pungo River Formation extend from the Aurora Area (hole NCPC) southward to hole PON-3 with consistent mineralogical and textural characteristics. The thickenend section of Pungo River sediments at hole PON-3 represents the depositional axis of the Aurora Embayment, but it does not coincide with the maximum accumulation of phosphate. The phosphate content of units A, B, and C increases northward from hole PON-1, reaching a maximum cumulative phosphate content in the formation at hole NCPC. South of PON-1, on the southern flank of the embayment, the phosphate content of units A, B, and C decreases dramatically as the terrigenous and carbonate contents increase and grade into unit CC at hole CNN-1. The slightly phosphatic, shelly, calcareous quartz sands of unit CC were probably deposited in a shoaling environment on the Cape Lookout High; the terrigenous sediments extended down the flank of this high and northward diluting the phosphate content of units A, B, and C and producing the mud interbeds in unit B at hole PON-1. The facies change of unit D to unit DD occurs between holes NCPC and BTN-9. The occurrence of unit DD in hole CTN-1 represents the northern extent of Pungo River sediments from the Onslow Bay depositional system (Riggs and others, 1982a). The calcareous and terrigenous sediments of unit CC underlie unit DD and, as in hole CNN-1, reflect sedimentation directly influenced by the Cape Lookout High.

Figure 5 is a northwest-southeast geologic cross section through the study area which shows 1) the sequential westward truncation of the vertical lithofacies of the Pungo River Formation by a late Miocene unconformity (Riggs and others, 1982b); and 2) the occurrence, in hole PON-4, of a diatomaceous facies that is considered

PUNGO RIVER FM	CENTRAL FACIES: COMPOSITE SECTION, AURORA EMBAYMENT				SOUTHERN FACIES: HOLES PON-1, CNN-1, CTN-1			EASTERN FACIES: HOLE PON-4		
	UNIT	THICKNESS		LITHOLOGY	UNIT	THICKNESS	LITHOLOGY	UNIT	THICKNESS	LITHOLOGY
	DD	0-7 M		White, slightly phosphatic and quartz sandy, calcareous bioclastic shell hash (barnacles, bryozoans) with less than 20 percent calcite mud			ABSENT	D	0-7 M	Yellowish-green, slightly phosphatic and quartz sandy, dolosilty bioclastic shell hash (bryozoans, barnacles, annelid tubes) to shelly dolomite muds
	C	0-9 M	0-5 M	Cream colored, nonindurated to indurated, fossiliferous and moldic, phosphatic and quartz sandy calcareous mud with limestone interbeds which decrease downward	↑			↑		
			0-6 M	Very dark greenish gray, massive, burrowed to mottled, moderately muddy quartz phosphorite sand with minor shell material				BB	0-11 M	Light grayish-green, slightly calcareous, slightly phosphatic and quartz sandy, diatomaceous mud; diatom fragments compose up to 70 percent of the sediment
	B	0-12 M	0-7 M	Light olive green, indurated to semi-indurated, highly burrowed and locally silicified, slightly fossiliferous and moldic, phosphatic and quartz sandy dolomite mud Moderate olive green, burrowed to mottled, dolomite muddy, phosphorite quartz sand	CC	0-17 M	White to light gray to olive green, calcareous silty muds to very shelly, calcareous muddy, sometimes gravelly, slightly phosphatic (less than 10 percent) quartz sands	↓		
			0-7 M	Dark olive green, massive and mottled, muddy phosphorite quartz sand which is locally gravelly (phosphorite granules) near base				B	0-12 M	Dark green, gravelly (phosphorite granules), muddy, phosphorite quartz sand
										?
	A	0-6 M	0-1 M	Light olive green, indurated to nonindurated, highly burrowed and locally silicified, slightly fossiliferous and moldic, phosphatic and quartz sandy dolomite mud				A		NOT RECOVERED
			0-5 M	Moderate olive green, burrowed to mottled, dolomitic, muddy phosphorite quartz sand which is locally gravelly (phosphorite and quartz gravels) near base	↓					

Figure 3. Description of the lithofacies of the Pungo River Formation in the Aurora Embayment south of the Pamlico River, North Carolina.

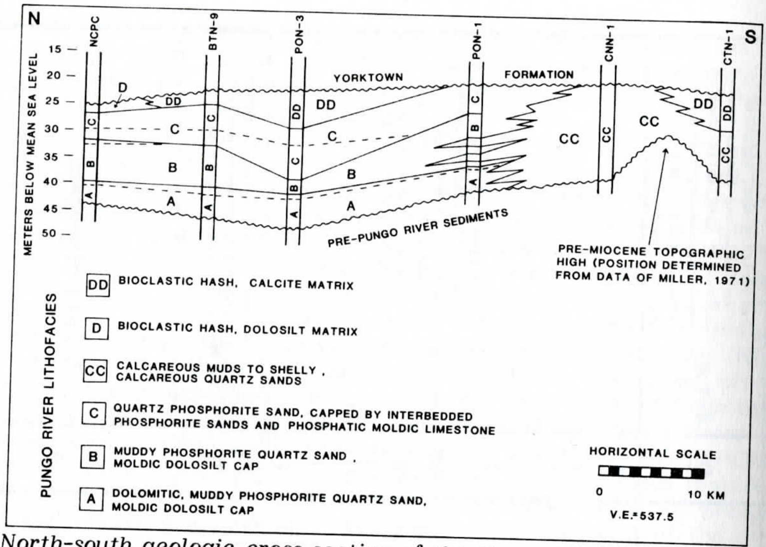

Figure 4. North-south geologic cross section of the Pungo River Formation through the study area; core hole locations are on Figure 1.

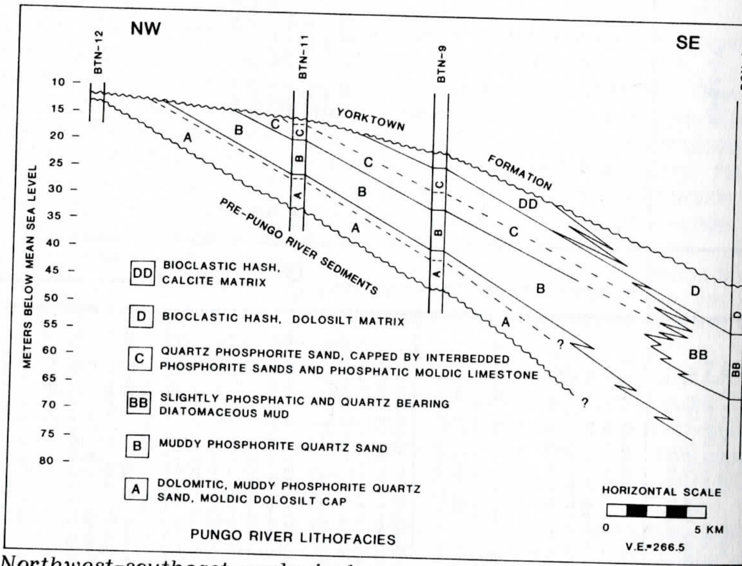

Figure 5. Northwest-southeast geological cross section of the Pungo River Formation through the study area; core hole locations are on Figure 1.

equivalent to the upper portion of unit B, and possibly all of unit C. Truncation of the Pungo River Formation prior to the deposition of the Pliocene Yorktown Formation was extensive and severe, eliminating the original western depositional extent of the formation, except for erosional outliers such as those noted by Miller (1971) west of the White Oak Lineament. Units A, B, and C on Figure 5 are characterized by consistent mineralogical and textural parameters. The calcareous matrix of unit DD at hole BTN-9 changes downdip to dolomite (unit D) at hole PON-4. Underlying unit D in hole PON-4 is the slightly sandy diatomaceous mud of unit BB. The diatomaceous sediments were probably deposited as a result of high organic productivity associated with upwelling currents and active phosphate sedimentation. This depositional regime existed during the later portions of the transgression when upwelling currents would have extended furthest into the Aurora Embayment and phosphate sedimentation would have been greatest (i.e., during deposition of units B and C). Gravelly, muddy, phosphorite quartz sands characteristic of the lower portion of unit B underlie unit BB at hole PON-4.

PHOSPHATE PETROLOGY

The megascopic phosphate grains (those greater than 0.063 mm in diameter) of the Pungo River Formation have been described according to the classification of sedimentary phosphorites proposed by Riggs (1979a). He subdivided authigenic phosphate into orthochemical phosphate mud (microsphorite), analogous to micrite in carbonates, and allochemical phosphate grains, analogous to carbonate allochemical grains. Phosphate allochems consist of intraclasts, pellets, oolites, and fossil skeletal material (Fig. 6). Lithochemical and metachemical phosphorites are products of secondary processes and have not been identified from the Pungo River Formation.

The majority of predominantly dark brown to black granule-sized and light to dark brown sand-sized phosphate grains of the Pungo River Formation possess the characteristics of intraclastic phosphate allochems. These characteristics include a cryptocrystalline carbonate fluorapatite matrix (Rooney and Kerr, 1967), terrigenous and authigenic mineral inclusions, laminae, mottles, and bored and burrowed sediment surfaces (Fig. 7). Intraclasts, which comprise approximately 80 percent of the phosphate grains in the Pungo River Formation, are angular to subrounded and irregular in shape, especially in the coarse-sand and gravel fractions. Rounding and sphericity increase with decreasing grain size, although some irregularity in shape, such as a flattened side, will persist down to the very fine sand-size fraction. The presence of inclusions and sedimentary structures diminishes with decreasing size of the intraclasts due to continued fragmentation of the grains during transport (Riggs, 1979a).

Inclusions constitute an important microscopic component of the Pungo River intraclast grains. The inclusions occur as disseminated particles throughout the carbonate fluorapatite matrix of the intraclasts. Of the inclusions found in the very fine to coarse sand-sized intraclasts, 50 percent are very fine sand to silt-sized quartz grains, 30 percent microfossil fragments, 10 percent phosphate allochems, 5 percent glauconite grains, approximately 1 percent each of feldspar, clay clasts, calcite allochems, dolomite rhombs, pyrite inclusions, and variable amounts of organic matter.

Pelletal allochems (Fig. 8) comprise the second major group of phosphate grain types, accounting for 20 percent of the phosphate in the Pungo River Formation. The uniformity in size and the regular geometric shapes of the pellets are the two main characteristics that distinguish pelletal phosphate grains from highly abraded fine to

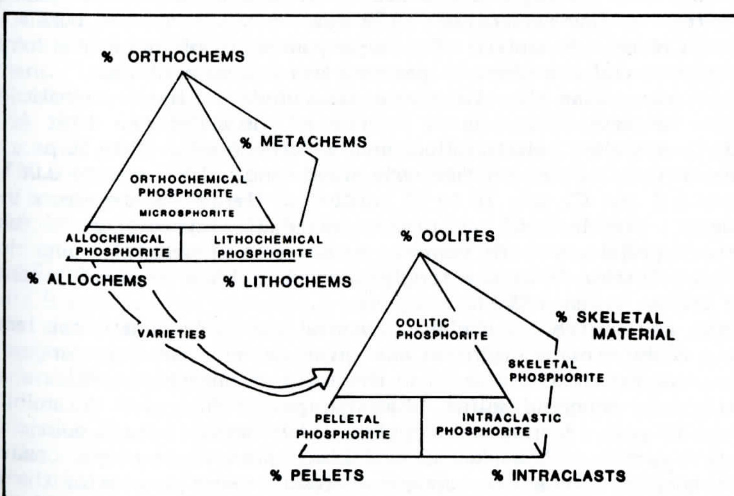

Figure 6. Classification scheme for megascopic sedimentary phosphate grains (modified from Riggs, 1979a).

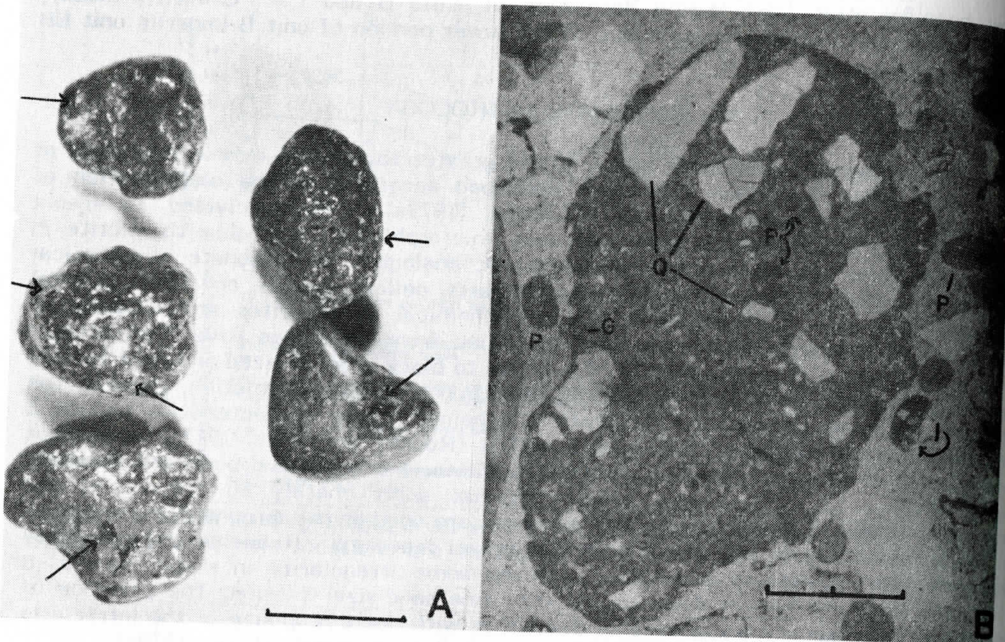

Figure 7. A) Coarse to very coarse sand-sized phosphate intraclasts. Notice the abundant inclusions of clear quartz; the subangular to subrounded, irregular surface texture of the intraclasts. Scale bar equals 1.0 mm. B) Thin section of a coarse sand-sized phosphate intraclast. The disseminated inclusions are dominantly bladed to angular, silt to fine sand-sized quartz grains (Q). Two very fine sand-sized phosphate pellets (P) and a glauconite grain (G) are also present as inclusions. Note the irregular surface of the intraclast which is partially due to the breaking out of the inclusions during transport. Very fine sand-sized phosphate pellets (P) and intraclasts (I) can be seen adjacent to the coarse sand-sized intraclast. Scale bar equals 0.2 mm.

very fine sand-sized intraclasts. The Pelletal phosphates are moderate to dark brown in color, extremely well sorted, and are ovoid, ellipsoidal, and rod-shaped. They are dominantly fine to very fine sand-sized (0.177 mm to 0.063 mm) and consist primarily of a cryptograined phosphate matrix with varying amounts of inclusions dominated by microfossil fragments and less than 10 percent terrigenous material.

All of the units within the study area are dominated by intraclastic phosphate grains in the fine to medium sand-sized fraction of the sediment. Unit A, however, is characterized by abundant pelletal allochems, which comprise 30 to 50 percent of the phosphate grains in the fine to very fine sand-sized range (0.177 mm to 0.063 mm). In the overlying units B and C, only 10 to 15 percent of the phosphate grains in this size range are pellets. The lack of observable concentric layering or microbotryoidal textures within the pellets, and the common occurrence of pelletal grains clustered in what appear to be burrow fillings, strongly suggest a fecal origin for some of the pellets (Riggs, 1979a; Riggs, 1980b).

Invertebrate and vertebrate skeletal material generally constitutes less than 15 percent of the phosphate macrograins in any given sample, but may range from 5 to 20 percent. Indirect evidence of fossils in the form of phosphatic molds and casts of pelecypods, ostracods, echonoid spines, diatoms, radiolarians, and foraminifera constitute less than 10 percent of most samples. Only an occasional oolitic grain was recognized in thin section. "Pseudo-oolites," which possess a nucleus grain but lack well-defined concentric laminations, comprise from 2 to 3 percent of the phosphate grains in many samples.

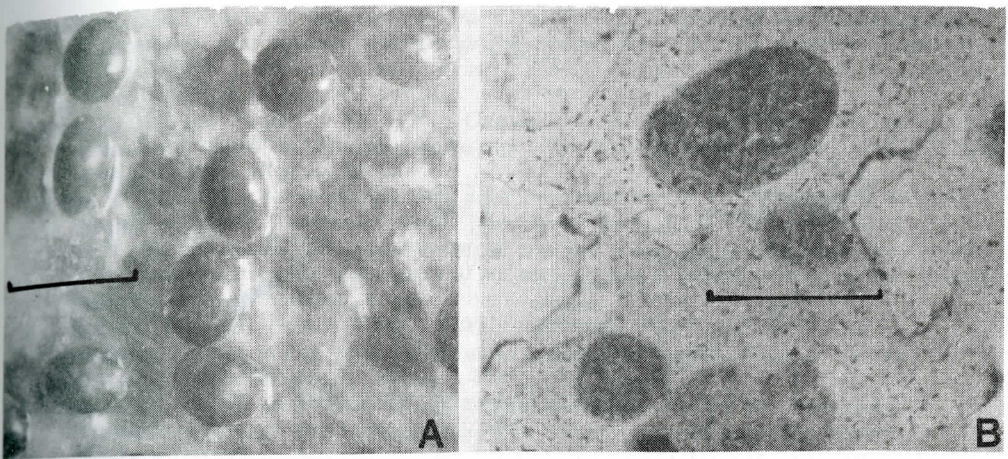

Figure 8. A) Very fine to fine sand-sized phosphate pellets. All grains illustrate the smooth and polished texture and the ovoid to spherical shape of the pellets. Scale bar equals 0.1 mm. B) Thin section of very fine to fine sand-sized phosphate pellets showing a regular outline, smooth surface, and a lack of terrigenous inclusions. The mottled interior of the grains results from the organic matter (bacterial rods, spheres, and aggregates) contained within the carbonate fluorapatite matrix (Riggs, 1979a). Scale bar equals 0.1 mm.

SUMMARY

The Aurora Embayment extends south from the Chowan Arch to the Cape Lookout High. The westward limit of the Embayment is a line approximately coincident with, and parallel to, the White Oak Lineament. Up to 30 m of phosphorites and phosphatic sediments of the Pungo River Formation were deposited in the eastern portion of the Aurora Embayment. The formation thins westward, pinching out at the White Oak Lineament, and thins southward to 10 to 15 m over the Cape Lookout High.

Seven major sediment units (units A, B, C, D, BB, CC, and DD) comprise the Pungo River Formation within the southern half of the Aurora Embayment. Throughout most of the study area, the formation consists of units A, B, C, and D or DD which are laterally persistent and correlative in terms of mineralogy and texture and reflect a distinct cyclical pattern of sedimentation as defined by Riggs and others (1982b) for the Aurora Area. These four units are erosionally truncated eastward from the White Oak Lineament. Units A, B, and C are the main phosphate-bearing units in the Aurora phosphate district. Vertical trends in sedimentation can be recognized throughout most of the study area and include: 1) decrease in phosphate content and increase in carbonate content upward within each of units A through C; 2) an overall increase in phosphate content upward from unit A through unit C; and 3) a slight decrease in grain size upward from unit A through unit C.

Unit BB is an 11-m-thick diatomaceous facies, which contains up to 70 percent diatom fragments, and occurs in the eastern portion of the Aurora Embayment. Facies BB is considered to be the downbasin equivalent of the shallower-water phosphorite sands of units B and C. The apparent contemporaneous depositon of the diatomaceous sediments in the east-central embayment area with the greatest development of phosphate sedimentation in the upslope area to the west suggests that both the phosphorite and diatomite were deposited in response to increasing organic productivity. Such a depositional regime could reflect the increasing influence of upwelling currents upward through the section and westward across the embayment in response to the early to middle Miocene transgression as described by Riggs and others (1982b). The depositional regime thought to have existed during this portion of the transgression is sketched in Figure 9.

Unit CC is a shelly calcareous medium-grained quartz sand facies that was deposited in the southern margin of the Aurora Embayment, forming contemporaneously

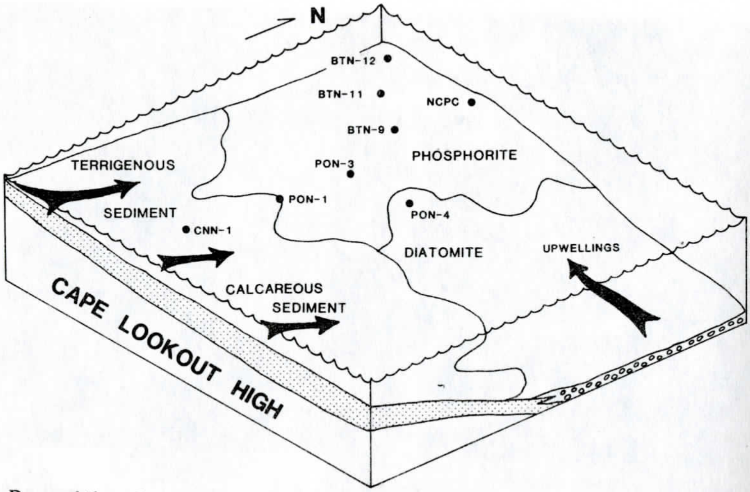

Figure 9. Depositional regimes which existed in the southern portion of the Aurora Embayment during the early to middle Miocene transgression which produced the Pungo River phosphorites and associated sediment facies. Phosphorites are forming in the central facies (units A, B, or C), diatomaceous sediments are forming in the eastern facies (unit BB), and terrigenous and calcareous-rich sediments are being deposited in the southern facies associated with the Cape Lookout High (unit CC).

with the phosphorites of units A, B, and C in the central portion of the embayment. Deposition of dominantly terrigenous and calcareous sediments on and adjacent to the Cape Lookout High effectively diluted and prohibited phosphorite sedimentation south of core hole PON-1 (Figs. 4 and 9).

The phosphate component of the Pungo River Formation is dominated by intraclastic allochemical grains. This suggests the development of orthochemical microsphorite muds within the Aurora Embayment; these muds were subsequently fragmented, transported, and deposited as intraclastic grains (Riggs, 1979a, 1980b). Unit A contains a significant concentration of pelletal phosphate grains. This may represent an environment in which the orthochemical phosphate mud remained in suspension and was biogenically extracted from the water, concentrated, and excreted as fecal pellets (Riggs, 1979a, 1980b). This interpretation supplies additional support for the in situ deposition of the phosphate in unit A as described by S. W. Snyder and others (1982).

Optimum conditions for the formation and deposition of phosphate occurred on the shelflike platform along the west-central embayment margin (Fig. 9). Downdip, to the east, is the axis of maximum thickness of units A, B, and C; phosphate deposition decreased rapidly downbasin while the deposition of diatomaceous sediments increased (Fig. 5). Along the southern margin of the embayment, increased terrigenous and carbonate sedimentation took place in association with the Cape Lookout High (Fig. 4). Updip, to the west, units A through D were sequentially truncated by post-Pungo River erosion (Fig. 5). Consequently, there is a narrow north-south zone of major phosphate concentration, which formed behind the Cape Lookout High and along the upper basin margin in the west-central portion of the Aurora Embayment (Fig. 9).

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DIAGNOSTIC FORAMINIFERA AND PALEOECOLOGY OF THE PUNGO RIVER FORMATION, CENTRAL COASTAL PLAIN OF NORTH CAROLINA

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ABSTRACT

Benthic foraminiferal assemblages of the Pungo River Formation (middle Miocene) from the central North Carolina Coastal Plain indicate deposition in continental shelf environments.

In Beaufort and Pamlico Counties, part of the Aurora Embayment, faunas from the lower part of the formation (units A and B) have an abundance of ***Buliminella elegantissima***, ***Bulimina elongata***, and ***Elphidium excavatum***. ***Florilus pizzarensis***, ***Cibicides lobatulus***, ***Elphidium limatulum***, ***Nonionella miocenica***, ***Hanzawaia concentrica***, and ***H. nipponica*** occur sporadically and are of secondary importance when present. High faunal dominance (averaging greater than 50 percent), low diversity values (Shannon-Wiener Information Function averaging 1.4), and rarity of planktonic foraminifera suggest that these units were deposited in inner or middle shelf environments. With the exception of ***E. limatulum***, predominant species from the upper part of the formation (units C, D, and DD) are those that are of secondary importance in the lower units. Faunal dominance averages 33 percent, diversity values are moderate (averaging 2.3), and planktonic specimens are more abundant. These units were deposited in more open water marine environments, probably on the middle or outer shelf.

In Craven County, along the northern flank of a pre-Miocene topographic high, the predominant species throughout the formation are ***Cassidulina laevigata*** and ***Uvigerina calvertensis***, forms suggesting an outer shelf environment. However, high faunal dominance, moderate diversity values (2.0 to 2.7), and the rarity of planktonic specimens are inconsistent with an outer shelf setting. Perhaps typical offshore species migrated shoreward in response to favorable conditions related to the adjacent high. Assemblages of the unit associated with this high (unit CC) grade laterally into those of units farther north.

In Carteret County, south of the high and along the northern edge of Onslow Bay, faunas are similar to those from units C, D, and DD in the Aurora Embayment. Several species present here are absent in the Aurora Embayment, their migration perhaps prevented by environments associated with the intervening topographic high.

INTRODUCTION

The Pungo River Formation is part of the middle Miocene to early-late Pliocene Chesapeake Group. Sediments of this group occur within the Atlantic Coastal Plain in Delaware, New Jersey, Maryland, Virginia and North Carolina. Brown (1958) first described sediments that were later assigned to the Pungo River Formation from the subsurface of Beaufort County, North Carolina. He correlated these sediments with the middle Miocene Calvert Formation of Maryland, thus placing them in the basal portion of the Chesapeake Group. Kimrey (1964) formally named the formation using a core from the vicinity of Belhaven, North Carolina as the type section. His lithologic description of the sediments has since been modified by Miller (1971) and Scarborough and others (this issue) to include an unconsolidated coquina that lies immediately above the originally designated sedimentary sequence of the type section.

Cores from a portion of the North Carolina Coastal Plain that includes Beaufort, Pamlico, Craven, and Carteret Counties were examined during this study (Fig. 1). Descriptions of the foraminiferal assemblages from the Pungo River Formation within this area are based on detailed studies of five cores (BTN-9, PON-1, PON-4, CNN-1, and CTN-1) selected from a series of 66 cores taken by Riggs (1967) during a study conducted for the International Minerals and Chemical Corporation. Each core is designated by two capital letters that represent the first and last letters of the county in which it is located, and by a capital "N" and numerals that indicate the position of the core within the series taken for that county. An additional core (NCPC) was selected from a series of cores taken by the North Carolina Phosphate Corporation. Several other cores from the International Minerals and Chemical Corporation Project (BTN-12, BTN-11, and PON-3) were spot sampled in order to check faunal characteristics noted within the six primary cores. Together, these cores provide a north-south transect through eastern North Carolina from central Beaufort County to southern Carteret County.

The study area can be subdivided into three regions on the basis of the lithologic and faunal characteristics of the Pungo River Formation. The northernmost region, hereafter referred to as the Aurora Embayment, includes Beaufort, Pamlico, and portions of northern Craven County. The sedimentary units and associated foraminiferal assemblages recognized within this embayment change rather abruptly just south of the Neuse River in southern Craven and northern Carteret Counties. These changes are related to the presence of a pre-Miocene topographic high (Miller, 1971) that demarcates the southern extent of the Aurora Embayment. The distincitive lithology and fauna of Pungo River sediments associated with this topographic high constitute the second subdivision of the study area. A third region lies immediately to the south, in central and southern Carteret County. The lithologic units and foraminiferal assemblages from this region are quite similar to those from the upper part of the Pungo River section in the Aurora Embayment.

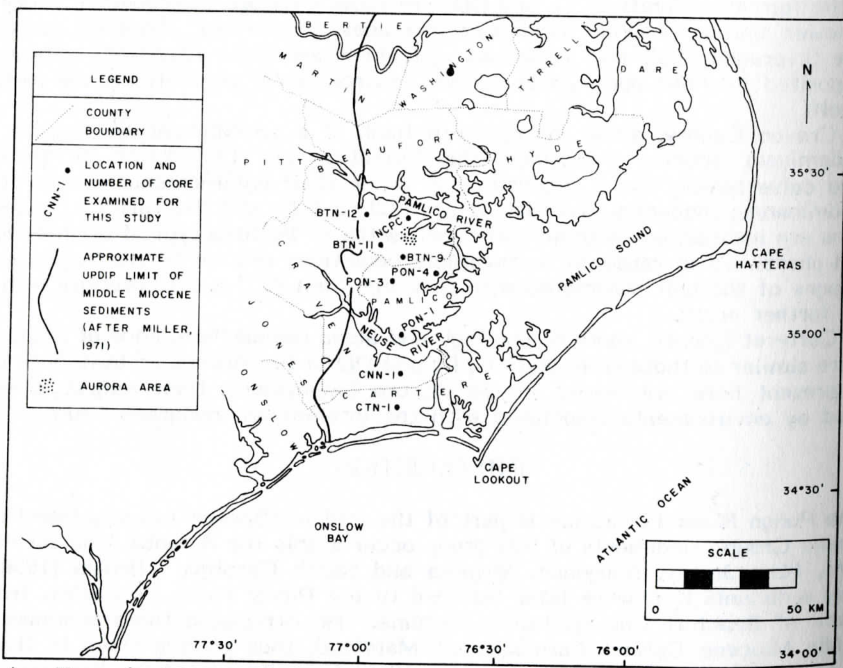

Figure 1. Map of study area showing location of cores.

The Pungo River Formation unconformably overlies sediments of Eocene to Oligocene age and is, in turn, unconformably overlain by the Yorktown Formation of early to early-late Pliocene age (Hazel, 1971; Akers, 1972; Snyder and others, in press) and by the Duplin Formation, which is correlative with the Yorktown (Gibson, in press). Pungo River sediments are present in the subsurface of North Carolina from approximately 77°00' west longitude eastward to the coastline (Miller, 1971). Within the study area the formation ranges from a maximum thickness of approximately 70 meters in Pamlico County to less than one meter near its updip limit in Beaufort County. It also thins to about 15 meters along the pre-Miocene topographic high located in southern Craven County. In addition, Pungo River sediments have now been identified from Onslow Bay off the southeastern coast of North Carolina (Blackwelder and others, 1982; Lewis and others, 1982).

OBJECTIVES

This study was undertaken in order to accomplish two primary objectives. First, we have interpreted the depositional environment for each of the lithologic units that have been recognized within the Pungo River Formation. This aspect of the study complements the work of Scarborough and others (this issue) by superimposing information from the foraminiferal assemblages on the lithologic framework provided by their study. Because the phosphate accumulations within the formation are economically important, delineation of the lithologic units and interpretation of their depositional environments will help to determine the extent of minable deposits in the central North Carolina Coastal Plain. This approach may also contribute to the understanding of phosphate genesis. Second, we have attempted to determine which foraminiferal species are diagnostic of the Pungo River Formation in the study area. Such information should facilitate recognition of the formation, even where lithologic evidence may be less than conclusive. We do not wish to imply that the formation can be defined on the basis of its fauna. However, because it does include a variety of lithologies, and because there is a significant unconformity both above and below it throughout eastern North Carolina, recognition of species that are diagnostic of the formation may be a valuable stratigraphic tool.

PREVIOUS WORK

Gibson (1967) examined the planktonic and benthic foraminiferal assemblages of the Pungo River Formation at Lee Creek, North Carolina. His correlation, based on the presence of key foraminiferal and molluscan species, of the upper calcareous Pungo River beds with the Calvert Formation corroborated the interpretations of Brown (1958). Gibson stated that Pungo River sediments were deposited in a northeast-southwest trending oceanic embayment located south of the Norfolk Arch in southern Virginia and north of a positive feature whose axis is in the vicinity of New Bern, North Carolina. The latter feature probably represents the same positive area mentioned by Riggs (1967) and Miller (1971). Gibson's interpretation of the depositional environment was as follows: water depths of 100 to 200 meters for the phosphorite beds, and depths of less than 70 meters for the upper calcareous beds. Leutze (1968) stated that water depths may have been significantly shallower than those suggested by Gibson.

Miller (1971) conducted an extensive regional study of the Pungo River Formation based on core data from the North Carolina Coastal Plain. On the basis of the benthic foraminiferal fauna, he proposed an open marine, normal salinity, shallow shelf environment of deposition. Down-basin wells containing a sequence of basal phosphorites and calcareous sands yielded foraminiferal species indicative of a middle Miocene age, thus leading Miller to interpret the entire formation as middle Miocene.

Gibson (in press) has refined the age assignment of the Pungo River Formation on the basis of key planktonic and benthic foraminiferal species. He correlates portions of the formation with planktonic foraminiferal zones N. 8 and N. 11 (Blow, 1969). Planktonic assemblages indicating zone N. 11 are reported only from northeastern North Carolina; those indicating zone N. 8, from the vicinity of Norfolk, Virginia to south of the Neuse River in North Carolina. Strata belonging to the intervening zones N. 9 and N. 10 have not been recognized. According to Gibson, strata of this age may have been deposited and subsequently eroded, but he has not formally proposed the presence of a major unconformity within the formation.

METHODS OF STUDY

Most samples from the Pungo River Formation were processed for microfossils by 1) boiling in a dilute solution of Quaternary "O" (alkyl imidazolinium chloride), 2) wet sieving (U.S. Standard Sieve No. 230), and 3) flotation using carbon tetrachloride. The sample fraction that did not float was routinely examined to ensure that no specimens were being preferentially lost. Some samples were washed and sieved but not floated. Comparison of the two techniques indicated that no significant bias was introduced by flotation.

Where available, a minimum of 300 benthic foraminiferal specimens were picked in order to ensure the statistical validity of the counts (Chang, 1967). Action pair analysis (Lawrence, 1971) was employed for the paleoecologic interpretations. These interpretations were supplemented by statistical analyses of faunal variability and equitability. For the reasons outlined by Gibson and Buzas (1973) and Sanders (1968), these values were determined by using the Shannon-Wiener Information Function. In samples where 300 specimens could not be recovered, benthic species were identified but statistical analyses were not employed.

Samples were also examined in order to identify planktonic species that might be biostratigraphically useful. The relative abundance of planktonic versus benthic specimens was calculated, but no detailed analysis of the relative abundance of individual species within the planktonic assemblages was attempted.

GENERALIZED LITHOLOGIC FRAMEWORK

Scarborough and others (this issue) have recognized six major lithologic units within the Pungo River Formation. The following brief descriptions characterize the general lithology of each unit. The geographic and stratigraphic distributions of the units, none of which is continuous throughout the entire study area, are presented in Figures 2 and 3. The lowermost unit in the Aurora Embayment (unit A) is a fine to medium, dolomitic, muddy phosphorite sand capped by a phosphatic, quartz-bearing dolomite. The overlying unit B is a fine, dolomitic, muddy phosphorite sand that is also capped by a phosphatic, quartz-bearing dolomite. A thick section of diatomaceous clay encountered in the easternmost portion of the study area (core PON-4) has been mapped as a facies of unit B. Unit C, a fine to medium, muddy phosphorite sand interbedded with phosphatic, quartz-bearing, moldic limestones, overlies unit B. With the exception of unit C, which thins and pinches out in an eastward direction, these three units extend laterally throughout the Aurora Embayment. Unit D is an unconsolidated, shelly, quartz-bearing dolomite that occurs only in the northern portion of the study area.

Three of the units described above (A, B, and C) appear to grade southward into unit CC, a shelly, calcareous mud or calcareous, muddy, quartz sand with very minor phosphate content. Unit CC is characteristic of the entire Pungo River section in southern Craven County where it is associated with a pre-Miocene topographic high mapped by Miller (1971). Unit CC caps the axis of the high and extends onto the southern flank of the feature in northern Carteret County. The lateral relationship between unit CC and other units is highly interpretive. If any of the laterally equivalent units extended across this high, subsequent erosion associated with the post-Pungo River unconformity has removed them. More detailed coverage along the flanks of the topographic high will be necessary for more detailed resolution.

Unit DD is a fine to medium, muddy, calcareous shell hash with minor amounts of quartz and phosphate. It lies above unit C throughout most of the Aurora Embayment. It is also present in Carteret County where it grades into and may be interbedded with unit CC.

BENTHIC FORAMINIFERA

Aurora Embayment (Beaufort and Pamlico Counties): Two distinct benthic for-

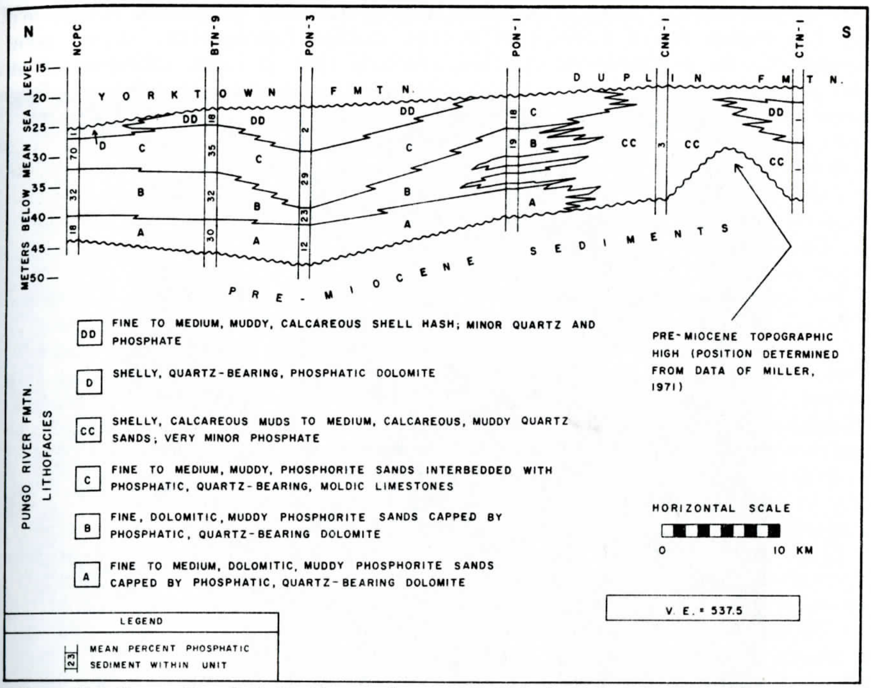

Figure 2. North-south distribution of major lithologic units in the Pungo River Formation (descriptions from Scarborough and others, this issue).

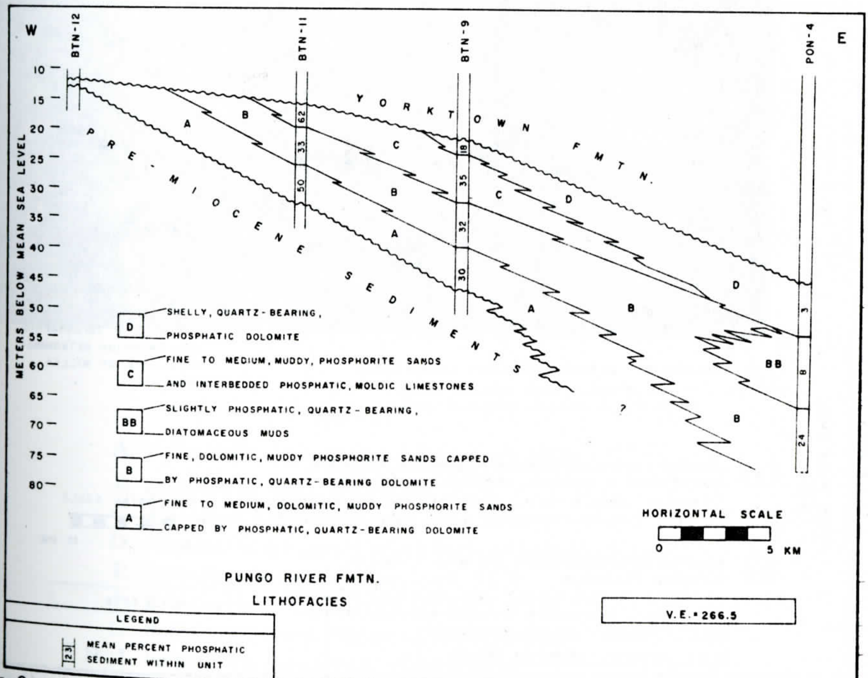

Figure 3. East-west distribution of major lithologic units in the Pungo River Formation (descriptions from Scarborough and others, this issue).

aminiferal assemblage zones, one lying stratigraphically above the other, are present within the Pungo River Formation in the Aurora Embayment. Each zone can be recognized by its predominant species, the one that is most abundant in any given sample (Poag, 1981), and by several species of secondary abundance. Because the predominant species varies from sample to sample, the several most abundant species of each zone are collectively described as predominant. They are listed according to the number of samples in which each is the most abundant form. Assemblage zone 1 corresponds to lithologic units A and B, the lower portion of the formation (Figs. 4 and 5). Assemblage zone 2 coincides with lithologic units C, D, and DD, the upper portion of the formation (Figs. 4 and 5). All species that are numerically important in either of these zones are figured in Plates 1-3.

The predominant species of assemblage zone 1 are: ***Buliminella elegantissima*** (d'Orbigny), ***Bulimina elongata*** d'Orbigny, ***Elphidium excavatum*** (Terquem). Species of lesser importance, both in terms of abundance and frequency of occurrence among the samples, include ***Florilus pizzarensis*** (Berry), ***Cibicides lobatulus*** (Walker and Jacob), ***Elphidium limatulum*** Copeland, ***Hanzawaia concentrica*** (Cushman), ***H. nipponica*** Asano, and ***Nonionella miocenica*** Cushman. ***Buliminella elegantissima*** and ***Bulimina elongata*** are abundant in both units A and B. ***Elphidium excavatum*** is most abundant in unit A and, although still an important faunal element, is less abundant than the previous two species in unit B. Species diversity values, expressed in terms of the Shannon-Wiener Information Function, are generally low. The mean value for all samples from this assemblage zone is 1.4 and many values below 1.0 were recorded. In this portion of the formation foraminiferal specimens are often too scarce to permit calculation of the information function. However, low diversity values characterize even the richest, best preserved samples. The abundance of the predominant species within assemblage zone 1 is generally high, averaging 51 percent and ranging as high as 90 percent in some samples. Planktonic specimens are rare or absent (mean P/B ratio of 1:42).

The predominant species of assemblage zone 2 are: ***Hanzawaia concentrica*** (Cushman), ***Hanzawaia nipponica*** Asano, ***Florilus pizzarensis*** (Berry), ***Cibicides lobatulus*** (Walker and Jacob), ***Nonionella miocenica*** (Cushman). Species of lesser importance

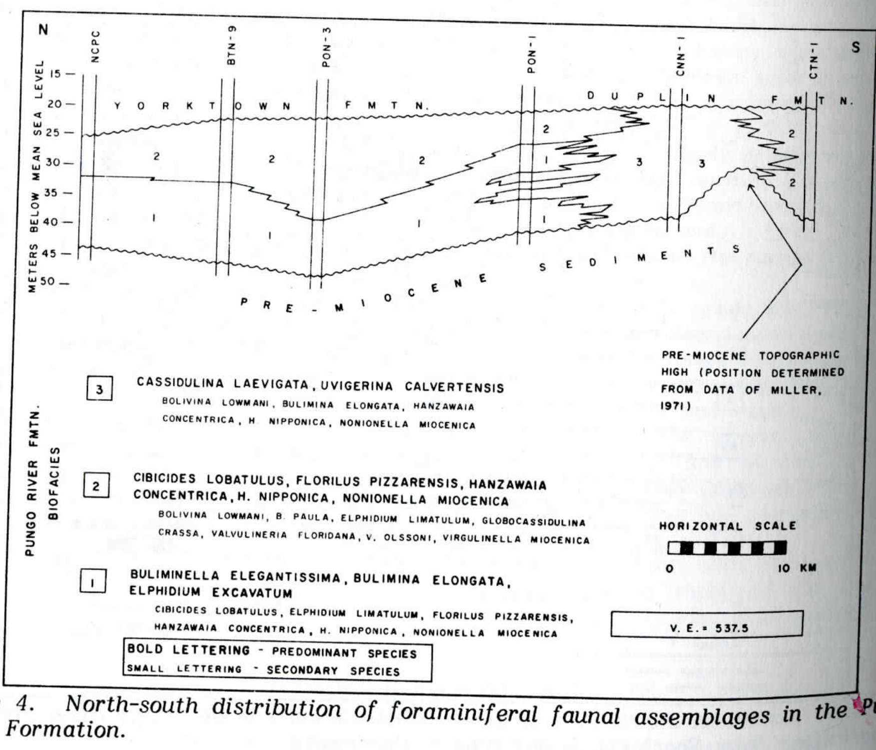

Figure 4. North-south distribution of foraminiferal faunal assemblages in the Pungo River Formation.

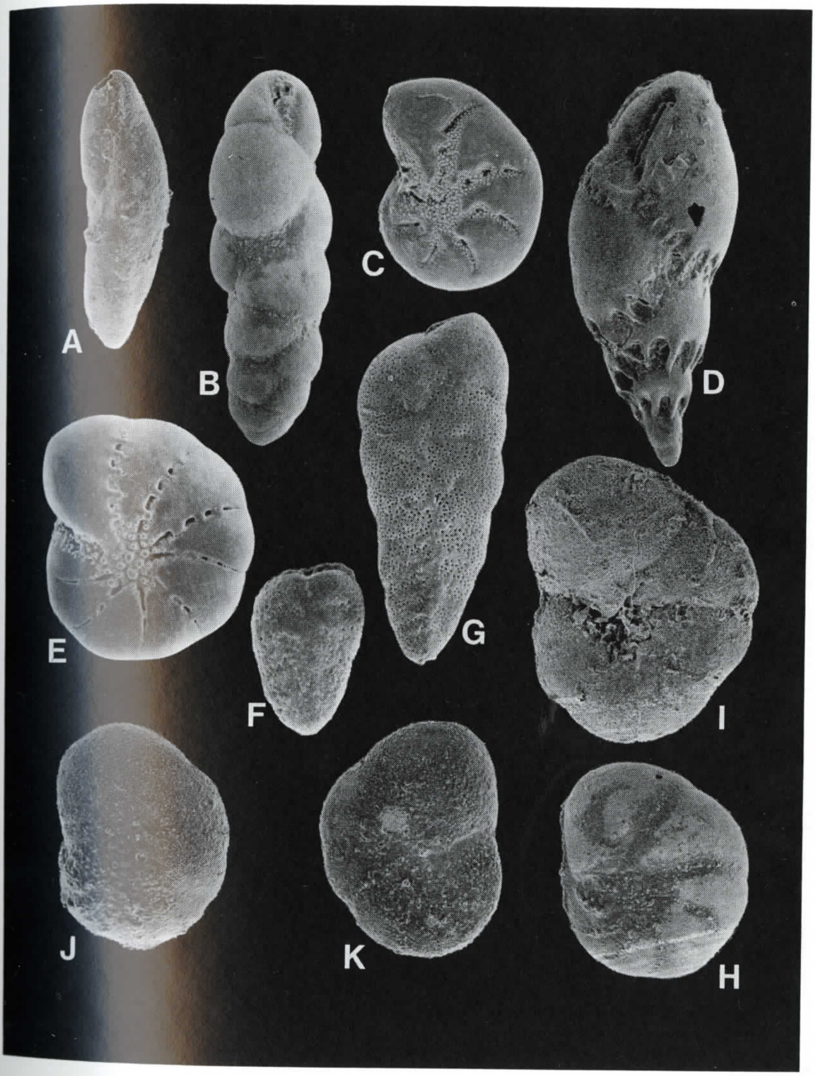

Plate 1

A. *Buliminella elegantissima* (d'Orbigny), X170
B. *Bulimina elongata* d' Orbigny, X170
C. *Elphidium excavatum* (Terquem), X170
D. *Virgulinella miocenica* (Cushman and Ponton), X130
E. *Elphidium limatulum* Copeland, X170
F. *Bolivina paula* Cushman and Cahill, X330
G. *Bolivina lowmani* Phleger and Parker, X250
H., I. *Valvulineria floridana* Cushman, X170
J., K. *Valvulineria olssoni* Redmond, X100

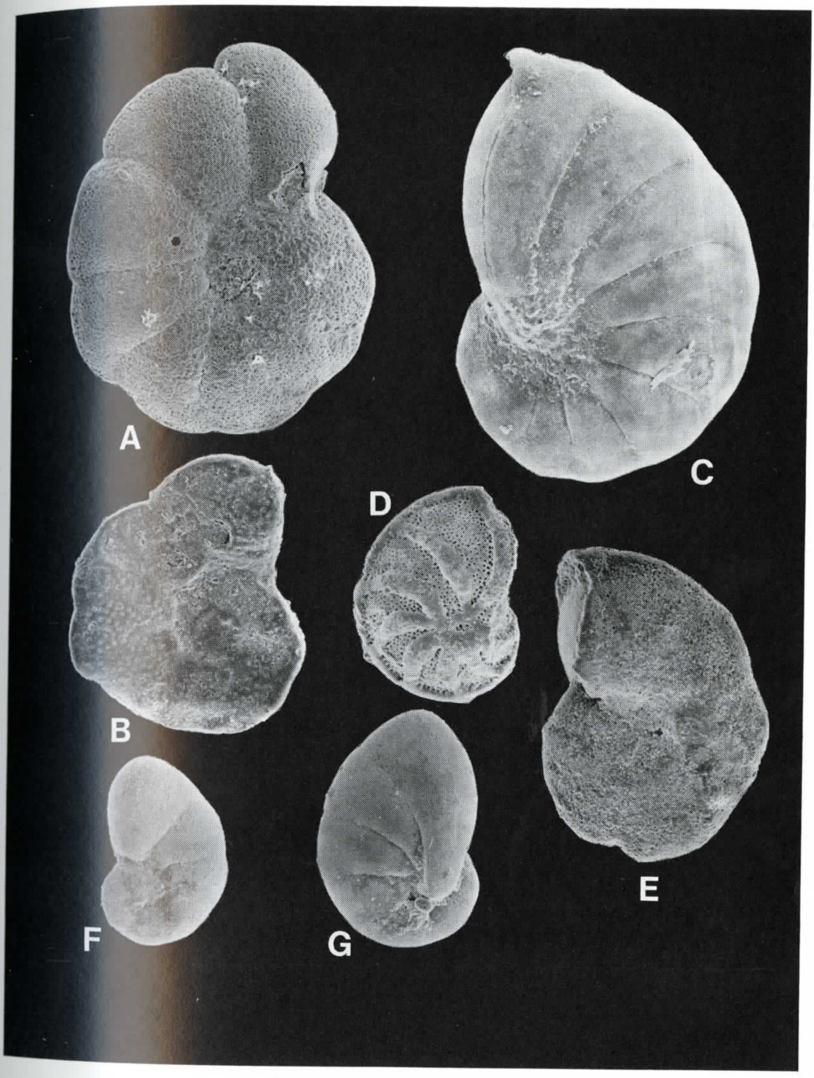

Plate 2

A., B. *Cibicides lobatulus* (Walker and Jacob), X170
C. *Florilus pizzarensis* (Berry), X170
D., E. *Hanzawaia nipponica* Asano, X170
F., G. *Nonionella miocenica* Cushman, X170

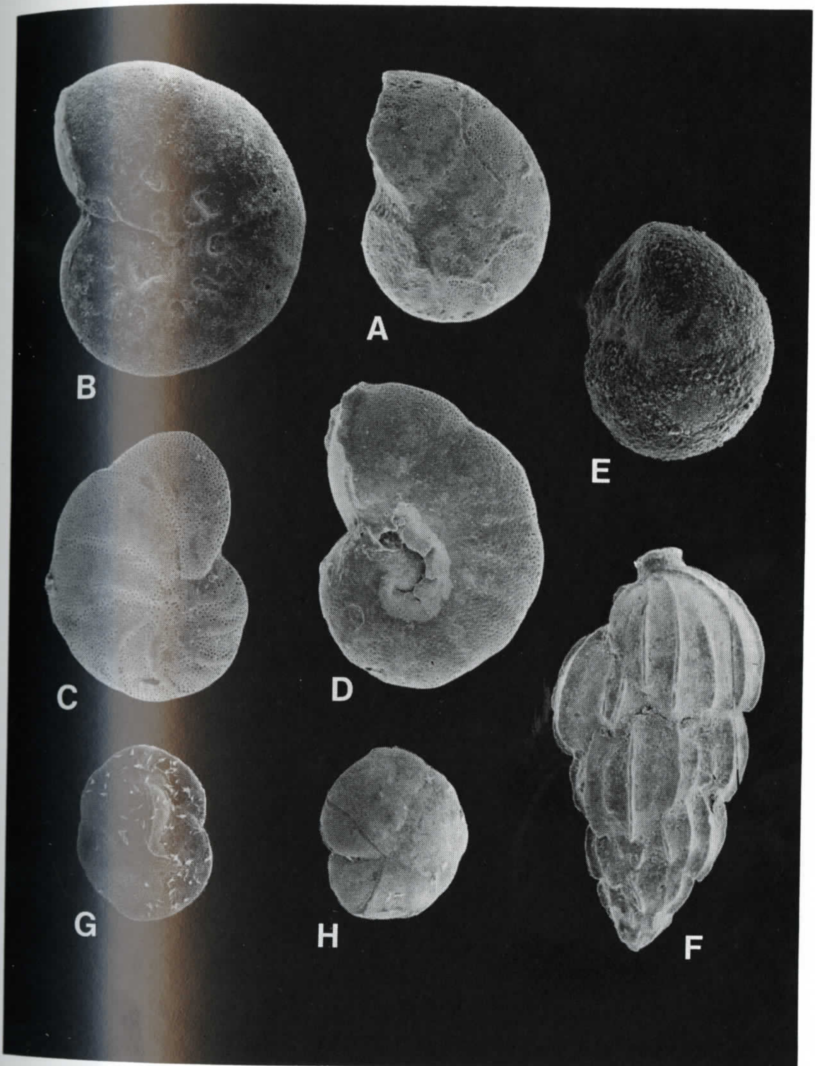

Plate 3

A.-D. *Hanzawaia concentrica* (Cushman), X170
E. *Globocassidulina crassa* (d'Orbigny), X250
F. *Uvigerina calvertensis* Cushman, X170
G., H. *Cassidulina laevigata* d'Orbigny, X170

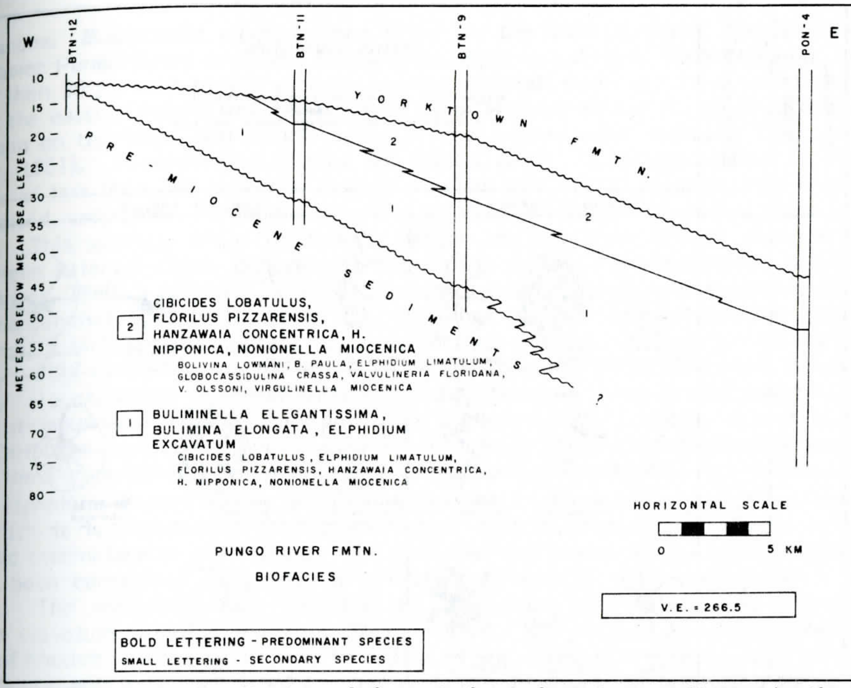

Figure 5. East-west distribution of foraminiferal faunal assemblages in the Pungo River Formation.

include *Virgulinella miocenica* (Cushman and Ponton), *Globocassidulina crassa* (d'Orbiqny), *Bolivina lowmani* Phleger and Parker, *Bolivina paula* Cushman and Cahill, *Elphidium limatulum* Copeland, *Valvulineria olssoni* Redmond, and *Valvulineria floridana* Cushman. *Buliminella elegantissima* and *Bulimina elongata* occur in nearly all samples from assemblage zone 2 but they are never numerically abundant. In the northern portion of the Aurora Embayment three sub-assemblages are present within assemblage zone 2 (Fig. 6). In subassemblage 2-A, stratigraphically the lowest of the three, *Cibicides lobatulus* is most abundant, with *Nonionella miocenica* and *Elphidium excavatum* ranking second and third respectively. Moving upward within the section, the predominant species of subassemblage 2-B are *Nonionella miocenica*, *Florilus pizzarensis*, and *Virgulinella miocenica*. *Hanzawaia concentrica*, *H. nipponica*, and *Cibicides lobatulus* are present in lesser abundance. The latter three species become predominant in subassemblage 2-C. Associated with them, but occurring in lesser abundance, are *Virgulinella miocenica*, *Valvulineria floridana*, *V. olssoni*, and *Globocassidulina crassa*. Southward toward the axis of the embayment these subassemblages are more difficult to recognize because *Bolivina lowmani* and *B. paula* become more abundant within each of them. Sediments along the southern margin of the embayment contain species characteristic of assemblage zone 2, but the subassemblages cannot be differentiated. It is in this area that *Elphidium limatulum* attains its greatest abundances.

Species diversity values for assemblage zone 2 are generally higher than those for assemblage zone 1. The mean value for all samples is 2.3 and only a few values below 2.0 were recorded. The abundance of the predominant species is generally lower, averaging 33 percent. Benthic foraminifera are abundant but preservation ranges from fair to poor. Planktonic specimens are more consistently present, more abundant, and more diverse (mean P/B ratio of 1:14) than in assemblage zone 1.

Pre-Miocene Topographic High (Southern Craven County): The southern extent of the Aurora Embayment is defined by a southwest-northeast trending pre-Miocene topographic high extending from southwest Carteret County through southeast Craven

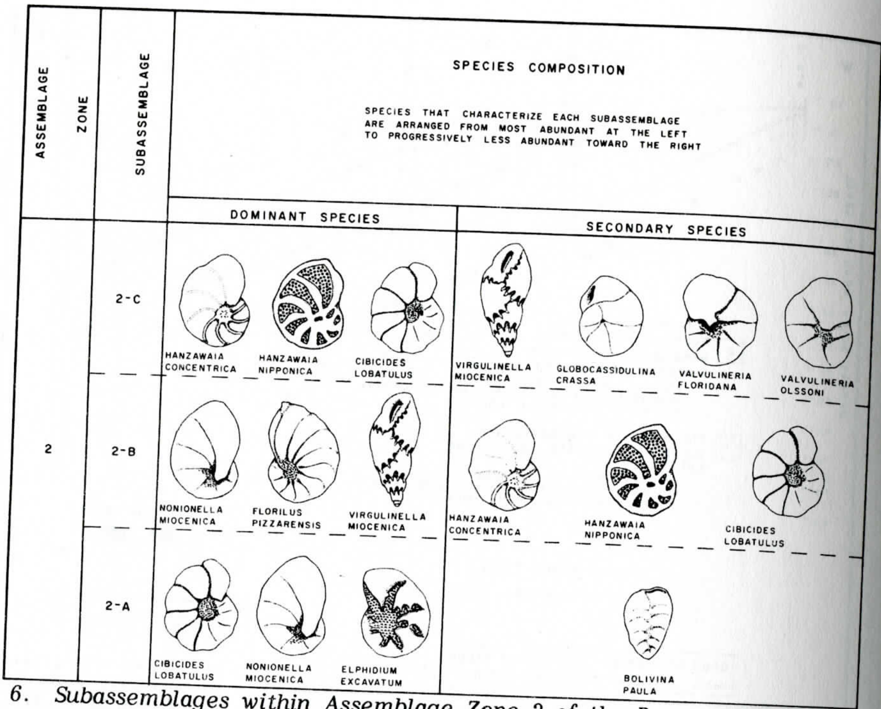

Figure 6. Subassemblages within Assemblage Zone 2 of the Pungo River Formation in the Aurora Embayment.

County (Miller, 1971). Pungo River sediments recovered from the northern flank of this high (core CNN-1) belong to Unit CC (Fig. 2), as defined by Scarborough and others (this issue).

The benthic foraminifera from the body of strata designated assemblage zone 3 are distinct from those found either to the north or to the south. Both geographic and stratigraphic distributions of this zone are shown in Figure 4. Predominant species of assemblage zone 3 are ***Cassidulina laevigata*** d'Orbigny and ***Uvigerina calvertensis*** Cushman (Plate 3). Species diversity values are moderate, ranging from 2.0 to 2.7; the abundance of the predominant species averages 27 percent. Planktonic specimens are consistently present but always rare (mean P/B ratio similar to that of assemblage zone 1).

Northern Edge of Onslow Bay (Carteret County): South of the pre-Miocene topographic high, along the northern edge of Onslow Bay, the Pungo River Formation consists of units CC and DD (Fig. 2). The foraminiferal assemblages are similar to those in units C, D, and DD of the Aurora Embayment, and they are characteristic of assemblage zone 2 (Fig. 4). Predominant species, diversity values, faunal dominance, and the abundance of planktonic specimens compare closely to those of upper Pungo River sediments of the Aurora Embayment. However, the subassemblages recognized in that embayment cannot be distinguished in samples from Carteret County. In addition, several forms that were not recorded from the Aurora Embayment are present in this southern region. These forms include ***Siphogenerina lamellata*** Cushman, which has been recorded by other authors (Miller, 1971; Gibson, 1967) from areas farther north, and ***Saracenaria sp.***

PALEOECOLOGICAL INTERPRETATIONS

Assemblage Zone 1: Two of the predominant species from this zone survive to the Recent, and information is available concerning their respective ecological optima and tolerances. *Buliminella elegantissima* is by far the most abundant species throughout the lower Pungo River section. *Buliminella spp.*, including *B. elegantissima*, comprise more than 20 percent of the modern benthic population on the inner continental shelf along the eastern side of the Mississippi Delta (Walton, 1964). *B. elegantissima* is most common on the inner and middle shelf of the western and southern Gulf of Mexico (Poag, 1981). According to Culver and Buzas (1981), *B. elegantissima* is limited to depths of less than 200 m in the Gulf of Mexico. Of the 50 recorded occurrences that they cited, only three lie deeper than the shelf edge and 40 are on the inner or middle shelf. This species, while limited to depths of less than 200 m along the North American Atlantic coast, occurs most frequently on the inner and middle shelf (Culver and Buzas, 1980). Although *B. elegantissima* occurs in small numbers on many modern continental shelves (Schnitker, 1971), it becomes the predominant benthic species only in areas of high organic content and nutrient-rich waters. According to Seiglie (1968), Bandy's work on sewage outfall areas along the southern California shelf demonstrated that *B. elegantissima* is consistently the most abundant living benthic species. Seiglie noted its abundance in sediments with high organic carbon content on several areas of the Caribbean continental shelf. The predominance of *B. elegantissima* in units A and B of the Pungo River Formation suggests deposition in nutrient-rich waters.

Elphidium excavatum is generally the third most abundant species in assemblage zone 1. It is occasionally the predominant species, comprising 48 percent of the benthic assemblage in one sample. The abundant occurrence of the genus *Elphidium* has often been considered diagnostic of shallow continental shelf environments (Walton, 1964). The morphologically variable *E. excavatum*, particularly the ecophenotypic forma *clavatum* (Feyling-Hanssen, 1972), exhibits just such a pattern in the northern Gulf of Mexico where it is limited to depths of less than 50 m (Culver and Buzas, 1981). Sen Gupta and Strickert (1982) noted that forma *clavatum* generally dominates the living benthic assemblage on the inner continental shelf between southern North Carolina and northern Florida; it is virtually absent at depths greater than 64 m. However, Poag and others (1980) reported *E. excavatum* forma *clavatum* as one of six species that dominate living and dead assemblages on the New Jersey outer continental shelf, an area of sluggish circulation with the hydrographic character of a huge estuary. Forma *clavatum* is abundant across the shelf and occurs in moderate frequencies on the upper slope of North Carolina (Schnitker, 1971). Streeter and Lavery (1982) noted that *E. excavatum* occurs sporadically over a wide depth interval along eastern North America. Culver and Buzas (1980) reported that along the Atlantic coast this species is ubiquitous, commonly occurring across the shelf and slope with a few occurrences in abyssal depths. *E. excavatum* is the most abundant living species at 1500 m depth on the continental slope of Newfoundland (Schafer and Cole, 1982). They believe that its occurrence on the mid-slope may be caused by passive transport from the shelf. Regardless of the dispersal mechanism, the occurrence of *E. excavatum*, even in significant numbers, is not definitive evidence of shallow, inner shelf environments. There is little doubt that this species is opportunistic, becoming numerically important where conditions are not suitable for most other species. Its presence in assemblages generally dominated by *Buliminella elegantissima* is therefore reasonable. Its distribution is not, however, directly related to bathymetry or to geographic locality (Miller and others, 1982).

Bulimina elongata, the second most abundant species in most samples from assemblage zone 1, is an extinct form. The *Bulimina* generic predominance facies characterizes continental slope environments in the Gulf of Mexico (Walton 1964; Poag, 1981). Although not among the six dominant species recognized by Schnitker (1971) off the North Carolina coast, species of *Bulimina* attain their greatest abundance on the continental slope. However, *Bulimina* is known from continental shelf environments in areas that have an intense and shallow oxygen minimum. Phleger and Soutar (1973) found buliminids in the high dominance, low diversity benthic populations of Santa Barbara Basin and the continental shelf off Baja California. Seiglie (1968) stated that species of *Bulimina* have symbiotic algae in their protoplasm that allows them to flourish in environments with a scarcity of oxygen. Modern examples of continental shelf areas with an oxygen minimum are associated with upwelling and high organic production. The association of *Bulimina*, in this case *B. elongata*, with *Buliminella elegantissima* is to be expected in such environments.

The three most abundant species of assemblage zone 1 generally comprise 60 to 93 percent of the benthic fauna, and paleoecological analysis is based largely on these taxa. As stated by Poag and others (1980, p. 56), ". . . when quantitatively establishing biofacies that reflect environmental conditions, fluctuations in the proportions of widespread and abundant species should yield about the same degree of resolution as is obtained from analyzing the entire assemblage." The association of *Buliminella elegantissima*, *Bulimina elongata*, and *Elphidium excavatum* indicates unusual conditions, probably related to high nutrient supply, that were not generally suitable for most species. High faunal dominance and low diversity support this interpretation. Although each of these species may exist over a wide depth interval, *B. elegantissima* and *E. excavatum* usually attain their greatest abundance on the inner or middle continental shelf. Associations of abundant *Buliminella* and *Bulimina* have been documented in nutrient-rich shelf environments. Combined with the scarcity of planktonic specimens, this evidence suggests an inner or middle shelf setting for the deposition of phosphorites in units A and B.

Assemblage Zone 2: Ecological tolerances for several of the species that characterize this zone are well known. *Hanzawaia concentrica* attains its greatest abundance (>15 percent) in the central continental shelf of North Carolina. Schnitker (1971) considered its presence in frequencies greater than 10 percent to be diagnostic of the central shelf. *H. concentrica* is rather evenly distributed across the continental shelf from Florida to Cape Cod (Culver and Buzas, 1980). This species occurs at depths approaching 1000 m in the Gulf of Mexico (as compared to 200 m along the Atlantic coast). However, of the 78 occurrences recorded in the Gulf by Culver and Buzas (1981), 56 are on the continental shelf. Frequencies of *Hanzawaia spp.* greater than 10 percent are limited to depths of less than 60 m in the northeastern Gulf of Mexico (Walton, 1964). *H. concentrica* is present in moderate to large numbers on the inner and middle shelf throughout the Gulf of Mexico (Poag, 1981).

Cibicides lobatulus has been recorded from littoral (Bhatia, 1956) to abyssal depths (Parker and others, 1953), probably because several species concepts have been included in this taxon. From Cape Hatteras to Newfoundland, *C. lobatulus* occurs in estuaries, across the shelf, and onto the slope. It is reported only from depths less than 200 m and most reported occurrences are from the shelf (Culver and Buzas, 1980). It is present in benthic populations from the Labrador shelf (Vilks and others, 1982) but Schafer and Cole (1982) also reported it from the lower continental slope of Newfoundland. *C. lobatulus* is among the six species that dominate living and dead assemblages on the New Jersey outer shelf (Poag and others, 1980). There it occupies topographic lows characterized by relatively warm, saline, and quiet waters. Reported occurrences in the Gulf of Mexico are too few to recognize any meaningful pattern (Culver and Buzas, 1981).

Bolivina lowmani and *B. paula* become more abundant southward in the Aurora Embayment, combining to account for 38 percent of the benthic assemblage in one sample. *B. paula* occurs across the Atlantic continental shelf from Cape Hatteras to Florida. Although present in samples from the slope, it is characteristically limited to depths less than 200 m (Culver and Buzas, 1980). *B. lowmani* is the most abundant benthic species on the main part of the Florida-Hatteras slope, but it also attains sizable populations on parts of the adjacent shelf (Sen Gupta and Strickert, 1982). In the Gulf of Mexico, *B. lowmani* is the predominant species of the genus along the outer shelf and upper slope of Texas and Campeche (Poag, 1981). Walton (1964) shows its greatest abundance between 100 and 400 m. However, it is also abundant on the inner shelf along the eastern side of the Mississippi Delta (Walton, 1964). This species occurs in moderate numbers from the inner shelf to the Sigsbee Plain (Poag, 1981). *B. paula* is too rare in the Gulf of Mexico to exhibit any meaningful distributional patterns.

Although *Nonionella miocenica* has been reported from the Recent (Cushman, 1939), its ecological tolerances are not well understood. Other species of the genus are ubiquitous along the Atlantic coast of North America, but most reported occurrences are from the continental shelf (Culver and Buzas, 1980). *Nonionella spp.* attain their greatest abundance on the continental shelf adjacent to the Mississippi Delta in the northeastern Gulf of Mexico (Walton, 1964; Poag, 1981). The genus is common elsewhere on the shelf around the Gulf, but is rare in deep-water facies.

Florilus pizzarensis has not been reported from Holocene sediments of the Atlantic coast or the Gulf of Mexico. The genus *Florilus* is sparsely represented along the Atlantic coast (Culver and Buzas, 1980), though Schnitker (1971) reports it in modest frequencies across the shelf and upper slope of North Carolina. Recorded occurrences of *Florilus spp.* in the Gulf of Mexico are nearly all from abyssal depths (Culver and Buzas, 1981).

The predominant species of assemblage zone 2 are typical of more normal marine conditions than were indicated for assemblage zone 1. Though many of these species may exist across a wide depth interval, they typically occur most frequently and most abundantly on the middle and outer continental shelf. Higher diversity values and lower faunal dominance suggest a more open shelf environment. The common occurrence of planktonic specimens supports this interpretation. The association of bolivinids, *Nonionella*, and *Florilus* has been correlated with high percentages of organic carbon in modern sediments (Seiglie, 1968; Phleger and Soutar, 1973). However, this faunal association typifies areas that are less productive than those dominated by *Buliminella spp.* The generic predominance of *Hanzawaia* in assemblage zone 2 also indicates more normal marine conditions.

The transition from nutrient-rich conditions to more normal marine conditions upward through the Pungo River sediments may have been the result of rising sea level. Although paleobathymetric interpretations are imprecise, several faunal trends (species composition, diversity, faunal dominance, abundance of planktonic specimens) are consistent with this interpretation. Sedimentological evidence (Scarborough and others, this issue) also suggests marine transgression.

Assemblage Zone 3: This zone is characterized by high frequencies of *Cassidulina laevigata* and *Uvigerina calvertensis*. *C. laevigata* is a common and consistent faunal element in the shelf edge waters of North Carolina (Schnitker, 1971). Todd (1979) listed it as characteristic of mid-shelf to upper slope environments. According to Culver and Buzas (1980), *C. laevigata* occurs most frequently on the outer shelf and slope from Florida to Cape Cod, with rare occurrences on the inner shelf and in abyssal depths. This species is ubiquitous in the Gulf of Mexico (Culver and Buzas, 1981; Poag, 1981), though Walton (1964) notes that its greatest abundance in the northeastern Gulf occurs on the continental slope. Modern species of the genus *Uvigerina* occur from inner shelf to slope environments (Todd, 1979). Culver and Buzas (1981) indicated that along the Atlantic coast *Uvigerina spp.* are ubiquitous, the area of most frequent occurrence varying among different species. Equally widespread distributional patterns occur in the Gulf of Mexico, but most species are especially abundant at the shelf edge and upper slope (Poag, 1981; Walton, 1964).

The most abundant taxa of assemblage zone 3 suggest an outer shelf to upper slope environment. However, the scarcity of planktonic specimens, relatively high faunal dominance, and moderate diversity values seem inconsistent with such an interpretation. Perhaps typical offshore species migrated shoreward in response to favorable conditions associated with the topographic high that existed in this region. Our evidence is not conclusive enough to document why such a migration might have occurred.

BIOSTRATIGRAPHY

Benthic Foraminifera: A number of benthic foraminiferal species are restricted to the Pungo River Formation throughout the study area. Unfortunately, most of them are rare and some individual samples contain no diagnostic forms. Those species found to be most useful as indicators of Pungo River sediments include *Bolivina calvertensis* Dorsey, *Siphogenerina lamellata* Cushman, *Hopkinsina bononiensis* (Fornasini), *Nonion marylandicum* Dorsey, *Virgulinella miocenica* (Cushman and Ponton), and *Uvigerina calvertensis* Cushman. Although several of these species have been reported from Miocene sediments that are younger than those of the Pungo River, the absence of such younger Miocene units within the study area makes them useful stratigraphic markers.

All of the species listed above are recorded by Gibson (in press) as reliable indicators of the Pungo River Formation. In addition, he describes several new species that are also restricted to the formation.

Planktonic Foraminifera: Planktonic foraminifera occur throughout the Pungo River section in the study area. However, it is only within sediments of assemblage zone 2 that they occur in any abundance. Specimens are scarce or absent in samples from assemblage zones 1 and 3. Planktonic species identified during this study are listed as follows: ***Globigerina praebulloides pseudociproensis*** Blow; ***G. juvenilis*** Bolli, ***G. woodi woodi*** Jenkins, ***Globigerinoides subquadratus*** Bronnimann, ***G. quadrilobatus quadrilobatus*** (d'Orbigny), ***Globigerinitella insueta*** Cushman and Stainforth, ***Globoquadrina altispira altispira*** (Cushman and Jarvis) ***G. altispira globosa*** Bolli, ***G. dehiscens*** (Chapman, Parr, and Collins) ***Globigerinita glutinata*** (Egger), ***G. uvula*** (Ehrenberg), ***Globorotalia (Turborotalia) birnageae*** (Blow), ***G. fohsi peripheroronda*** Blow and Banner, ***G. scitula praescitula*** Blow, ***G.*** cf. ***G. siakensis*** (Le Roy), ***Praeorbulina glomerosa glomerosa*** (Blow), ***Cassigerinella chipolensis*** (Cushman and Ponton). Although many of these species are long ranging, the forms that are biostratigraphically useful are essentially the same as those discussed by Gibson (in press). He has correlated this planktonic assemblage with zone N. 8 of Blow (1969), an interpretation with which we agree.

CONCLUSIONS

The Pungo River Formation of the central North Carolina Coastal Plain represents deposition within three distinct areas: 1) the Aurora Embayment in Beaufort, Pamlico and northern Craven Counties; 2) a pre-Miocene topographic high in southern Craven and northern Carteret Counties; and 3) another embayment in central and southern Carteret County that corresponds to the northern edge of the section exposed in Onslow Bay.

Two benthic foraminiferal assemblage zones are present in the Aurora Embayment. assemblage zone 1, the lower portion of the Pungo River Formation that includes lithologic units A and B, is characterized by high faunal dominance, low diversity, a sparse planktonic fauna, and an abundance of benthic species that indicate inner or middle shelf conditions. The abundance of ***Buliminella elegantissima*** suggests that water chemistry or nutrient supply was an important factor in limiting faunal diversity within the embayment. Occasional pulses of more normal marine circulation are indicated by the sporadic occurrence of mid-shelf faunal elements. Assemblage zone 2 is associated with the upper part of the section that includes lithologic units C, D, and DD. It is characterized by greater diversity, lower faunal dominance values, more abundant planktonic specimens, and benthic species that indicate more open marine, probably middle to outer shelf conditions.

Although the faunal trends indicate that Pungo River sediments in the Aurora Embayment were deposited during a marine transgression, the actual change in water depth may have been small. The association of assemblage zone 2 may have existed at depths as shallow as those inferred for assemblage zone 1. Assemblages from the Aurora Embayment are similar to those described by Smith (1968) for the middle to late Miocene phosphorites of the Monterey Shale in California. Smith interpreted the assemblages as representing deposition in water depths of 200 feet or less. Perhaps the faunal transition from zone 1 to zone 2 was due in large part to changes in organic content and nutrient supply. Another factor that may have contributed to this transition is the nature and mode of accumulation of the sediments. ***Cibicides lobatulus***, an attaching form that is influenced more by substrate type than by depth (Parker, 1952), is a minor constituent of assemblage zone 1, but it suddenly becomes abundant in zone 2. Certainly, the factors that caused observed faunal changes cannot be linked solely, or even primarily, to bathymetry.

The pre-Miocene topographic high in southern Craven County is composed of sediments (unit CC) containing foraminiferal assemblages that are conspicuously different from those in the Aurora Embayment. The numerically dominant species, ***Cassidulina laevigata*** and ***Uvigerina calvertensis***, suggest deposition in an outer shelf environment. But relatively high faunal dominance, moderate diversity values, the scarcity of planktonic specimens, and the association of this assemblage with a topographic high are inconsistent with such an interpretation. Perhaps these offshore species migrated shoreward in response to favorable environments associated with the flank of the high. Grain size of the substrate, current activity, and nutrient levels were probably important factors, but our evidence is not conclusive. The lateral relationships of this sediment system are highly interpretive; more concentrated coverage will be necessary to precisely determine them.

Benthic foraminiferal assemblages from the northern edge of the Onslow Bay system are similar to those of assemblage zone 2 in the Aurora Embayment, and a similar depositional environment is indicated for them. However, several species are present here that were not recognized in samples from the Aurora Embayment. Their migration into the more northern embayment may have been prevented by environments associated with the intervening topographic high. No sediments containing the fauna of assemblage zone 1 were encountered in this area. However, detailed work on the Onslow Bay system has just begun, and accurate comparisons between the two embayments cannot be made until this work is completed.

A number of benthic and planktonic species are reliable indicators of Pungo River sediments within the study area. Further studies, especially more detailed studies of the entire planktonic assemblage, may refine the precision of biostratigraphic interpretations.

TAXONOMIC NOTE

Elphidium excavatum (Terquem) and *Elphidium limatulum* Copeland, two of the species identified during this study of Miocene assemblages, are generally considered indicative of Pliocene or younger sediments. Specimens from the Pungo River Formation that are here placed in *E. excavatum* appear to lie within the limits proposed for that species by Feyling-Hanssen (1972). The presence of a similar species, frequently referred to in the literature as *Nonion inexcavatum* (Cushman and Applin), would be less problematical from a biostratigraphic viewpoint because it is known to occur lower within the Tertiary section. However, our specimens have fewer chambers, are less compressed, have more broadly open sutures, and lack the projecting knob of clear calcite that occurs in the umbilical area of *N. inexcavatum*. Specimens that we place in *E. limatulum* compare closely with Copeland's figures and descriptions for that species, except that they possess fewer and somewhat better developed sutural bridges. The presence of a similar form, described by Gibson (in press) as a new subspecies of *Nonion advenum* (Cushman), would be less problematical from the viewpoint of its previously established stratigraphic range. But unlike Gibson's subspecies, our specimens possess well developed sutural bridges, have fewer chambers, and lack any sort of umbilical boss.

Our interpretation extends the stratigraphic range of *E. excavatum* and *E. limatulum* downward into the Miocene. We wish to emphasize, however, that detailed work on the succession of morphologically similar Paleogene and Neogene forms may reveal that Pungo River specimens differ, perhaps at the subspecific level, from those of both older and younger sediments. Until such work has been completed, we interpret the Pungo River forms as more closely allied with those of younger sediments than with older forms.

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SYNTHESIS OF PHOSPHATIC SEDIMENT-FAUNAL RELATIONSHIPS WITHIN THE PUNGO RIVER FORMATION: PALEOENVIRONMENTAL IMPLICATIONS

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ABSTRACT

The lower part of the Pungo River Formation in the Aurora Embayment (units A and B) consists of phosphorite sands and interbedded dolomites that grade southward into calcareous quartz sands (unit CC) associated with a pre-Miocene topographic high. Within this embayment phosphate content decreases southward and becomes negligible in unit CC. Units A and B contain foraminiferal assemblages whose most abundant benthic species indicate inner or middle continental shelf environments. Planktonic specimens range from rare to absent in these units. Similar assemblages persist as the units thicken to the east. The sporadic occurrence of more diverse species associations in units A and B suggests that the depositional embayment was not restricted; but conditions were not generally suitable for most open shelf species. The predominance of *Buliminella elegantissima*, which flourishes in sewage outfall areas in modern seas, suggests that water chemistry or organic nutrient supply, perhaps related to phosphate genesis, limited foraminiferal faunal diversity.

Upper Pungo River sediments within the Aurora Embayment (units C, D, and DD) consist of phosphorite sands and interbedded phosphatic, quartz-bearing, moldic limestones. Units C and DD also grade southward into the calcareous quartz sands of unit CC. These upper units contain richer, more diverse benthic assemblages with high frequencies of middle and outer shelf species. Planktonic specimens are common within these units. Unlike the assemblages of units A and B, those of unit C suggest no unusual depositional conditions. Phosphorites of unit C are richer in phosphatic

sediments than are those of units A and B. The enrichment may reflect concentration by physical sedimentary processes. Faunal and sedimentary characteristics suggest that the phosphate of unit C was transported, perhaps being derived from adjacent areas of the embayment or directly from underlying units (A and B), in which the phosphorites appear to have formed in situ.

INTRODUCTION

The literature on phosphates is voluminous, and theories concerning the origin of sedimentary phosphate are diverse, often appearing to be somewhat contradictory. Among the theories that have been proposed in the past, several basic schemes that address the problem of phosphate genesis have received considerable support.

Most of the world's phosphorous resources occur in the form of ancient, bedded sedimentary phosphorites of marine origin (Manheim and Gulbrandsen, 1979). The importance of plants and organisms as a direct source for phosphorous has been emphasized by many authors. Seeley (1866), Bushinskii (1966), and Brongersma-Sanders (1957) cited the decomposition of marine organisms as a critical factor in phosphate genesis. Brongersma-Sanders (1957) and Rooney and Kerr (1967) suggested that episodes of mass mortality might be necessary to generate sufficient volumes of such decomposing matter. Others have contended that the upwelling of deep, phosphorous-rich water and its associated high productivity rates are the most essential elements for phosphate production (Kazakov, 1937, 1938; McKelvey, 1963). However, Manheim and Gulbrandsen (1979) pointed out that high nutrient concentrations are not the only factor involved in phosphate formation. Such concentrations occur near Antarctica and in the Gulf of Alaska, but there are no associated phosphorites. Also, there are phosphorites which have formed in areas where no large-scale upwellings are known to have occurred, such as the Blake Plateau and the Chatham Rise. Mansfield (1940) and Rooney and Kerr (1967) linked vulcanism with the occurrence of phosphate, suggesting that volcanic activity might affect water chemistry or cause mass mortality of marine organisms as a result of massive ash falls. Some workers have suggested that phosphate forms below the sediment-water interface, and thus its occurrence may not be directly related to characteristics of the overlying water mass. The phosphorous-rich interstitial water of some marine sediments is known to produce sedimentary phosphorite by the replacement of carbonates (Ames, 1959; Manheim and others, 1975). Baturin (1971), Cook (1967, 1976), and Bremner and Willis (1975) viewed replacement as an important mechanism in forming low grade phosphate, adding that mechanical reworking and concentration would then be necessary to produce high grade deposits. Miller (1971) and Riggs (1979) demonstrated that structural and geographic setting strongly influence the accumulation of significant amounts of phosphate. Riggs (1980) has also postulated a connection between the origin of economically important phosphate deposits and regional tectonism. Clearly, phosphorites respresent a complex sediment system in which any of the mechanisms discussed above, or any combination of those mechanims, may play a significant role.

Nearly as complex and controversial as the processes responsible for phosphate genesis are questions concerning the environment of deposition in which phosphorites accumulate. Shaler (in Penrose, 1888) suggested that phosphates originate in paludal environments in association with peats. Pevear (1966) linked phosphorites with phosphorous-rich waters supplied by estuarine marshes, thus implying accumulations in nearshore, marginal marine environments. Gibson (1967) and Miller (1971) associated economic phosphate deposits with shallow shelf, open marine environments ranging in depth from 100 to 200 meters. According to Riggs (1979), coastal environments and shallow water structural platforms serve as optimum areas for phosphorite formation. Manheim and others (1975) documented the formation of contemporary phosphorites in marine environments ranging to depths of 1000 meters. It appears that phosphate may originate in a variety of environments as a result of several different mechanisms or combinations of mechanisms.

Weaver and Beck (1977) pointed out that one very essential concern should be to distinguish between in situ and transported phosphatic sediments. This distinction is difficult to recognize, and little has been done to determine specific criteria that are useful for its recognition. However, distinguishing between in situ and transported phosphatic sediments has great potential importance because: 1) it may serve to focus investigations concerning phosphate genesis on in situ deposits, thus eliminating the complexity of dealing with the complete spectrum of phosphorite accumulations; and 2) it may aid in understanding the mode of accumulation of phosphatic sediments in a variety of depositional environments.

OBJECTIVES

It is not our intent in this paper to directly address the question of phosphate genesis. Rather, we investigate the relationships that exist between phosphatic sediments and their associated foraminiferal assemblages within the Pungo River Formation of eastern North Carolina. Detailed analyses of the physical stratigraphy and petrology of this formation (Riggs and others, this issue; Scarborough and others, this issue) combined with analysis of its foraminiferal assemblages (Katrosh and Snyder, this issue), provide an opportunity to determine the paleoenvironmental conditions in which individual units of the formation were deposited. This, in turn, may reveal which units represent in situ deposits and which, if any, appear to be the result of sediment transport from areas of phosphate genesis into areas that merely served as passive collection sites for phosphatic sediments.

We use the term in situ to indicate phosphorites that accumulated within areas of active phosphate formation. Minor amounts of transport and reworking within the geographic confines of each phosphorite unit are not only possible, but probable. However, those units interpreted as in situ should be expected to reflect paleoenvironmental conditions that are in some way different from normal marine environments. It is clear from the literature review that phosphogenesis is associated with unusual environmental conditions. Regardless of the explanation for phosphate genesis that one might prefer, phosphorites are characteristically associated with abnormal sediment packages (Riggs, 1980). Transported phosphorites represent accumulations outside of the areas of active phosphate formation. This does not imply that phosphate formation cannot continue within adjacent portions of the region; but it indicates that transported phosphorite units lay beyond the limits of environments conducive to phosphate genesis. Transported units should, therefore, be expected to reflect more normal marine conditions. The onset of normal marine conditions within a sequence of phosphorites may simply indicate the migration of environments conducive to phosphate formation rather than complete cessation of phosphate generating mechanisms.

STUDY AREA

In order to investigate sediment-faunal relationships, the phosphorite units and foraminiferal assemblages from a portion of the Aurora Embayment have been selected. The study area includes Beaufort, Pamlico, and portions of northern Craven Counties (Fig. 1). Economically important phosphate deposits in the North Carolina Coastal Plain occur only in this area, which lies to the north of a pre-Miocene topographic high in southern Craven County. This high demarcates the southern boundary of the Aurora depositional embayment, and it represents an area where phosphorite units grade southward into calcareous quartz sands with little or no phosphate content (Fig. 2). Interpretations are based on data from the following cores: NCPC, BTN-9, BTN-11, PON-1, PON-3, and PON-4 (Fig. 1). See Katrosh and Snyder (this issue) for an explanation of the system used to designate the cores.

LOWER PUNGO RIVER PHOSPHORITES

Sediments: The Pungo River sediments of the Aurora Embayment have been divided into four primary lithic units that are designated by the letters A through D, with A representing the oldest depositional unit and successive letters representing progressively younger deposits (Riggs and others, this issue). Each of these units is laterally continuous across the study area (Fig. 2). Units A and B, both of which contain phosphorites, constitute the lower part of the formation.

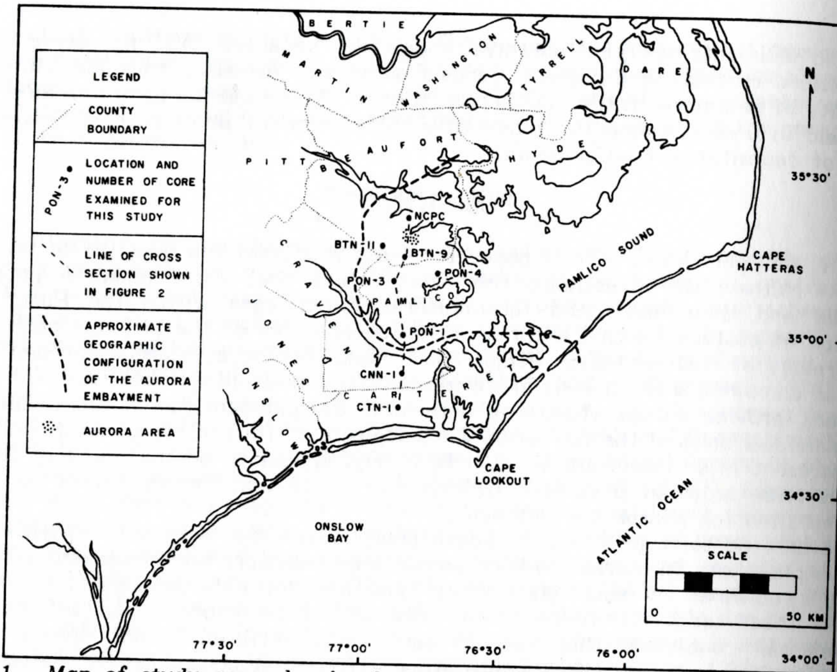

Figure 1. Map of study area showing location of cores.

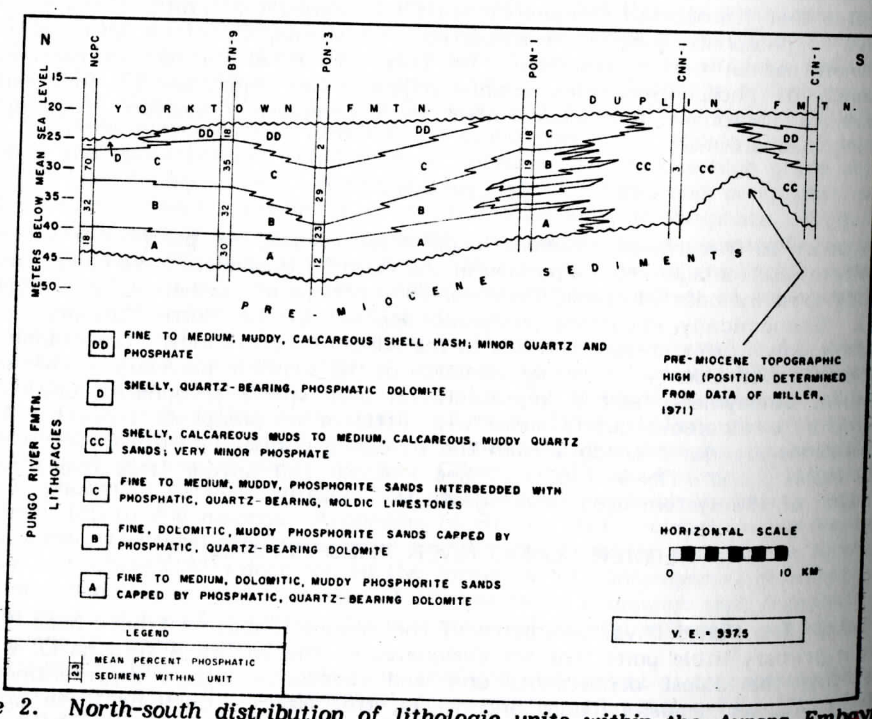

Figure 2. North-south distribution of lithologic units within the Aurora Embayment (core NCPC through core PON-1).

The lower portion of unit A is an olive-green, dolomitic, muddy phosphorite sand (Fig. 3). It is slightly gravelly to gravelly near its base and grades upward into fine to medium sands with dolomitic and terrigenous muds. The sand fraction coarsens to the east, changing from fine sand at BTN-11 to medium sand at BTN-9. In a north-south direction across the study area, sands of the unit A phosphorite are coarsest at PON-3 (medium sand), grading southward into very fine sand at PON-1 and northward into fine sand at NCPC (Fig. 4). Average phosphate content, expressed as a percentage of the sediments that are phosphatic, is 21 percent in the Aurora area (Fig. 3). Phosphate concentrations are highest in the northwestern portion of the study area (34%) and decrease to both the south and the east (Fig. 5). Both pelletal and intraclastic phosphate grains are present, with pellets dominant in the very fine to fine sand fractions and intraclasts most abundant in the medium sand fraction. Immediately above the phosphorite sequence in unit A is a moldic, quartz-bearing, phosphatic, irregularly indurated dolomite that is best developed in the northwestern portion of the study area.

Unit B contains phosphorites that are thicker and richer in phosphate than the unit A phosphorite (Fig. 3). The basal portion of unit B is a dark olive-green, slightly gravelly to gravelly, medium grained, quartz-bearing phosphorite sand with terrigenous mud. Immediately above is an olive-green, fine to medium grained, quartz-bearing phosphorite sand that is muddier than the basal portion of the unit. The mud fraction contains minor amounts of dolomite, glauconite, diatoms, and radiolarians. The uppermost part of the unit B phosphorite sequence is an olive-green, predominantly fine grained, quartz-bearing phosphorite sand with dolomitic muds and some dolomite in the very fine sand fraction. When considered as a single unit, the phosphorite sands of these three subdivisions are slightly finer grained than are those of unit A. The sand fraction in unit B coarsens to the east, ranging from fine sands at BTN-11 and BTN-9 to medium sand at PON-4 (Fig. 4). Sands of unit B coarsen from north to south across the study area, grading from fine sand at NCPC to medium sand at PON-3 and PON-1. Average concentrations of phosphate range from 36 percent in the lower part to 39 percent in the middle, to 33 percent in the upper part (Fig. 3). Southward and eastward from the Aurora area the average phosphate concentration decreases, but unit

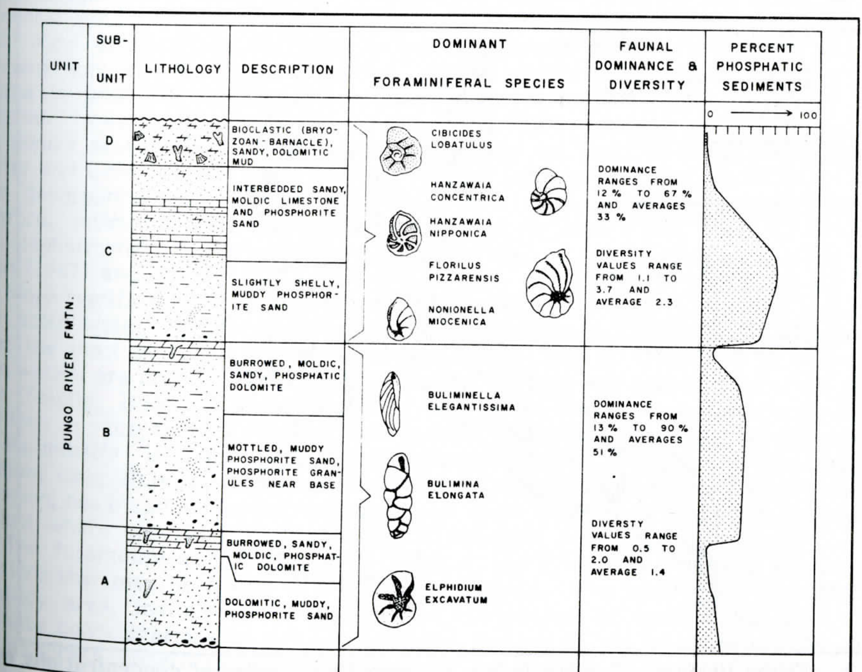

Figure 3. Composite section of the Pungo River Formation in the Aurora area.

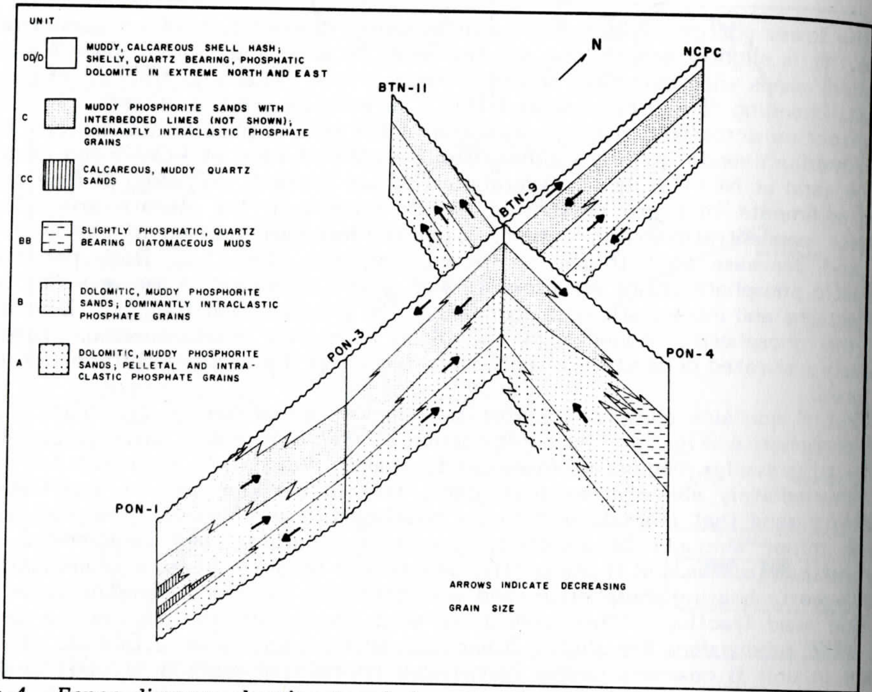

Figure 4. Fence diagram showing trends in grain size for each of the phosphorite units in the Pungo River Formation.

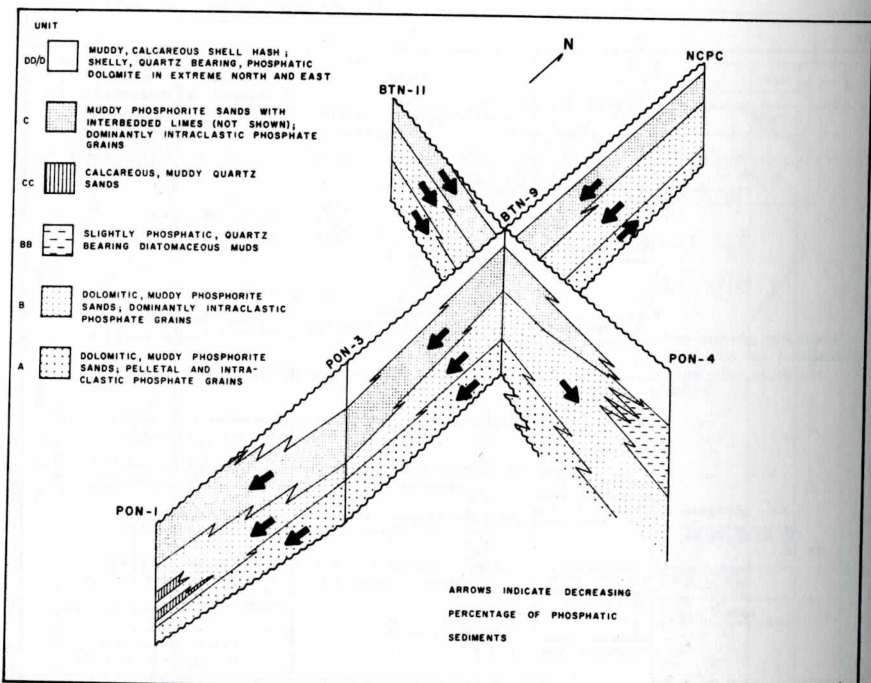

Figure 5. Fence diagram showing trends in phosphatic sediment concentrations within each of the phosophorite units of the Pungo River Formation.

B is consistently richer in phosphate than unit A across the entire study area. The phosphate of unit B is predominantly intraclastic. Capping unit B is a phosphatic, quartz-bearing, irregularly indurated dolomite that is similar to the dolomite that occurs at the top of unit A.

Changes in grain size within the phosphorite sands of units A and B are erratic and show no consistent regional trends (Fig. 4). Grain size was probably most strongly influenced by localized bottom topography, a view that was first expressed by Miller (1971). Average phosphate concentrations, on the other hand, do show regional trends within both units. Phosphate is most abundant in the Aurora area and decreases progressively to the south and east. This suggests that the optimum environmental conditions for phosphate genesis and accumulation existed only in the northwestern portion of the study area.

Foraminiferal Assemblage: Lithologic units A and B are both characterized by a benthic foraminiferal assemblage in which the predominant species are *Buliminella elegantissima* (d'Orbigny), *Bulimina elongata* d'Orbigny, and *Elphidium excavatum* (Terquem) (Fig. 3). The first two species are abundant in both units A and B; the latter, although common in both units, is most abundant in unit A. Species diversity values exhibited by this assemblage are generally low, with an average value of the Shannon-Wiener Information Function of 1.4. Faunal dominance is generally high, averaging 51 percent. It ranges as high as 90 percent in several samples where *B. elegantissima* proliferates (Fig. 3). Planktonic specimens are rare (mean P/B ratio of 1:42).

Occasional samples contain a greater variety of species. Though always of secondary importance, species such as *Florilus pizzarensis* (Berry), *Cibicides lobatulus* (Walker and Jacob), *Hanzawaia concentrica* (Cushman), *H. nipponica* Asano, and *Nonionella miocenica* Cushman occur in moderate numbers where the units become increasingly dolomitic.

Paleoenvironmental Interpretations: The several most abundant foraminiferal species of assemblages from units A and B thrive in modern seas on the inner to middle continental shelf (Walton, 1964; Schnitker, 1971; Poag, 1981; Culver and Buzas, 1980, 1981). Low diversity values, high faunal dominance, and the rarity of planktonic specimens support this interpretation. If the modern continental shelf of North Carolina is used for comparison, a paleobathymetric setting of 50 m or less is suggested. However, living benthic foraminifera may be transported into deeper waters and colonize areas that are not considered typical for the particular species involved (Schafer and Cole, 1982). Also, just as the shelf configuration and depth to shelf break varies geographically, so might it have varied at a given locality through time. Therefore, estimates of paleobathymetry should be considered just that--estimates. Our paleobathymetric interpretation is consistent, at least generally, with that of Gibson (1967) and Miller (1971).

More significant than paleobathymetric interpretations are inferences that may be drawn about water chemistry and/or organic nutrient supply. *Buliminella elegantissima*, by far the most abundant species of both units A and B, flourishes in modern seas where waters are characterized by high organic content and exceptionally high nutrient levels (Seiglie, 1968). Its dominance in the lower Pungo River sediments suggests deposition in exceptionally nutrient-rich waters. Species of *Bulimina* frequently occur with *Buliminella* in such environments (Seiglie, 1968; Phleger and Soutar, 1973). *Elphidium excavatum*, a common associate of *B. elegantissima* in the lower Pungo River Formation, has broad ecological tolerances. It is an opportunistic species that becomes abundant where conditions are not suitable for most other species.

The foraminiferal assemblage of units A and B suggests unusual environmental conditions that may be linked to high nutrient levels. The assemblage persists across the study area, indicating the widespread occurrence of such conditions. Higher phosphate concentrations in the northwestern portion of the study area may indicate that phosphate generating mechanisms were optimal in that area. More southern portions of the Aurora Embayment may have been equally productive, but the phosphorites were probably diluted by detrital mineral matter introduced from sources associated with the adjacent topographic high. In either case, the phosphorites appear to have formed in the same area in which they are now preserved.

UPPER PUNGO RIVER PHOSPHORITES

Sediments: The upper part of the Pungo River Formation in the Aurora Embayment includes units C and D. Unit D, as treated here, actually includes two distinct facies: 1) a shelly, quartz-bearing, phosphatic dolomite limited to the northern portion of the study area and mapped as unit D by Scarborough and others; and 2) a muddy, calcareous shell hash present across the central portions of the study area and mapped as unit DD by Scarborough and others (Fig. 2). They are combined into a single unit here because neither contains significant concentrations of phosphate. Because these units are not relevant to the central theme of this paper, no further mention of them will be made.

Phosphorites in the upper Pungo River sediments are confined within unit C. This unit can be subdivided into four subunits, the stratigraphically lowest of which is a dark greenish-gray, slightly gravelly, muddy fine sand, primarily a phosphorite but with substantial amounts of quartz (20% to 40%). Immediately above is a dark greenish-gray, slightly shelly, slightly calcareous, muddy, fine grained phosphorite sand. The quartz content has diminished and does not exceed 30 percent. In places overlying the subunit just described, but frequently interbedded with it, is a cream to white, irregularly indurated, phosphatic, quartz-bearing moldic limestone or calcareous mud. The upper subunit of unit C is a dark green to greenish-tan, shelly, fine grained, phosphatic quartz sand with calcareous to dolomitic muds. The phosphorite sands of unit C, when treated collectively as a single unit, are finer grained than those of either unit A or unit B. Although there are minor changes in grain size laterally within the unit, the phosphorites of unit C are almost entirely within the fine sand fraction. Fine sand is present at BTN-11 and BTN-9, but the unit thins and pinches out before reaching PON-4. Sands become slightly finer toward the south, but the change in grain size is extremely small (Fig. 4). Average concentrations of phosphate range from 49 percent to 62 percent within the lower phosphorite sands of unit C, and they diminish to approximately 9 percent in the overlying interbedded sesquence (Fig. 3). Maximum phosphate concentrations occur in the Aurora area, and phosphate content decreases progressively and rather dramatically to both the south and east (Fig. 5). However, unit C is much richer in phosphate than either unit A or unit B when comparisons among them are made at any specific locality within the study area. Like the phosphorites of unit B, those of unit C are composed predominantly of intraclastic grains.

Changes in grain size within the phosphorite sands of unit C are too small to be of significance, and no meaningful regional trends are apparent. Average phosphate concentrations do, however, mirror the trends noted for units A and B. Optimum environmental conditions for phosphate accumulation still appear to lie within the northwestern extremities of the study area. In fact, this trend is more pronounced in unit C than it is in either of the lower units, indicating that the optimum environment for phosphate genesis may have migrated even farther to the northwest.

Foraminiferal Assemblage: Unit C is characterized by a benthic foraminiferal assemblage in which the following species are most abundant: ***Hanzawaia concentrica*** (Cushman), ***H. nipponica*** Asano, ***Florilus pizzarensis*** (Berry), ***Cibicides lobatulus*** (Walker and Jacob), and ***Nonionella miocenica*** Cushman (Fig. 3). Species of secondary importance include ***Virgulinella miocenica*** (Cushman and Ponton), ***Globocassidulina crassa*** (d'Orbigny), ***Bolivina lowmani*** Phleger and Parker, ***Bolivina paula*** Cushman and Cahill, ***Valvulineria olssoni*** Redmond, and ***Valvulinera floridana*** Cushman. Species diversity values for this assemblage are generally higher than are those for the assemblage that characterizes units A and B. The mean value of the Shannon-Wiener Information Function for all samples from unit C is 2.3 (Fig. 3). Faunal dominance is generally lower, averaging 33 percent. Benthic foraminifera are abundant; planktonic specimens, generally common but occasionally rare (mean P/B ratio of 1:14).

Paleoenvironmental Interpretation: The ecological tolerances for several of the benthic foraminiferal species that characterize unit C are well known. All of the most abundant species, or in some cases closely related species within the same genus, range across broad depth intervals in modern seas (Walton, 1964; Schnitker, 1971; Todd, 1979; Poag, 1981; Culver and Buzas, 1980, 1981). The area in which most of these taxa attain their maximum relative abundances corresponds to a middle or outer shelf environment. Moderate diversity values, lower faunal dominance, the common occurrence of planktonic specimens, and the ecological tolerances of abundant species suggest a more open marine environment of deposition than was indicated for the lower Pungo River phosphorites. However, water depths may not have been significantly greater than they were during the deposition of units A and B. Comparison with the bathymetric profile of the modern North Carolina continental shelf suggests that deposition of unit C phosphorites occurred in depths as shallow as 50 to 60 meters. For reasons outlined previously, this estimate is not to be considered precise. The faunal transition from lower to upper Pungo River phosphorites may be interpreted in two ways: 1) as a marine transgression in which the middle or outer shelf fauna of unit C migrated westward and replaced the fauna of units A and B; or 2) as a change in oceanographic conditions that displaced the nutrient-rich waters, which characterized the study area during the deposition of units A and B, with more normal open marine waters. It is also quite possible that this faunal transition resulted from a combination of these two events.

In any case, it appears that the nutrient-rich conditions that probably supported phosphate genesis during the deposition of units A and B had migrated beyond the area where unit C phosphorites now occur. In contrast to the conditions indicated for the phosphorites in the lower Pungo River units, faunal evidence suggests that the phosphate in unit C did not accumulate in the same area where it was initially generated.

DISCUSSION

It might be argued that phosphate originated in interstitial waters below the sediment-water interface, and that changes in the benthic foraminiferal assemblage would, therefore, have no direct relationship to areas of phosphate genesis. If phosphates of the Pungo River Formation had been generated in this manner, foraminiferal tests within the sediments at the time of phosphate genesis should be replaced. Very few specimens from our samples show any indication of alteration to phosphatic compositions. Of those few that appear to be phosphatic, most are simply coated with a thin veneer of phosphate. When broken, such specimens reveal an underlying calcareous test wall that is compositionally unaltered. Nor did we find many phosphorite grains that resembled the gross shape of foraminiferal specimens. If phosphatization of the sediment infillings of foraminiferal tests contributed significant numbers of phosphate grains, they were subsequently broken and abraded to such an extent that they are no longer recognizable. In additon, it would be difficult to explain the abundance of unaltered tests that persist through phosphorites that were generated by replacement. Thus, we favor a model involving extremely nutrient-rich bottom waters to explain the origin of the Pungo River phosphorites; and the following discussion is predicated on that supposition.

When faunal and sedimentary data are combined, a compelling argument can be made that the phosphorites in the lower and upper portions of the Pungo River Formation represent two different types of accumulation.

The foraminiferal assemblage characteristic of units A and B indicates an unusual set of environmental conditions, probably related to extremely high nutrient supplies. The restricted nature of the foraminiferal fauna indicates that conditions were not generally suitable for most species. However, the Aurora Embayment was not a restricted basin in the classic sense of that concept. Occasional samples contain a more diverse assemblage that includes species indicative of more normal marine conditions. These samples, which lie within the dolomitic intervals characterized by reduced phosphate production, represent pulses of more normal marine circulation. Evidently, a specific set of oceanographic conditions that were subjected to periodic breakdown, perhaps as a consequence of fluctuating sea level, controlled environmental conditions within the embayment.

The foraminiferal assemblage of unit C marks the onset of more normal marine conditions, at least in that part of the embayment sampled for this study. The faunal transition from lower to upper Pungo River units suggests a marine transgression. Perhaps the configuration of the embayment changed in response to transgression and altered the oceanographic conditions responsible for the nutrient-rich environments that had previously existed within the study area, or large-scale circulation changes, like the shifts in the Gulf stream axis described by Pinet and Popenoe (1982), may have altered regional oceanographic conditions. The nutrient-rich environments conducive to phosphate genesis most likely migrated westward beyond the geographic limits of the area sampled for this study.

Sedimentary evidence corroborates the interpretations based on faunal evidence. Although lateral changes in grain size within individual phosphorite units are erratic and exhibit no recognizable regional trends, a significant trend does occur vertically within the formation. Phosphorites become progressively finer grained upward through the stratigraphic section. The most notable change occurs between units B and C. Grain size reduction may reflect continued reworking and transport of successive phosphorite units, a concept that has been proposed to explain the origin of other phosphorite accumulations (Baturin, 1971).

Regional changes in the average phosphate concentration within individual units indicate that the northwestern part of the study area was an optimum area for phosphate production and accumulation (Fig. 5). More significant, however, are changes in phosphate concentration upward through the Pungo River section. Average concentrations characteristic of each phosphorite unit in the vicinity of Aurora are as follows: unit A, 27 percent; unit B, 36 percent; unit C, 55 percent (Fig. 3). This progressive enrichment might result from concentration of phosphorite grains by physical sedimentary processes, another concept that has been suggested by Baturin (1971). For reworking and transport to produce such enrichment, there must be a minimum of extraneous detrital mineral matter introduced into the system. Such conditions appear to have existed in the northern part of the study area. The decrease in phosphate concentration toward the south probably reflects the introduction of detrital matter from sources associated with the pre-Miocene topographic high that formed the southern boundary of the embayment.

The geometry of individual phosphorite units within the study area is also of interest (Fig. 2). Units A and B are thick along the flanks of the embayment, unit A maintaining approximately the same thickness across the area and unit B thinning dramatically toward the embayment axis. Both units are continuous from west to east across the study area, although the presence of unit A at PON-4 has not been documented because the core did not penetrate deep enough to encounter it (Figs. 4 and 5). Unit C is relatively thin along the flanks of the embayment and attains maximum thickness in its axis. The embayment axis may have been merely a passive receptacle for the accumulation of phosphate that formed in adjacent areas along the flanks. Unit C also thins and pinches out toward the east, and its progressive thinning parallels a regional trend toward decreasing phosphate concentrations (Fig. 5). This geometry suggests that the phosphorites of unit C were transported from a source area that lay to the west and northwest. The regional distributions, geometries, and paleoenvironmental settings of units within the Pungo River Formation indicate that the ancient shoreline lay far to the west of its present updip limit. The maximum westward extent of the ancient shoreline would, of course, correspond to the maximum marine transgression, which occurred during the deposition of unit C.

Planktonic foraminiferal evidence supports the assertion that Pungo River phosphorites were deposited during a marine transgression. Gibson (in press) and Katrosh and Snyder (this issue) assign the upper part of the formation in the Aurora area to the ***Praeorbulina glomerosa*** zone (Stainforth and others, 1975), which is roughly equivalent to zone N 8 (Blow, 1969). This corresponds to eustatic cycle TM 2.1 (Vail and others, 1977), a transgressive phase within the larger-scale middle Miocene transgression.

All evidence points toward an interpretation of the phosphorites of units A and B as in situ accumulations (that is, they accumulated in the same environment in which they formed). Phosphorites of unit C appear to have been transported from source areas that lay to the west and northwest, having accumulated outside of the environment in which they formed. The source area for unit C phosphorites has not been preserved, evidently having been destroyed during the subsequent erosional cycle that truncated units of the Pungo River Formation and produced the regional unconformity that marks its upper surface.

CONCLUSIONS

A model to explain the origin of the Pungo River phosphorites has been developed. It should be considered tentative at this point as modification will likely accompany the acquisition of more detailed information. The events, as we interpret them, are presented sequentially in the order of their occurrence.

1) The in situ deposition of unit A phosphorites.

The nutrient-rich conditions responsible for phosphate formation are controlled by oceanographic conditions and the configuration of the embayment. Environmental conditions conducive to phosphate formation are present across the study area, but optimum conditions are associated with the flanks of the embayment.

2) Reduction in phosphate production and deposition of dolomitic sediments at the top of unit A.

More normal marine conditions prevail at this time, as evidenced by changes in the foraminiferal fauna.

3) Re-establishment of nutrient-rich conditions and the in situ deposition of unit B phosphorites.

Again, phosphate formation is embayment-wide but seems to be concentrated toward the western flanks.

4) A second reduction in phosphate formation and transition to dolomite deposition at the top of unit B.

5) Deposition of unit C phosphorites which, unlike those of units A and B, were transported into the area of accumulation.

This sequence is marked by the onset of normal open marine conditions, probably caused by marine transgression and subsequent alteration of oceanographic conditions. Environments conducive to phosphate formation are still associated with the flanks of the embayment, but these environments have migrated in response to the transgression and now lie to the west, beyond the present updip limit of the formation. Transported phosphates accumulate in the embayment axis, forming a wedge that thins eastward. Dilution by dertital mineral matter from other sources is minimal in the north but significant in the south.

6) Reduction in phosphate formation and gradual transition to calcareous sediments in the upper portion of unit C.

The cyclic nature of alternating phosphate and carbonate systems is discussed by Riggs and others (this issue).

7) Cessation of phosphate formation and the initiation of carbonate sedimentation.

The sediment sequence of units D and DD is dominated by carbonates. The termination of phosphate production may be related to the initiation of marine regression that eventually produced the regional unconformity at the upper surface of the formation.

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MIOCENE SEISMIC STRATIGRAPHY, STRUCTURAL FRAMEWORK, AND SEA-LEVEL CYCLICITY: NORTH CAROLINA CONTINENTAL SHELF

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ABSTRACT

Preliminary interpretations of over 1000 km of high-resolution seismic reflection data, supplemented by over 100 9-m vibracores, have delineated the shallow stratigraphic and structural framework for several Miocene depositional sequences overlying the Carolina Platform in the area of Onslow Bay, North Carolina. Comparison of the observed stratigraphy with published seismic, gravity, magnetic, and core hole data indicates that the distribution, thickness and depositional pattern of each sequence has been controlled by: 1) the regional tectonic framework; 2) several, local structural features; and 3) numerous, relative, sea-level fluctuations.

A broad zone of phosphate-rich, Miocene sediments and rocks crops out at mid-shelf across the northern segment of the Carolina Platform. This outcrop belt trends northeast-southwest, and extends from Frying Pan Shoals off Cape Fear to the middle shelf off Bogue Banks. Older Tertiary and Cretaceous sequences crop out southwest of Frying Pan Shoals owing to the presence of the Cape Fear Arch, a mid-Carolina Platform high. In the vicinity of Bogue Banks, the Miocene sequences abruptly change strike and run parallel to the north-south oriented White Oak Lineament. North of Bogue Banks, the Miocene depositional sequences thin and/or pinch out over the Cape Lookout High, which is presently thought to be a pre-Miocene, erosion-originated paleotopographic feature. In southwestern Onslow Bay the Miocene sequences change strike and thicken along a third local structure, herein referred to as the Cape Fear Monocline. Several shallow Miocene outliers, which are the surficial expression of subbottom "flexures," were also identified in this area. These structures are deformational in origin, and may be a consequence of differential movement along deep-seated structures within the Carolina Platform.

The Miocene depositional sequences and associated unconformities indicate several cycles of relative sea-level change. Comparison of the Miocene relative sea-level cyclicity with the proposed global eustatic sea-level curve of Vail and others (1977) depicts a potentially strong correlation. However, the present lack of high-resolution biostratigraphic data precludes exact correlations.

INTRODUCTION

This paper presents a brief sketch of the Miocene structural and stratigraphic framework for the Onslow Bay Embayment of the North Carolina continental shelf (Fig. 1) as defined by the preliminary results of an ongoing high-resolution seismic survey. We have identified several local structures which separate this portion of the Carolina Platform into a series of Neogene depositional basins. Basin geometries, infilling histories, as well as regional and local deformation events, have been defined by correlating the seismic data to vibracore (Meisburger, 1979; Lewis and others, this issue) and existing drill hole data on the lower North Carolina Coastal Plain.

Seismic sequence analyses (Mitchum and others, 1977) was used to identify several distinct depositional sequences within the study area. Each depositional sequence is a package of concordant reflectors and represents a given interval of geologic time as defined by the sequence boundaries (Vail and others, 1977). The boundaries in this case are basin-wide unconformities that can be readily identified by onlap, toplap, and downlap relationships. The majority of these depositional sequences were found to be Miocene in age.

Comparison of the observed stratigraphy with published seismic, magnetic, gravity, and drill hole data suggests the distribution, thickness and depositional patterns for each Miocene sequence have been dictated by: 1) the regional tectonic framework; 2) several, local structural elements; and 3) numerous, relative, sea-level fluctuations.

METHODS

The interpretations presented here are the preliminary results of a comprehensive, single-channel, high frequency, high-resolution seismic survey of Onslow Bay, North Carolina (Fig. 1). This survey includes approximately 1200 km of sparker profiles (200 Hz -5 kHz), over 1000 km of uniboom profiles (300 Hz -15 kHz), and over 2500 km of 3.5 kHz profiles. Most of the seismic data were collected on the inner and middle shelf between Cape Fear and Cape Lookout. However, a number of seismic

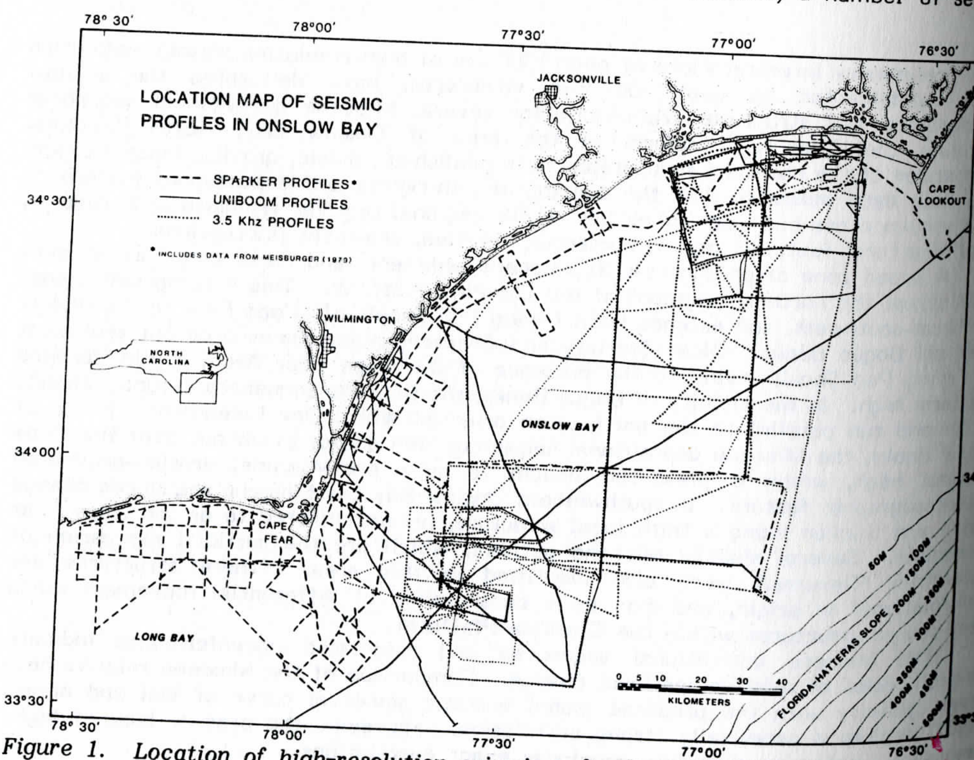

Figure 1. Location of high-resolution seismic reflection profile tracks.

lines were run through the back-barrier lagoons and estuaries in the vicinity of Cape Lookout, where an abundance of drill and core hold data were available for stratigraphic control. These seismic lines were carried out onto the shelf for chronostratigraphic correlations. Over 100 vibracores (Lewis and others, 1982) have provided a check for our stratigraphic correlations as well as determination of lithologic facies.

Most profiles have been graphically reduced to stratigraphic sections (line-drawings) with a vertical exaggeration of 90:1 or 100:1. The approximate vertical scale for each section was determined using a seismic velocity of 1500 m/sec in water and 1695 m/sec in the subsurface (13 percent increase).

REGIONAL TECTONIC FRAMEWORK

Carolina Platform

Onslow Bay is located on the Carolina Platform, which is a major tectonic component of the trailing-edge continental margin of North America (Fig. 2). The platform proper is a broad region of shallow pre-Jurassic continental crust, which extends from the Florida Platform to the Baltimore Canyon Trough (Klitgord and Behrendt, 1979; Fig. 2). The Brunswick Magnetic Anomaly (Taylor and others, 1968) marks the seaward limit of the platform where the overlying wedge of Mesozoic and Cenozoic sediments thicken abruptly from generally less than 2 km to over 10 km in the Carolina Trough (Sheridan, 1974a; Grow and Markl, 1977; Paull and Dillon, 1980; Klitgord and Behrendt, 1979).

The Carolina Platform is the dominant structural feature governing the post-rift evolution of this part of the margin (Klitgord and Behrendt, 1979). A southwest to northeast transect across the present inner shelf of the Carolina Platform (Fig. 2) depicts three regional segments separated by the Cape Fear Arch, a mid-platform topographic high. Each regional segment displays relatively distinct Mesozoic-Cenozoic depositional histories.

Southern Carolina Platform

The Carolina Platform descends south of Cape Romain, South Carolina, forming the northeastern limb of the Southeast Georgia Embayment. Here, the platform is broken into a series of basins of probable Triassic age (Fig. 2; Marine and Siple, 1974; Popenoe and Zietz, 1977; Popenoe, 1977; Dillon and others, 1979; Buffler and others, 1979). A prominent seismic reflector, previously thought to be the top of the crystalline basement (Antoine and Henry, 1965; Sheridan and others, 1966; Dowling and others, 1968; Emery and others, 1970; Sheridan, 1974a), has recently been interpreted as an extensive Late Triassic (?) or Early Jurassic (?) volcanic layer overlying both the crystalline crust and Triassic rift-basins (Fig. 2; Dillon and others, 1979). The top of this reflector forms a relatively smooth, erosional topographic surface, and underlies the Southeast Georgia Embayment which has been filled with over 2.5 km of Mesozoic-Cenozoic sediments (Shipley and others, 1978; Poag and Hall, 1979; Dillon and others, 1979; Paull and Dillon, 1980).

Northern Carolina Platform

East of Cape Lookout, North Carolina, the overlying wedge of post-Triassic sedimentary sequences thickens abruptly as the Carolina Platform descends into the marginal Mesozoic basin of the Carolina Trough (Fig. 2). Here, the Carolina Platform is thought to consist of a series of fault blocks bound by rift-originated, normal faults (Sheridan, 1974a). Over 3 km of coastal plain sediments were drilled at Cape Hatteras (Maher, 1965; Brown and others, 1972) where the coastline is proximal to the seaward edge of the Carolina Platform.

Central Carolina Platform

As illustrated in Figure 2, the Central Carolina Platform is relatively flat and

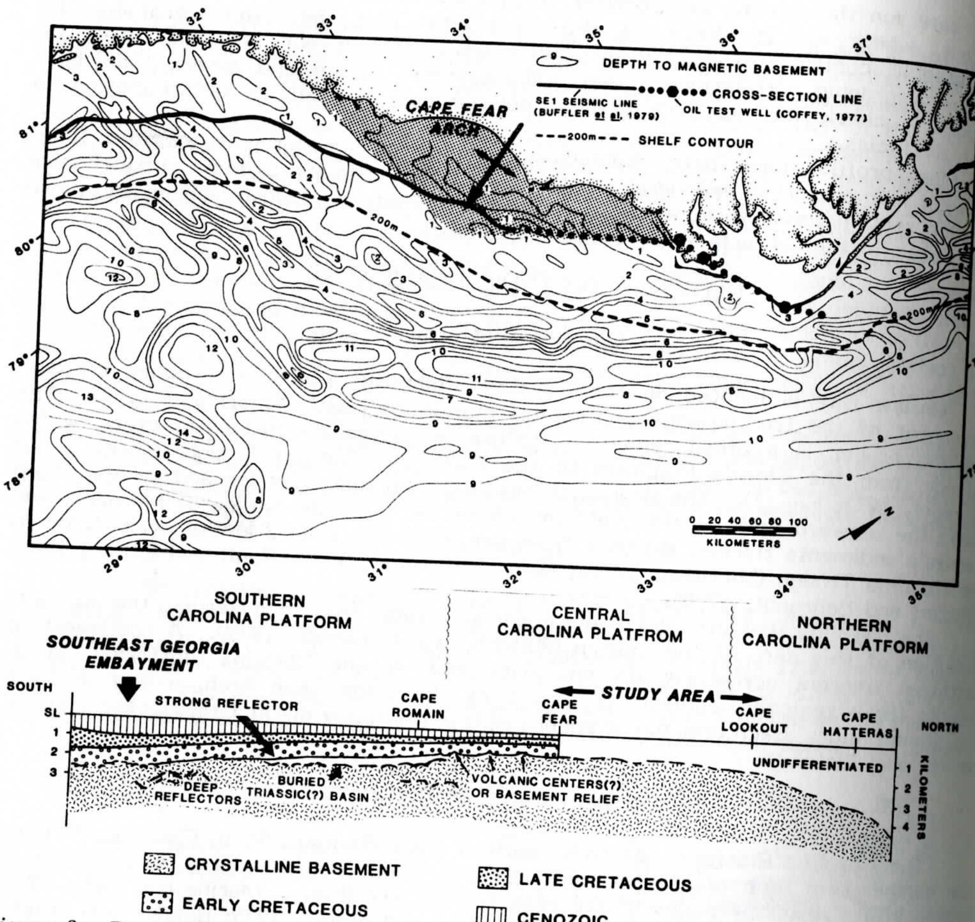

Figure 2. Regional subdivision of the Carolina Platform. Magnetic basement map from Klitgord and Behrendt (1979); SE-1 seismic line and interpretations from Buffler and others (1979).

shallow (< 1 km). The shallowest segment of the Platform is located in the vicinity of Cape Fear, North Carolina, and has been traditionally recognized as the Cape Fear Arch (Stephenson, 1923; McCarthy, 1936; Mansfield, 1937; Richards, 1945, 1974; Straley and Richards, 1950; Maher, 1965; Baum and others, 1978). It is becoming clear from magnetic depth analyses (Klitgord and Behrendt, 1979), CDP seismic analyses (Dillon and others, 1979) and mapping of the basement surface from well data onshore (Brown and others, 1972; Popenoe and Zietz, 1977) that the Cape Fear Arch is not a discrete anticlinal structure as first described by Stephenson (1923), but rather a broad mid-platform high consisting of very shallow continental crust extending from Cape Romain, South Carolina, to Cape Lookout, North Carolina (Fig. 2).

No known major fracture zones or Triassic basins exist within this segment of the Carolina Platform. However, recent seismic investigations by Dillon and others (1979) and Buffler and others (1979) have identified several low-relief basement topographic features between Cape Romain, South Carolina, and Cape Fear, North Carolina (Fig. 2). These features coincide with several concentric magnetic anomalies, and are presently thought to be the volcanic centers for the extensive Early Jurassic (?) volcanic layer covering the southern segment of the Carolina Platform.

Our seismic survey was conducted on the shallow central portion of the Carolina

Platform, overlying the northeast limb of the mid-platform high of the Cape Fear Arch (Fig. 2). Unlike the adjacent northern and southern segments, this portion of the Platform is overlain by a relatively thin (<1 km) cover of Mesozoic-Cenozoic sediments. Interpretations of the seismic data, supplemented by the magnetic survey and magnetic depth analyses of Klitgord and Behrendt (1979), suggest that recurrent movement along subtle, local basement structures has been translated through the relatively thin overlying stratigraphic sequences. These tectonic events have, in part, regulated the depositional patterns and infilling histories of the basins that formed, particularly in the Miocene.

STRATIGRAPHIC AND STRUCTURAL FRAMEWORK

Analysis of the seismic data from Onslow Bay depicts several, discrete depositional sequences. Each sequence and its associated unconformities were correlated with existing drill and core hole data on the adjacent emerged lower North Carolina Coastal Plain for stratigraphic control. Chronostratigraphic correlations were subsequently checked by a series of vibracores collected along the seismic lines (Lewis and others, 1982). The stratigraphic correlations and subdivision of the Onslow Bay depositional sequences are illustrated in Table 1.

The general distribution of the southeastern North Carolina depositional sequences has been controlled by the morphology of the Carolina Platform. These sequences form a northeast-southwest band of successively younger, onlapping stratigraphic units which closely parallel the regional strike of the basement. However, several local structures identified via seismic profiling have strongly influenced the local distribution and thickness of the Onslow Bay sequences, particularly in the Miocene. Three of these structures form the boundaries for three Miocene depocenters (Fig. 3), herein referred to as: 1) the Aurora Embayment; 2) the Northeast Onslow Bay Embayment; and 3) the Frying Pan Shoals Embayment.

Table 1. Stratigraphic and subdivision of Onslow Bay depositional sequences and correlations with lower North Carolina Coastal Plain Tertiary formations.

UNCONFORMITY	DEPOSITIONAL SEQUENCE	PROBABLE CORRELATIVE FORMATION
	Q_u	QUATERNARY SEQUENCES UNDIFFERENTIATED
δ_1		
	P_y-B	PLIOCENE YORKTOWN FM
γ_2		
	P_y-A	
γ_1		
	M_{pr}-E	MIOCENE PUNGO RIVER FM
β_6		
	M_{pr}-D	
β_5		
	M_{pr}-C	
β_4		
	M_{pr}-B	
β_3		
	M_{pr}-A	
β_2		
	M_s	LOWER MIOCENE SILVERDALE FM
β_1		
	O_b	UPPER OLIGOCENE BELGRADE FM

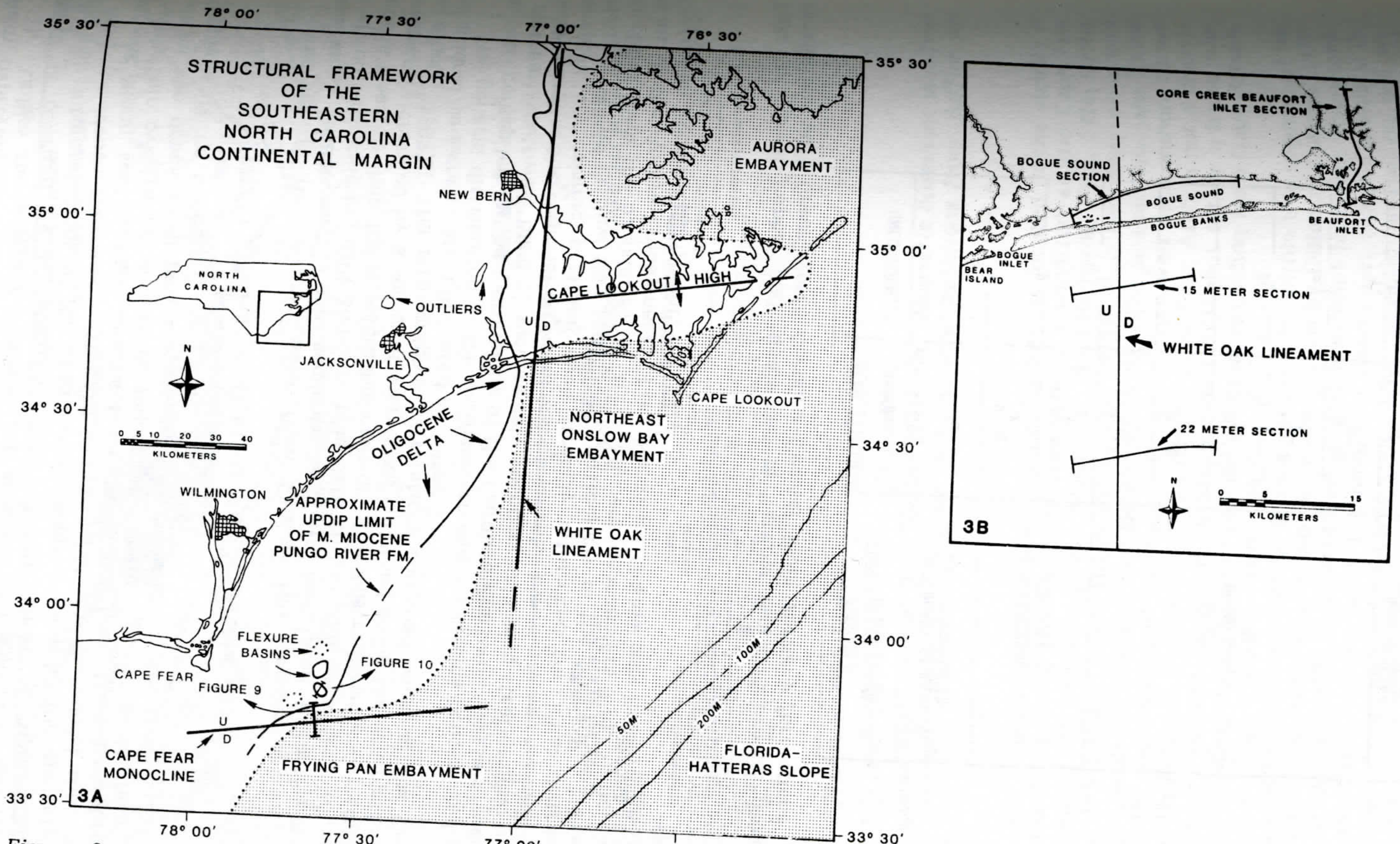

Figure 3. A) Structural framework of the upper southeastern North Carolina continental margin. B) Location of interpreted seismic profiles discussed in text (Figures 5, 6, 7, and 8).

Oligocene Delta

Vibracore and seismic data depict a broad outcrop belt of phosphate-rich Miocene rocks and sediments on the middle to inner shelf of Onslow Bay. The updip limit of these Miocene sequences parallels the seaward limit of an Oligocene depositional package characterized by a series of prograding clinoforms (Fig. 3). Vibracores have identified this depositional unit as a fine quartz arenite to calcarenite (Meisburger, 1979; Lewis and others, 1982). Faunal analysis suggests this unit is Oligocene in age (Meisburger, 1979). Seismic data depict a series of clinoforms prograding out in a radial fashion from a central point located in the vicinity of New River, North Carolina (see Meisburger, 1979). The distribution, lithology, internal structure, and overall geometries suggest this depositional unit is deltaic in origin. This interpretation agrees with the earlier work of Lawrence (1975) who recognized the existence of a late Oligocene-deltaic system in the adjacent emerged coastal plain from paleoecological and paleoenvironmental investigations of ***Crassostrea gigantissima.*** This depositional structure has, in part, controlled the local outcrop pattern of the Miocene sequences in central Onslow Bay as illustrated in Figure 3.

White Oak Lineament

The Miocene sequences of the Pungo River Formation thicken abruptly across a generally north-south striking lineament in northeastern Onslow Bay. This structural lineament has been referred to as the White Oak Lineament. Through a series of seismic profiles, we have traced the White Oak Lineament across the shelf from the outermost profile at approximately 76^{0} 50' longitude / 34^{0} 08' latitude to the shallow lagoon behind Bogue Banks (Fig. 3). On the emerged coastal plain north of Bogue Banks, the White Oak Lineament marks the updip outcrop limit of the Pungo River Formation (Fig. 4).

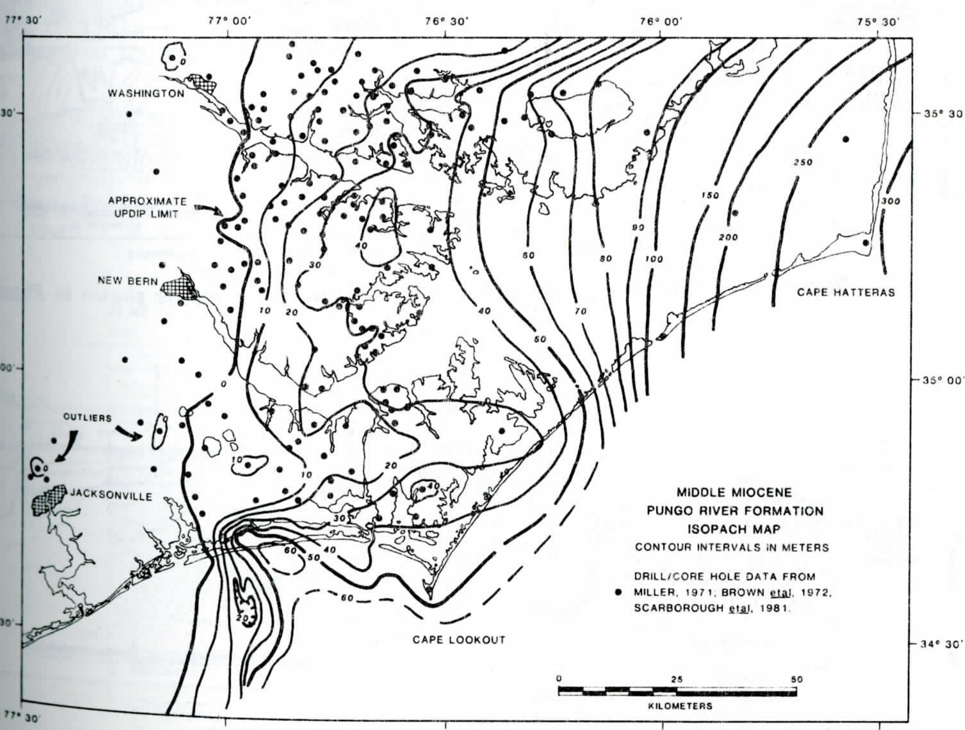

Figure 4. Isopach map of the Miocene Pungo River Formation. Modified from Miller (1971) with additional data from seismic profiles in northeast Onslow Bay area.

This lineament is a broad monoclinal structure in Bogue Sound. Here, the Pungo River Formation thickens from its western updip limit to over 50 meters in less than 6 km of horizontal distance (Fig. 5). This same abrupt eastward thickening of the Pungo River Formation was observed on every profile south of Bogue Banks (i.e., Figs. 6 and 7), and possibly continues south to the shelf-slope break. Figure 7 is a seismic section from the middle shelf where the White Oak Lineament is more dramatically represented by a subbottom scarp with over 25 meters of relief. A series of middle Miocene prograding clinoforms extends eastward from the scarp, and are characteristic of most of the mid-shelf profiles crossing this feature.

The White Oak Lineament closely approximates the orientation and position of several structural elements previously reported in the literature (Spangler, 1950; Miller, 1971; Brown and others, 1972). These structures are described as flexure zones and/or fault zones related to basement tectonics. The White Oak Lineament also coincides with the position of increased basement declivity (Klitgord and Behrendt, 1979; Brown and others, 1972: Plate 5), where the northern segment of the Carolina Platform starts a rapid descent into the Carolina Trough to the east. Sheridan (1974a; 1974b) suggests this segment of the Carolina Platform contains a series of normal faults which originated through a sequence of rift/drift processes (Schneider, 1972; Kinsman, 1975) during the late Triassic-early Jurassic rifting of North America from Africa.

The apparent relative movement, regional extent, local vertical relief, and proximity to a major change in basement slope suggests the White Oak Lineament may be a consequence of recurrent movement along an older, rift-originated (?), normal fault zone. This lineament may be the surficial expression of one in the series of tensional fault systems thought to comprise the northern segment of the Carolina

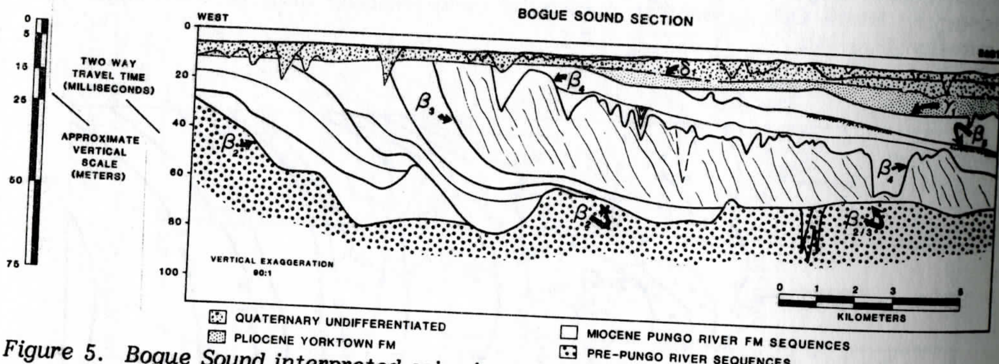

Figure 5. Bogue Sound interpreted seismic section. Location of profile shown in Figure 3B.

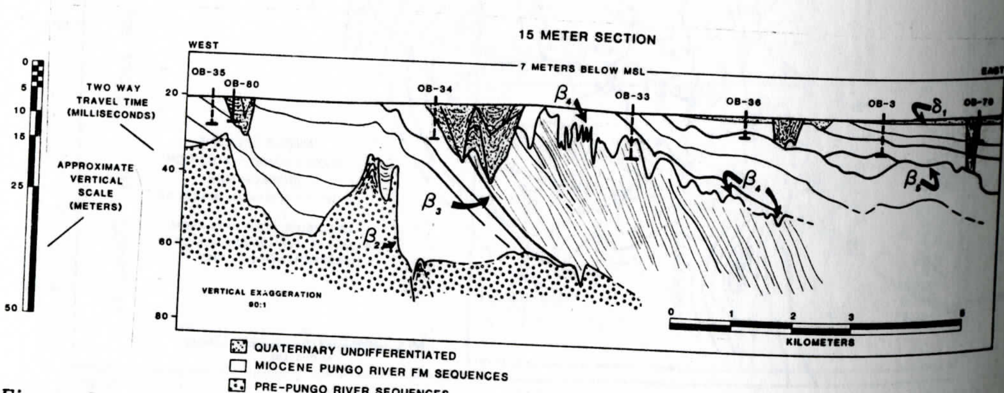

Figure 6. 15 meter interpreted seismic section. Location of profile shown in Figure 3B.

Platform. Down-faulting to the east of the lineament created a large Neogene basin, which is locally broken by the generally east-west striking Cape Lookout High.

Cape Lookout High

A relatively thick sequence of Miocene Pungo River sediments lies beneath Bogue Banks. Figure 8 depicts a northward thinning of this sediment package (bounded by reflectors β_2 and γ_1) from approximately 35 m near Beaufort Inlet to less than 15 m on the emerged coastal plain. This relatively abrupt thinning to the north is the product of an antecedent topographic feature referred to as the Cape Lookout High (Snyder and others, 1980). The axis of this pre-Miocene topographic high lies north of the northern limit of our seismic data. A middle Miocene isopach map (Fig. 4) delineates the general orientation and areal extent of this structure.

Regional stratigraphic studies by Gibson (1967; 1970), Miller (1971) and Riggs (1979) have denoted a similar structural element in this area. Although the location and orientation of their respective structures differ, each investigator demonstrates that a discrete positive structure has controlled the depositional patterns of the Miocene Pungo River Formation. Comparison of a series of Neogene isopach and structural maps (Miller, 1971; Brown and others, 1972), supplemented with our seismic data, suggests this structure was a positive topographic feature preceeding, during and immediately following deposition of the Pungo River Formation, and may be the result of pre-Pungo River differential erosion. This interpretation conforms with the paleoenvironmental interpretations from several detailed lithostratigraphic and biostratigraphic studies of the Pungo River Formation along the Cape Lookout High (Scarborough and others, this issue; Katrosh and Snyder, this issue; Riggs and others, this issue).

The Cape Lookout High separates the large Neogene Basin east of the White Oak Lineament into two distinct Miocene depocenters (Fig. 3). The basin north of this structural element is known as the Aurora Embayment (Riggs and others, 1981; Snyder and others, 1981); and the depositional basin south of the Cape Lookout High is herein referred to as the Northeast Onslow Bay Embayment.

Cape Fear Monocline

The Miocene sequences of the Pungo River Formation change strike and thicken over a generally northeast-southwest structural lineament in southwestern Onslow Bay. This structure is herein referred to as the Cape Fear Monocline (Fig. 3).

Figure 9 is a north-south interpreted seismic section crossing the Cape Fear

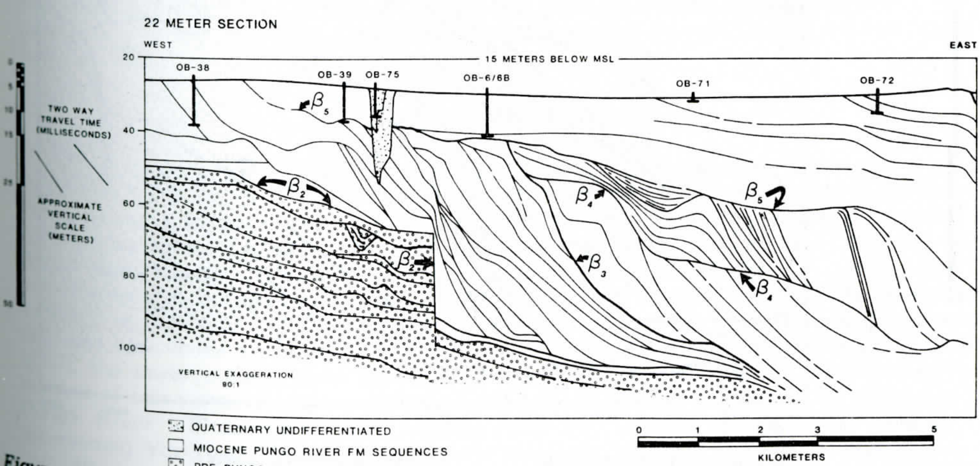

Figure 7. 22 meter interpreted seismic section. Location of profile shown in Figure 3B.

Monocline. Note that the Pungo River sequences thin from greater than 60 m to their updip outcrop limit in less than 8 km horizontal distance. This abrupt northward thinning is a consequence of relative subsidence to the south along the Cape Fear Monocline, as evidenced by the uniformly folded, pre-Pungo River sequences. The sigmoidal to divergent clinoforms characterizing the Miocene Pungo River sequences (bound by β_2 and δ_1) suggest these sequences were deposited in an actively subsiding basin (Vail and others, 1977).

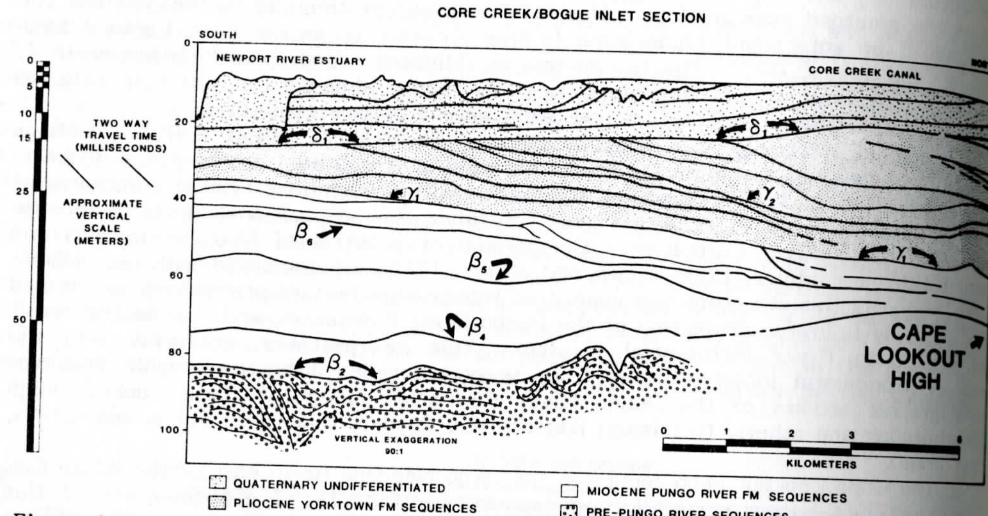

Figure 8. Core Creek/Beaufort Inlet interpreted seismic section. Location of profile shown in Figure 3B.

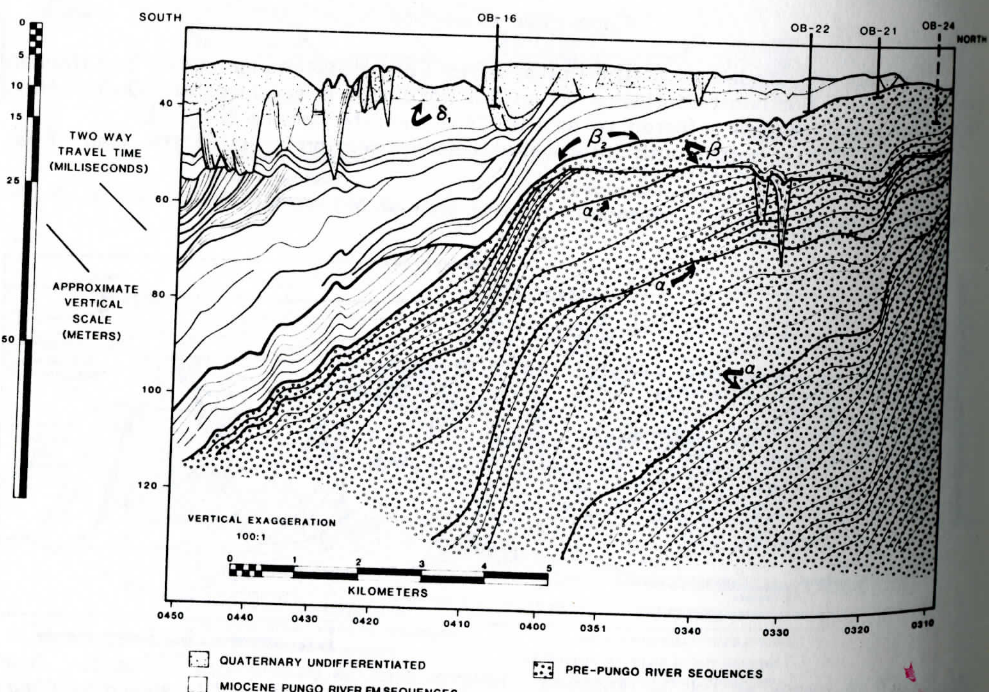

Figure 9. EN-1 interpreted seismic section. Location of profile is shown in Figure 3A.

The relative thickening of the Pungo River sequences to the south and southeast as illustrated in Figure 9 was found on all the profiles crossing the Cape Fear Monocline. However, this structure becomes more of a broad homoclinal feature to the east.

Flexure Basins

Several Miocene outliers of the Pungo River Formation were identified via seismic and vibracore data (Lewis and others, 1982) in the area of the Cape Fear Monocline (Fig. 3). These outliers are relatively thin (<15 m) and limited in areal extent (<20 km^2). Seismic data crossing the outliers depict multiple flexures in the underlying strata (Fig. 10), which suggests they are structurally controlled. Furthermore, the sigmoidal-progradational to divergent fill geometries of the Pungo River sediments within the flexure basins indicate the flexures were active penecontemporaneous with Miocene deposition.

As illustrated in Figure 10, the phosphatic Miocene sequences of the Pungo River Formation are restricted to the troughs of the flexures. This relationship between the troughs of the flexures and the occurrence of Pungo River outliers is relatively consistent throughout the Frying Pan Shoals area.

MIOCENE SEISMIC STRATIGRAPHY

As discussed earlier, seismic sequence analysis (Vail and others, 1977) has defined several depositional sequences which can be traced throughout the depositional basins. In the Northeast Onslow Bay Embayment, where we have the greatest seismic and stratigraphic control, four major unconformities mark the boundaries between 5 depositional epochs:

1) β_1 - Upper Oligocene Belgrade Formation/Lower Miocene Silverdale Formation
2) β_2 - Lower Miocene Silverdale Formation/Miocene Pungo River Formation
3) γ_1 - Miocene Pungo River Formation/Pliocene Yorktown Formation
4) δ_1 - Pliocene Yorktown Formation/Undifferentiated Quaternary Sequences

Lower Miocene Silverdale Formation

Reflector β_2 in Figures 5, 6, 7 and 8 represents a major unconformity between the lower Miocene Silverdale Formation and the Miocene Pungo River Formation. This reflector was traced via seismic profiling to western Bogue Banks where Steele (1980) drilled a thick sequence of unconsolidated, poorly sorted, calcareous, clayey quartz sands intercalated with occasional coarse horizons where shells constitute up to 50 percent of the sediment. Faunal analyses indicate this unit is part of the lower Miocene Silverdale Formation of Baum and others (1978). A vibracore (#OB-37) penetrating reflector β_2 along the 15 meter seismic section obtained a similar lithology (Lewis, 1981).

Miocene Pungo River Formation

The Miocene Pungo River Formation is bound by reflectors β_2 and γ_1 or δ_1. Reflector γ_1 (Figs. 6 and 9) represents a major erosional unconformity between the Pungo River Formation and the Pliocene Yorktown Formation as demonstrated by correlations to several drill and core holes in the lower coastal plain (Miller, 1971; Brown and others, 1972; Mixon and Pilkey, 1976). Reflector δ_1 represents the velocity/density contrasts between basal Quaternary sediments and the underlying Tertiary sequences. This relationship has been verified by correlations to numerous drill and core holes on Bogue and Shackleford Banks (Susman and Heron, 1979; Steele, 1980), the lower coastal plain (Daniels and others, 1972; Berelson, 1979), as well as a number of vibracores along the seismic lines (Lewis, 1981). Reflector δ_1 truncates the Pungo River Formation in the western segment of the Bogue Basin where the intervening Yorktown Formation has been removed by erosion (Figs. 6 and 7).

We have delineated five major depositional sequences (A, B, C, D, and E) within the Pungo River Formation. Each depositional sequence is a package of generally

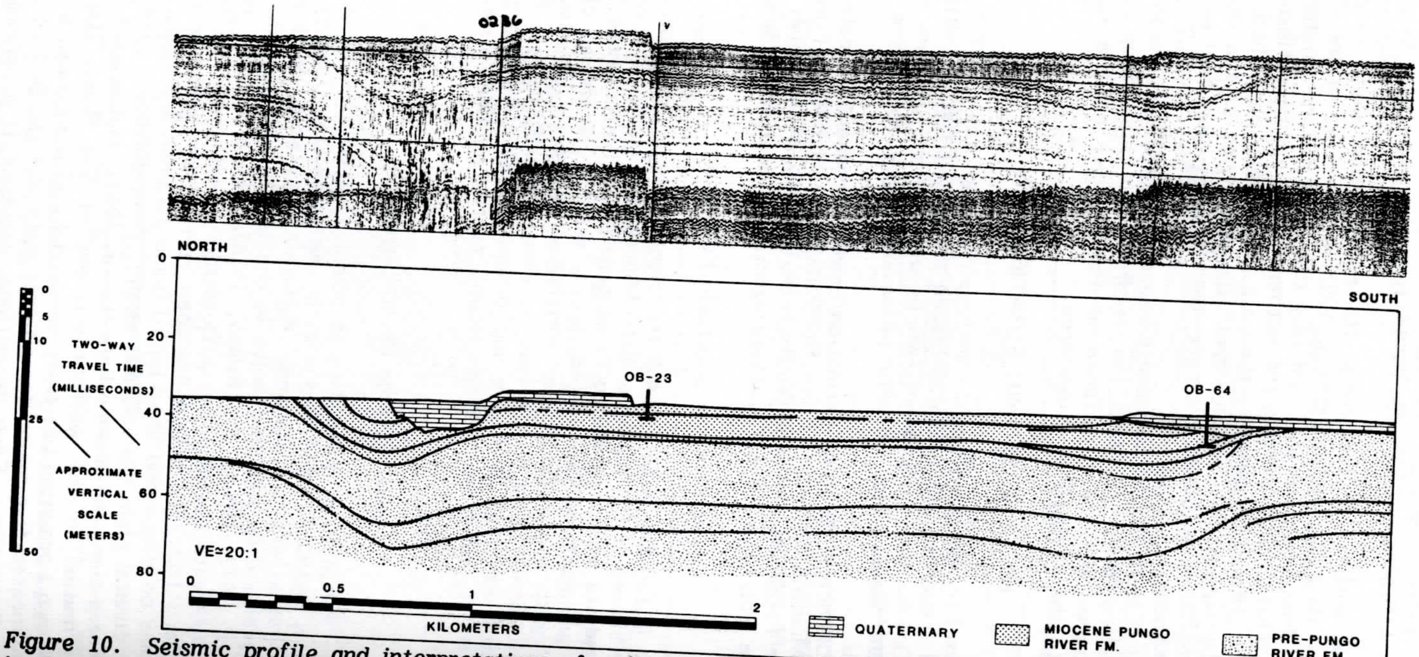

Figure 10. Seismic profile and interpretations of a flexure basin from southwestern Onslow Bay. Location of profile is shown in Figure 3A.

concordant reflectors consisting of genetically related strata bound at their top and base by unconformities as illustrated in the seismic sections (Figs. 6, 7, 8, and 9).

Sequence A--Pungo River Formation: Sequence A is bound by reflectors β_2 and β_3 (Figs. 6, 7, and 8), and represents the oldest depositional sequence of the Pungo River Formation. The sequence reflectors exhibit both onlap and downlap terminations on reflector β_2 which marks the top of the Silverdale Formation. In Figures 6, 7, and 8 the reflectors within the overlying sequence (sequence B) consistently terminate in a downlap fashion on reflector β_3 illustrating the unconformable relationship between these two sequences.

Correlations with several drill holes on Bogue Banks (Steele, 1980), as well as a number of vibracores penetrating sequence A (Figures 6 and 7), indicate this lower depositional unit consists of highly desiccated quartz-bearing, silty clay to clayey silt with occasional interbeds of fine calcareous sands. The silt fraction is predominantly rhombohedral dolomite. Several chert nodules were also recovered from this sequence (Lewis, 1981).

Sequence B--Pungo River Formation: The velocity/density contrast between sequence B and the overlying section is defined by reflector β_4, which forms a highly dissected, erosional unconformity truncating reflectors within the B sequence (Figures 6 and 7). The base of this sequence is marked by reflector β_3.

Correlations to drill hole data on Bogue Banks (Steele, 1980) indicate sequence B consists of a clayey, coarse barnacle shell hash to fossiliferous, clayey, fine-medium quartz sand. The uppermost section of sequence B is a tightly bound fossiliferous clay to indurated barnacle biomicrudite, and forms the karst-like topography illustrated by reflector β_4 in Figures 5 and 6.

Sequence C--Pungo River Formation: Sequence C is bound by reflectors β_4 and β_5 (Figs. 5, 6, 7 and 8). Reflector β_5 is an erosional unconformity between sequences C and D, as illustrated by the truncation of the reflectors within the C sequence in Figure 7.

Vibracores obtained from sequence C (OB-33 and OB-36 in Fig. 6) depict a similar lithology to sequence B except the quartz sand fraction comprises generally less than 5 percent of the sediment. In a series of correlative holes drilled on Bogue Banks, Steele (1980) encountered a similar trend. The uppermost section of sequence C is a lithified biomicrite (Steele, 1980) which has apparently impeded the vertical excavation of several Pleistocene channels (Fig. 7).

Sequence D--Pungo River Formation: The top of sequence D is defined by reflector β_6, where the youngest sequence (E) of the Pungo River Formation has not been removed by subsequent transgressions (Fig. 9). In Figure 5 the top of this sequence is marked by reflector γ_1, which is the erosional base of the Pliocene Yorktown Formation. In Figure 6 the top of sequence D is defined by reflector δ_1, which represents the base of an early Quaternary transgression. This sequence outcrops on the middle shelf (Fig. 7), and is currently being eroded by the Holocene transgression. A number of vibracores penetrating sequence D (Figs. 6 and 7; Lewis, 1981) indicate this sequence consists of a clayey, fine to medium, phosphorite sand to phosphatic quartz sand.

Sequence E--Pungo River Formation: Sequence E is the youngest sequence of the Pungo River Formation, and is limited to the eastern segment of the Bogue Basin due to the erosion by Pliocene and younger transgressions. This sequence is bound by reflectors β_6 and γ_1 in Figure 8. Reflector γ_1 truncates the reflectors within sequence E (Fig. 8) illustrating a major unconformity between sequence E and the Yorktown Formation. A vibracore (OB-5) off Beaufort Inlet has identified this sequence as a clayey, fossiliferous, fine calcareous quartz sand (Lewis and others, 1982).

Pliocene Yorktown Formation

The Pliocene Yorktown Formation is limited to the eastern segment of the Bogue Basin due to the erosional truncation by subsequent Pleistocene transgressions. Where present, the Yorktown Formation is bound by reflectors γ_1 and δ_1. An unconformity within the Yorktown Formation (reflector γ_2 in Fig. 8) separates this formation into two distinct depositional sequences. Reflectors γ_1 and γ_2 bound the lower Yorktown member, and reflectors γ_2 and δ_1 define the upper Yorktown member. These two sequences are similar to those defined in the Aurora Basin by Riggs and others (1980; 1981) and Snyder and others (in press).

DISCUSSION

Origin of Structures

Recent interpretations of magnetic surveys, supplemented by multi-channel and single-channel seismic data, depict the Carolina Platform as a relatively smooth topographic surface containing several, small, topographic features (Klitgord and Behrendt, 1979; Dillon and others, 1979; Buffler and others, 1979; Klitgord and Grow, 1980; Paull and Dillon, 1980). Many of these basement features have been mapped and interpreted as basement faults which originated during the Early Mesozoic rifting of North America from Africa (Sheridan, 1974a; 1974b). Recurrent movement along these fault zones has produced numerous small shallow sedimentary basins within this trailing-edge margin (Dillon and others, 1979; Paull and Dillon; 1980). The infilling history of each basin has been regulated by the timing, relative direction and magnitude of movement along these basement faults.

Most of the local structures we have identified within Onslow Bay appear to be coincident with mapped gravity anomalies, magnetic anomalies and/or sharp magnetic gradients. Some of the magnetic features have been interpreted as basement-rooted structures having subtle topographic relief (Klitgord and Behrendt, 1979), while the large (-60 mgal) Bouguer gravity anomaly in the Frying Pan Shoals area is thought to be, in part, a product of a syn-rift basin (Grim and others, 1980). The local deformation, depositional infilling patterns and coincidence with mapped geophysical anomalies suggests the Onslow Bay structures may be the surficial expression of recurrent movement along older, rift-originated or pre-rift faults within the Carolina Platform.

Miocene Stratigraphy and Sea-Level Cyclicity

The Miocene depositional sequences and associated unconformities indicate several cycles of relative sea-level change. These relative sea-level fluctuations can be attributed to: 1) global sea-level events produced by geoeustatic and/or glacio-eustatic fluctuations; 2) local, relative sea-level fluctuations produced by changes within the depositional basin from sedimentary infilling and/or local tectonism; or 3) a combination of both eustatic and local relative sea-level events.

Comparison of the Miocene relative sea-level cyclicity identified in the depositional sequences of Onslow Bay with the global eustatic sea-level curve proposed by Vail and others (1977) depicts a potentially strong correlation. The late Paleogene through Neogene segment of Vail's curve consists of four second-order supercycles (Td, Te, Tf, and Q in Fig. 11). Three major unconformities identified in Onslow Bay (Reflectors β_1, γ_1, and δ_1) may be correlative to the maximum regressions separating these four second-order cycles. Vail and others (1977) depict the maximum transgressions of eight Neogene third-order cycles at or above present-day sea level. We have tentatively correlated the depositional sequences and associated unconformities found in Onslow Bay to these third-order cycles of eustatic sea level change. These ***preliminary*** correlations are shown in Figure 11.

Our tentative correlations between the observed Miocene relative sea-level cyclicity and the global eustatic cycles of sea-level change of Vail and others (1977) are speculative at best. We currently lack the high-resolution biostratigraphic data needed to justify these correlations. Also, the magnitudes (maximum trans-

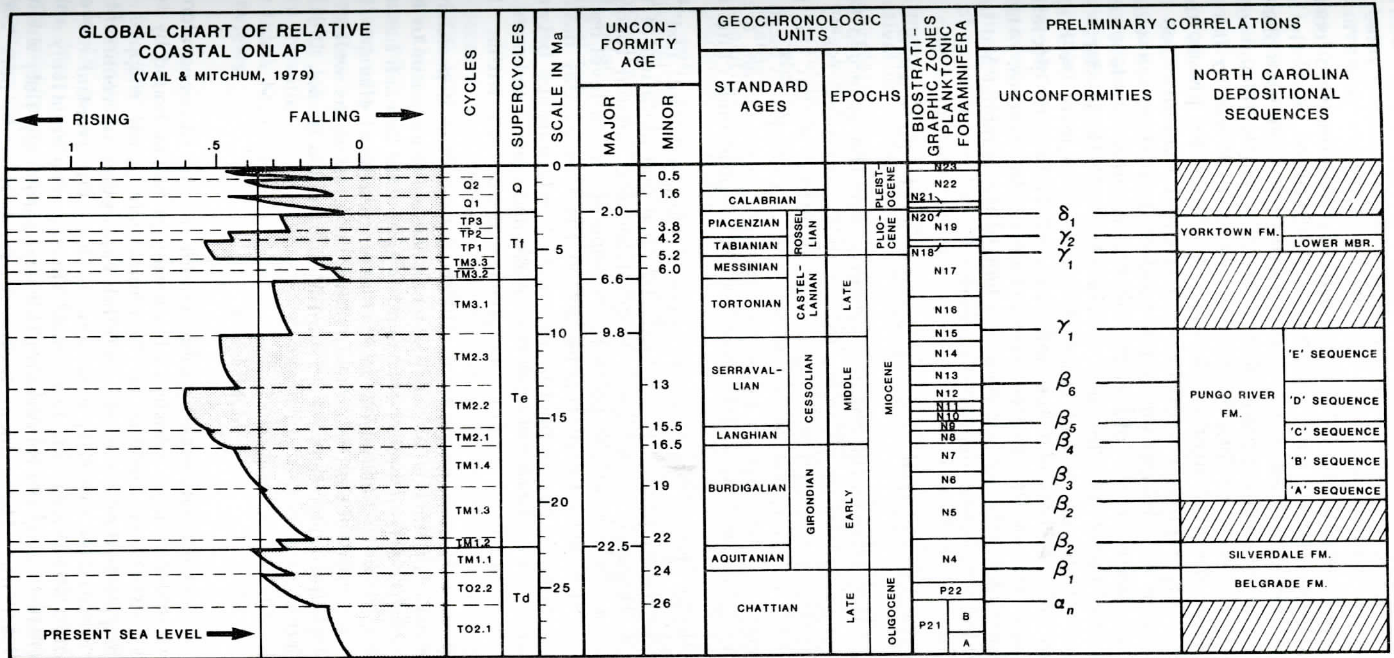

Figure 11. Preliminary correlations of the Onslow Bay depositional sequences and associated unconformities with the proposed eustatic sea-level curve of Vail and Mitchum (1979).

gressions/regressions) of the cycles within the relative sea-level curve for the North Carolina margin may deviate significantly from the eustatic curve of Vail and others due to local and/or regional tectonic overprint. Furthermore, the observed Miocene relative sea-level cyclicity may represent fourth or higher-order cycles of sea-level change.

Gibson (in press) has examined the planktonic Foraminifera content of the Miocene Pungo River Formation from the Aurora Embayment, directly north of our study area. He correlates portions of the Pungo River Formation with planktonic zones N 8 and N 11, with the intervening planktonic zones N 9 and N 10 not recognized. If the Pungo River sequences of Onslow Bay are correlative in age to the Pungo River Formation of the Aurora Embayment as defined by Gibson (in press), then many of these sequences probably represent fourth or higher-order cyclicity (see Fig. 11).

As high-resolution biostratigraphic data become available, we will refine our tentative correlations between the observed Miocene *relative* sea-level cyclicity and the proposed, eustatic curve of Vail and others (1977). These data will help to differentiate between third order and higher-frequency sea-level events, as well as evaluate the potential link between the initiation of Antarctic glaciation and the observed Miocene sea-level oscillations within the Onslow Bay system. Also, anomalous departures from Vail's global curve will help to identify the regional and local tectonic overprint for the North Carolina continental margin.

Miocene Depositional Response to Sea-Level Fluctuations

Significant paleoenvironmental changes accompanied the observed Miocene sea-level fluctuations, as evidenced by vibracore data (Lewis and others, 1982). Alterations in the paleobathymetry and paleo-oceanographic conditions within the basins were concomitant with each relative rise or fall in sea level. Changes in basin circulation, both within the basin and interaction between basin and open ocean, are thought to have controlled major fluctuations in the chemical and depositional climate within the basins.

Popenoe and Pinet (1980), Pinet and Popenoe (1980), and Paull and Dillon (1980) have documented modifications in the position and flow configuration of the Western Boundary Current in response to sea-level fluctuations and bottom topography. We believe that changes in the circulation patterns in response to sea-level oscillations had a major influence on the depositional regime within the Onslow Bay basins, and may be the primary control over the temporal and spatial relationships between sites of deposition and erosion, alternations between carbonate and clastic sediment regimes, as well as the episodic nature of major phosphorite deposition within the Miocene sequences.

The vibracore data (Lewis and others, 1982) suggests the depositional response accompanying each relative change in sea level has varied from basin to basin due to the new set of physical/chemical/biological constraints unique to each basin. Although the lithologies differ between basins for each relative sea-level change, the sea-level cyclicity seems to be consistent within the Onslow Bay system, as well as throughout the southeast U. S. (Riggs and others, this issue; Missimer and Banks, 1981), indicating regional or global control.

SUMMARY

The emerging structural and stratigraphic model for the Miocene along the upper North Carolina continental margin consists of a series of basins bound by several local structures. These structures appear to be coincident with mapped geophysical anomalies, which suggests they may be surficial expression of recurrent movement along older, rift-originated or pre-rift, basement faults. Differential movement along these basement-rooted structures was translated through the relatively thin Mesozoic to Cenozoic sedimentary cover characterizing this comparatively flat, shallow segment of the Carolina Platform. These local tectonic events have in part controlled the position of basin centers, as well as basin geometries through time, and have had a significant role in manipulating the local distribution, thickness and overall depositional pattern of the Miocene stratigraphic sequences.

The basin infilling histories have been dominated by several cycles of relative sea-level change. Six Miocene depositional sequences were identified in the Northeast Onslow Bay Embayment via high-resolution seismic profiling, vibracore analysis and correlations to existing drill and core hole data on the emerged coastal plain. We have tentatively correlated the observed Miocene depositional sequences and their associated unconformities to the proposed third-order global eustatic sea-level cycles of Vail and others (1977). These correlations are speculative at best since we lack the high-resolution biostratigraphic data needed to tie the observed Miocene cyclicity to the global sea-level curve of Vail and others (1977).

Each relative sea-level event identified in the Miocene depositional sequences of Onslow Bay produced modifications in the physical parameters within the basins. The depositional response to these paleoenvironmental changes differed for each basin, resulting in dissimilar lithologies for each change in relative sea level. Although the lithologic sequences for each sea-level event differ, the sea-level cyclicity seems to be consistent throughout Onslow Bay system. This suggests a regional or global eustatic factor rather than local tectonic control.

Both the Neogene tectonism controlling the structures delineated in Onslow Bay and the observed Miocene relative sea-level cyclicity may be related to major fluctuations in the rate of plate motion. Rona (1973) has indicated that the Miocene was a time of greater sea-floor spreading rates. Increased plate motion may result in an incipient rise in eustatic sea level and greater subsidence along the North Carolina Margin (Pittman, 1978). Differential subsidence within the Carolina Platform may initiate reactivation of basement-rooted structures. These local tectonic events would produce local relative sea-level changes. Subsidence of the faulted basement platform as a whole may result in regional, relative sea-level fluctuations. Both of these would modify the magnitudes of second and third order eustatic cycles of sea-level change, generating a *relative* curve unique to this portion of the upper North Carolina continental margin.

High-resolution biostratigraphic analysis, currently being done at East Carolina University (planktonic foraminifera) and the University of South Florida (calcareous nannofossils), will allow us to refine our preliminary correlations with the global eustatic sea-level curve of Vail and others (1977). Departures of the observed Miocene sea-level cyclicity in Onslow Bay from the global curve will help to differentiate local and regional relative sea-level fluctuations genetically related to tectonism from the proposed global eustatic sea-level oscillations.

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