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

By

Stanley R. Riggs
Department of Geology
East Carolina University
Greenville, North Carolina 27834

And

Don W. Lewis
Mobile Oil Exploration
1250 Poydras Building
New Orleans, Louisiana 70113

And

A. Kelly Scarborough
Texaco Inc.
P.O. Box 60252
New Orleans, Louisiana 70160

And

Scott W. Snyder
Department of Geology
East Carolina University
Greenville, North Carolina 27834

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.

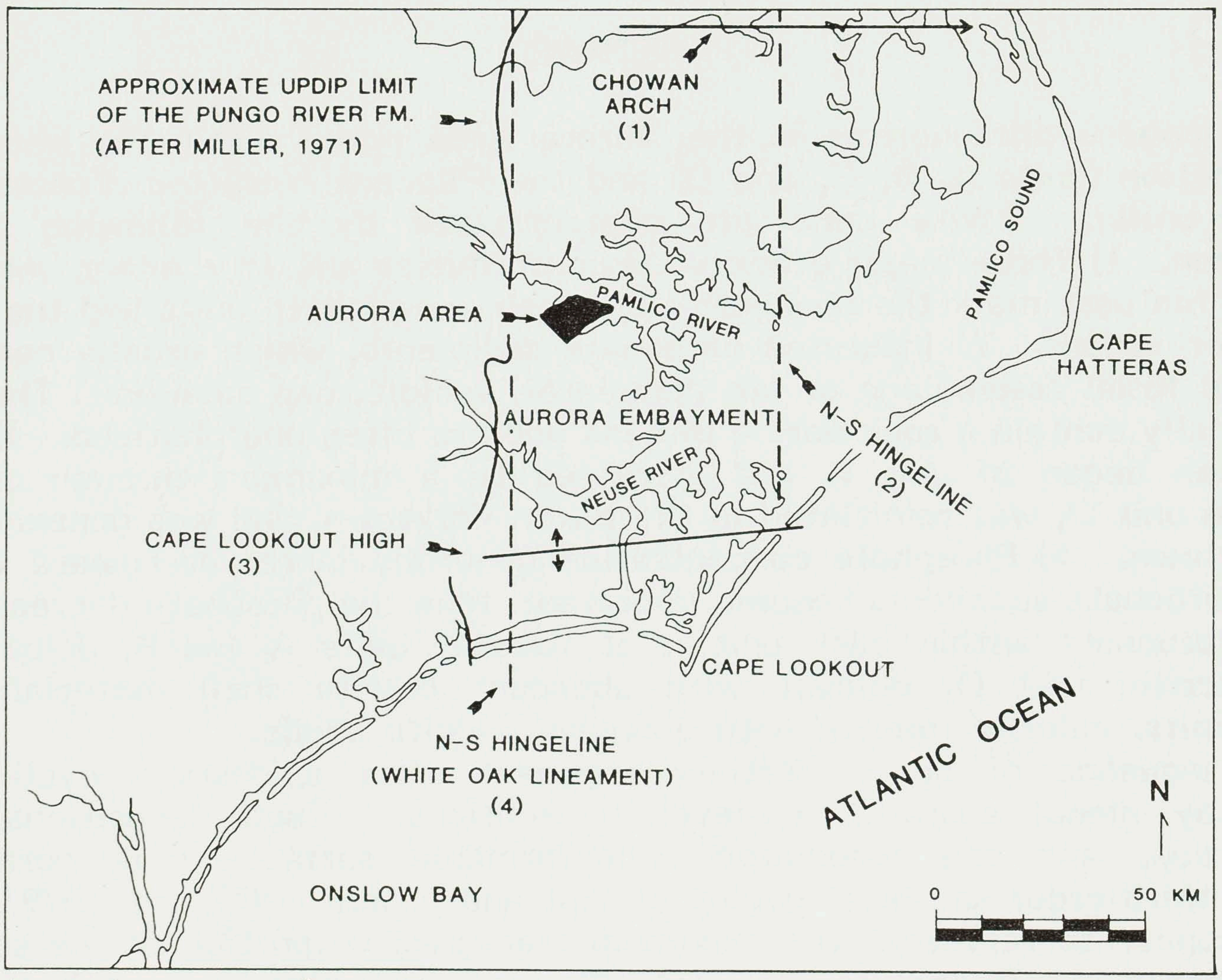


Figure 1. Location map of the Aurora Area, North Carolina. The Aurora Embayment is enclosed by structures 1-4 which are from the following sources: 1. Miller (1971); 2 and 4. Brown and others (1972), Miller (1971); 3. Scarborough and others (1982); S. W. P. Snyder and others (1982).

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		KIMREY, 1965 AURORA QUADRANGLE			ROONEY & KERR, 1967 LEE CREEK MINE		GIBSON, 1967 LEE CREEK MINE			RIGGS et al., THIS PAPER AURORA AREA		
YORKTOWN FM.	INTERBEDDED SHELL BEDS, MARL, SAND, & CLAY	YORKTOWN FM.		SHELL MARLS, UNCONSOLIDATED TO INDURATED SANDY SHELL BEDS, MASSIVE CLAYS & INTERBEDDED SAND	UPPER YORKTOWN FM.	MARL	YORKTOWN FM.	UNITS 7-9	VERY FOSSILIFEROUS CLAYEY SAND	CROATAN FM.		
						CALCAREOUS SANDSTONE		UNITS 3-6	FOSSILIFEROUS CLAYEY SAND	UPPER YORKTOWN FM.		
						MARL						
	REWORKED PHOSPHATE			REWORKED PHOSPHATE	LOWER YORKTOWN FM.	MARL		UNIT 2	PHOSPHATIC CLAYEY SAND	LOWER YORKTOWN FM.		
						PHOSPHORITE		UNIT 1	CLAYEY SAND & PHOSPHATE PEBBLES			
PUNGO RIVER FM.		PUNGO RIVER FM.					PUNGO RIVER FM.	UNIT 7	YELLOW GREEN SAND & BRYAZOAN HASH	PUNGO RIVER FM.	UNIT D	SHELLY DOLOSILT
	DOLOMITIC SHELL LIMESTONE		ZONE 1	COQUINA	CALVERT FM.	COQUINA		UNIT 6	YELLOW GREEN SAND & HYDROZOAN HASH			
								UNIT 5	MOLDIC LIMESTONE		UNIT C	MOLDIC LIMESTONE
	PHOSPHATIC SAND & DOLOMITIC SHELL LIMESTONE					PHOSPHORITE & COQUINA		UNIT 4	ALTERNATING LIMESTONE & PHOSPHATE			INTERBEDDED
	PHOSPHATIC SAND		ZONE 2	HIGH GRADE PHOSPHORITE	PUNGO RIVER FM.	PHOSPHORITE		UNIT 3	PHOSPHATIC SAND			PHOSPHORITE SAND
	DOLOMITIC SHELL LIMESTONE		ZONE 4	LOWER GRADE CLAYEY PHOSPHATIC SAND		DOLOMITIC LIMESTONE		UNIT 2	DIATOMACEOUS CLAY		UNIT B	BURROWED DOLOSILT
	PHOSPHATIC SAND					PHOSPHORITE		UNIT 1	PHOSPHATIC SANDS BOTTOM OF PIT			MUDDY PHOSPHORITE SAND
	DOLOMITIC SHELL LIMESTONE		ZONE 5	PHOSPHATIC CLAY		DOLOMITIC LIMESTONE					UNIT A	BURROWED DOLOSILT
	PHOSPHATIC SAND					PHOSPHORITE						MUDDY PHOSPHORITE SAND
CASTLE HAYNE LIMESTONE		CASTLE HAYNE LIMESTONE			CASTLE HAYNE LIMESTONE					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

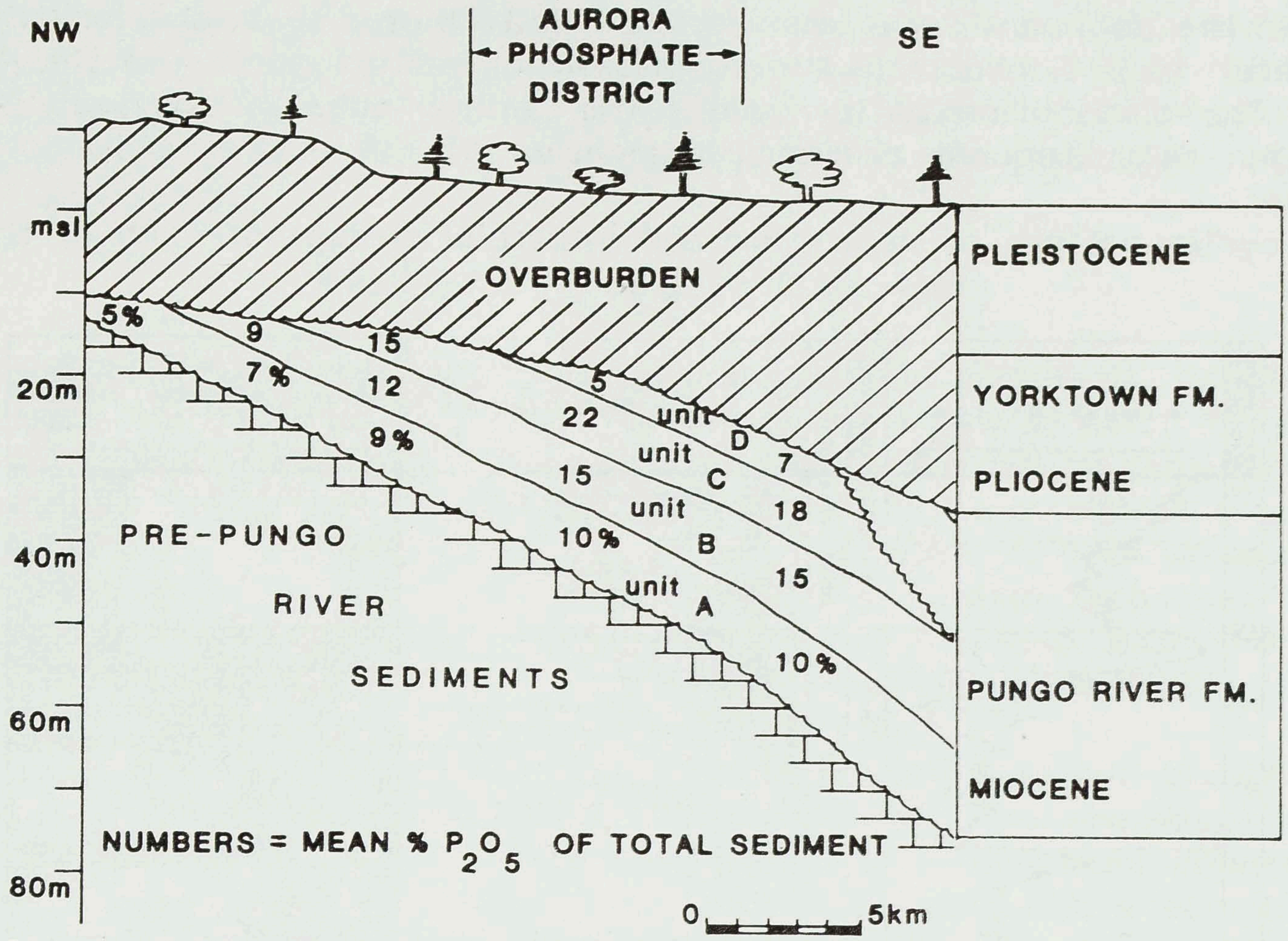


Figure 2. Idealized NW-SE geologic cross section through the Aurora phosphate district showing a) the mean P_2O_5 for each of the depositional units in the Pungo River and b) the changing phosphate concentrations vertically up the section and laterally down the slope of the basin.

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

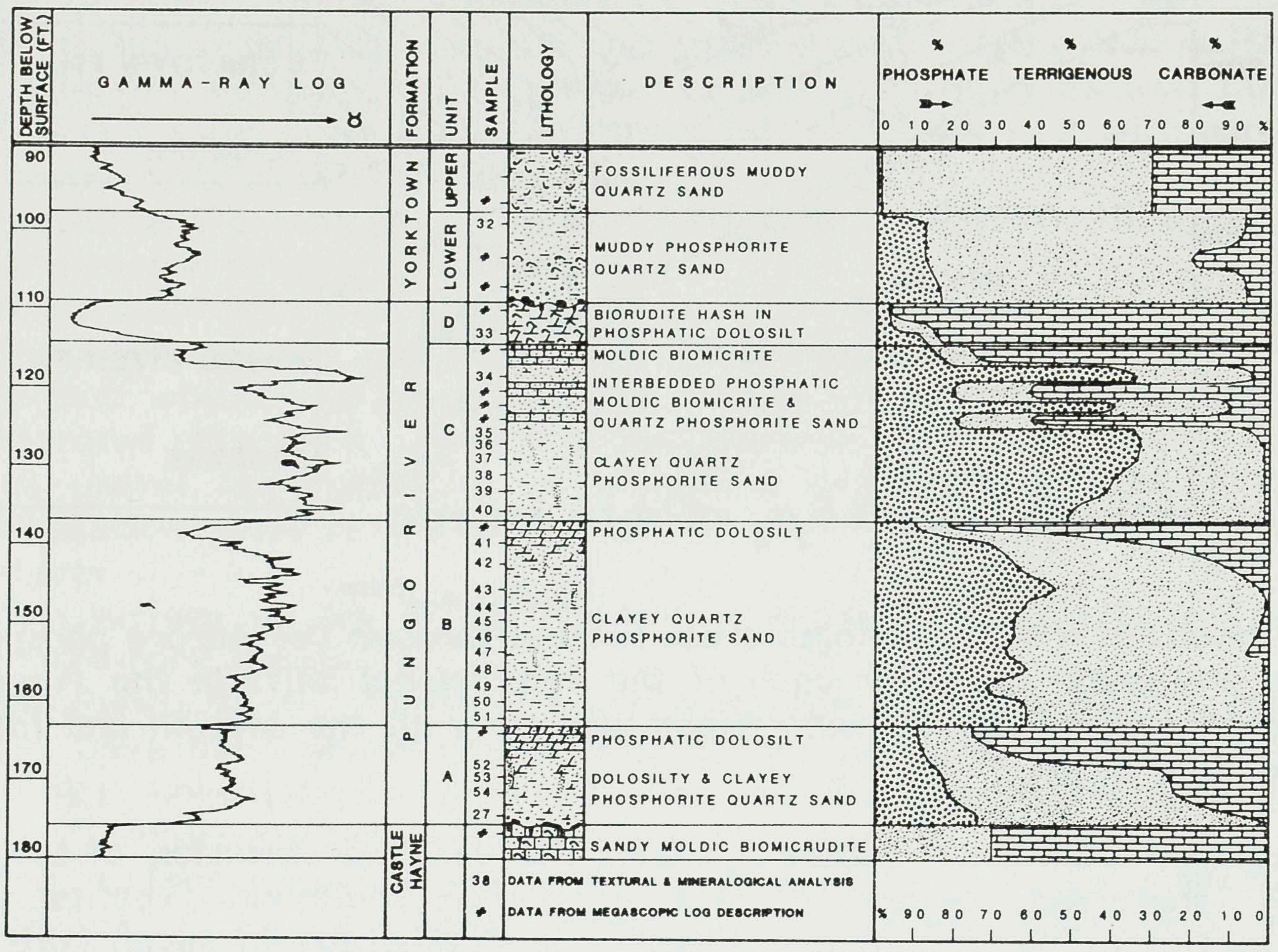
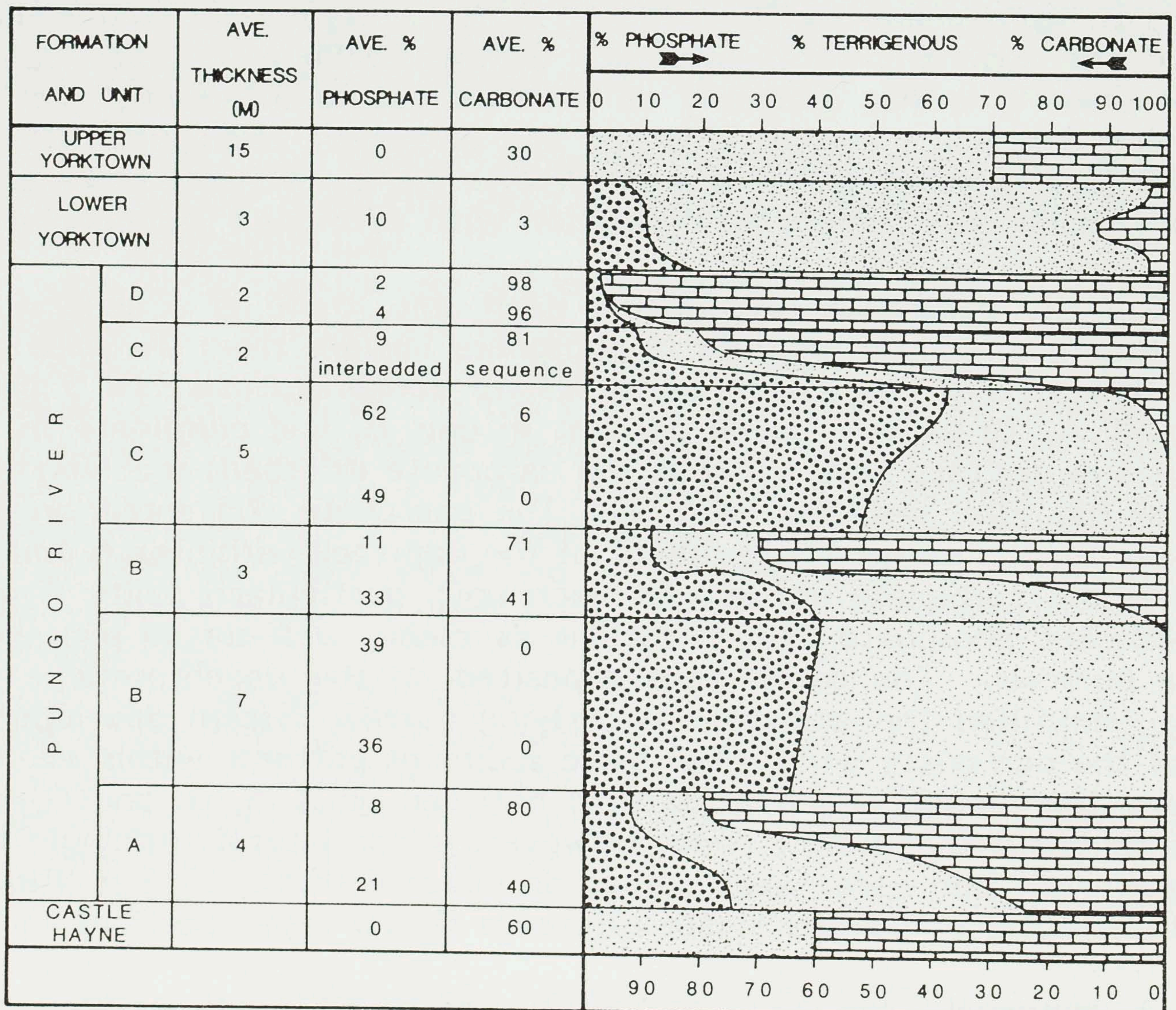


Figure 3. Relationship of phosphate, carbonate, and terrigenous sediment to the stratigraphic units and the gamma-ray log of the phosphorite section in the Aurora Area, N.C. (North Carolina Phosphate Corp. core holes H10 and GH8.5).



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 4	98 96
	C	2	9 interbedded	81 sequence
	C	5	62 49	6 0
	B	3	11 33	71 41
	B	7	39 36	0 0
	A	4	8 21	80 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

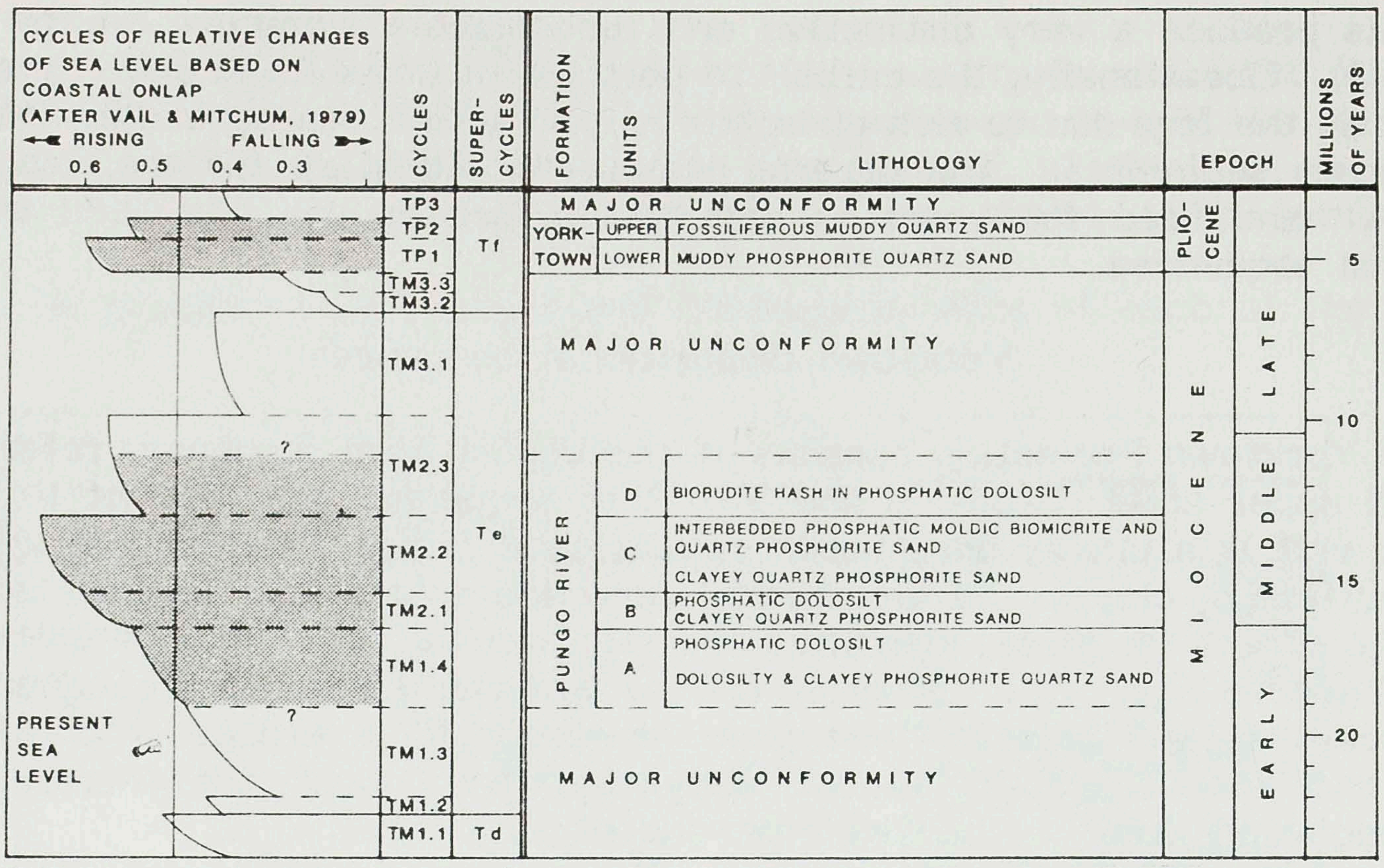


Figure 5. Proposed relationship of the upper Tertiary stratigraphic units to global sea level curves.

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 (TP1 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

This work was partially supported by grants from the National Science Foundation (DAR-79-08949 and OCE-81-10907). We would like to thank the personnel of North Carolina Phosphate Corporation, Washington, North Carolina, and Texasgulf, Inc., Aurora, North Carolina, who have allowed us to utilize drill-hole samples and supplied access to the operating open-pit mine for sampling and stratigraphic analysis, respectively. We would specifically like to thank Mr. Ronald Crowson of North Carolina Phosphate Corporation; Mr. Ralph Chamness of Texasgulf; and Dr. Don Neal, Mr. Doug Ellington, Mr. David Reid, and the many graduate and undergraduate students and faculty at East Carolina University, who contributed greatly to our present understanding of this complex sediment system. Thanks are also due to the many participants of the on-going programs associated with the International Geological Correlation Program (I.G.C.P.) 156 on phosphorites.

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