A. Kelly Scarborough. STRATIGRAPHY AND PETROLOGY OF THE PUNGO RIVER FORMATION, CENTRAL COASTAL PLAIN OF NORTH CAROLINA. (Under the direction of Dr. Stanley R. Riggs) Department of Geology, March 1981.

The Middle Miocene Pungo River Fm. is an economically important sedimentary phosphorite deposit which underlies the east-central Coastal Plain of North Carolina. The formation was deposited in the northeast-southwest trending Aurora Embayment, and is presently being mined for its phosphate content in the Aurora Area, Beaufort County, North Carolina. Fifty-four sediment samples of the Pungo River Fm. from nine cores in Beaufort, Pamlico, Craven, and Carteret Counties were analyzed in order to: 1) describe the lithologies which comprise the formation in the study area; 2) correlate the lithologies from their economic occurrence in the Aurora Area, southward and westward into the embayment margins; and 3) evaluate the environmental and structural controls which led to the accumulation of the formation in the Aurora Embayment.

Up to 30m of phosphatic sediments of the Pungo River Fm. were recovered from the easternmost core hole in the study area. These sediments thin to approximately 15m over the Cape Lookout High, a pre-Miocene topographic feature which forms the southern boundary of the Aurora Embayment. The western and updip limit of the formation parallels the White Oak Lineament, a regional north-south structure. At this lineament the formation is abruptly truncated and thins to a feather edge; however, deposition of the Pungo River Fm. extended beyond this present updip erosional limit of the formation some unknown distance to the west of the White Oak Lineament. The formation thickens rapidly to the east and southeast.

The Pungo River Fm. consists of seven major lithologies (units A, B, C, D, BB, CC, and DD). Phosphorite sedimentation was concentrated in units A, B, and C which possess regionally persistent mineralogical and textural characteristics and thus are laterally correlative throughout a large portion of the study area. The phosphorite sediments of units B and C grade downdip to the southeast into an 11m thick diatomaceous facies (unit BB). Units A, B, and C grade into a slightly phosphatic, calcareous, shelly, quartz sand facies in the area of the Cape Lookout High which probably represents a shoaling environment (unit CC). The dolomitic unit D of the northern and eastern portions of the study area grades laterally into the calcareous unit DD in the central portion of the embayment.

Allochemical phosphate grains of the intraclastic variety dominate all the units in the formation. However, unit A contains abundant pelletal phosphate in the very fine to fine sand-size fraction. The highest phosphate concentrations were found mid-slope in the west-central portion of the embayment. Updip to the west, the volume of phosphatic sediments decreases rapidly as the phosphorite units have been sequentially truncated by subsequent erosion. Facies changes to the east and southeast also result in a decreased phosphate content within the formation.

Several regionally persistent vertical and lateral sedimentological trends were recognized within the formation. 1) Phosphate content increases upsection from unit A through unit C. 2) There is a fining upward trend in mean grain size from unit A through unit C. 3) The phosphate content of the formation increases northward and northwestward from the southern embayment margin to the Aurora Area. 4) In the Aurora Area each of the phosphorite units is separated from the overlying unit by a period of increased carbonate sedimentation and decreased phosphate deposition.

The depositional pattern of the lithologies which comprise the Pungo River Fm. suggests that units A, B, and C were deposited through a relatively rising sea level. Phosphate deposition was periodically interrupted by regional increases in carbonate sedimentation, non-deposition, and possibly erosion. The transgression culminated with the deposition of the rich phosphorite unit C, the diatomite of unit BB, and the quartz sands of unit CC. Units D and DD were deposited during the following regression which was followed by a major erosional period and severe truncation of the Pungo River Fm. across the western margin of the embayment and across the Cape Lookout High. This post-Miocene erosional truncation has produced an apparent offlap geometric configuration of the Pungo River sediments which actually represent a transgressive or onlap depositional sequence.

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

A Thesis

Presented to

the Faculty of the Department of Geology

East Carolina University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Geology

by

A. Kelly Scarborough

March 1981

STRATIGRAPHY AND PETROLOGY OF THE PUNGO RIVER FORMATION,

CENTRAL COASTAL PLAIN OF NORTH CAROLINA

by

A. Kelly Scarborough

APPROVED BY:

COMMITTEE

Dr. Stanley R. Riggs

Dr. Scott W. Snyder

Dr. Don W. Neal

Dr. Vincent T. Bellis

DIRECTOR OF GRADUATE STUDIES, DEPARTMENT OF GEOLOGY

Dr. Scott W. Snyder

CHIARMAN OF THE DEPARTMENT OF GEOLOGY

Dr. Charles Q. Brown

DEAN OF THE GRADUATE SCHOOL

Dr. Joseph G. Boyette

ACKNOWLEDGEMENTS

I would like to express my most sincere thanks to Dr. Stanley R. Riggs who supervised this thesis and various other related projects which facilitated by these research. Thanks are also extended to the other members of the committee, Dr. Scott Snyder and Dr. Don Neal, for their encouragement, prompt and critical reading of the manuscript, and geological expertise which they shared frequently. Special thanks go to Dr. Vincent Bellis who served as outside consultant and also reviewed the manuscript. I would also like to acknowledge the accurate and time-saving laboratory assistance provided by David Reid.

Special thanks are extended to the International Minerals and Chemical Corporation, North Carolina Phosphate Corporation, and Texasgulf, Inc. which supplied samples and cores used in this study. Thanks also to Ralph Chamness and Ron Crowson, geologists for Texasgulf, who supervised numerous field trips to the active phosphate mine in Aurora, North Carolina. Appreciation is expressed to the North Carolina Department of Natural Resources and Community Development for a generous research grant.

Of course, nothing would have been accomplished without the confidence, patience, and unwavering support of my wife, Lynn, who always wanted me to study volcanism.

TABLE OF CONTENTS

TABLE OF ILLUSTRATIONS

Plates

INTRODUCTION

The Middle Miocene Pungo River Fm. is an economically important sedimentary phosphorite deposit that underlies the outer Coastal Plain of North Carolina (Fig. 1). The formation is part of the eastward dipping and thickening wedge of sediments which have accumulated on the trailing edge of the North American plate since the Cretaceous Period (Fig. 2). The greatest portion of these sediments are 'normal' marine limestones or terrigenous sands and clays, such as the Eocene Castle Hayne Limestone or the Pliocene Yorktown Fm. However, the Pungo River Fm. formed during a period of 'abnormal' sedimentation during the Miocene. The resulting sediment package includes the extensive phosphorite deposits and the associated dolomite, diatomite, glauconite, and magnesium-rich clay deposits of the Atlantic Coastal Plain which extend from Florida to Virginia (Riggs, 1980 and 1979b; Weaver and Beck, 1977; Gibson, 1970).

The Pungo River Fm. has been correlated, at least in part, with the Calvert Fm. of Maryland and Virginia, and the Hawthorn Group of Florida and Georgia. The Calvert is the oldest of four Middle Miocene to Lower Pliocene formations that comprise the Chesapeake Group of the middle Atlantic Coastal Plain. The youngest of these formations is the Pliocene Yorktown Fm. which was deposited over most of northeastern North Carolina and southern Virginia as a major transgressive-regressive sediment sequence (Riggs et al., in press; Katrosh, 1981; Mauger, 1979). The middle two formations, the Choptank and St. Marys, are absent in North Carolina. The Yorktown Fm. unconformably overlies the Pungo River Fm. throughout east-central North Carolina (Miller, 1971; Gibson, 1967).

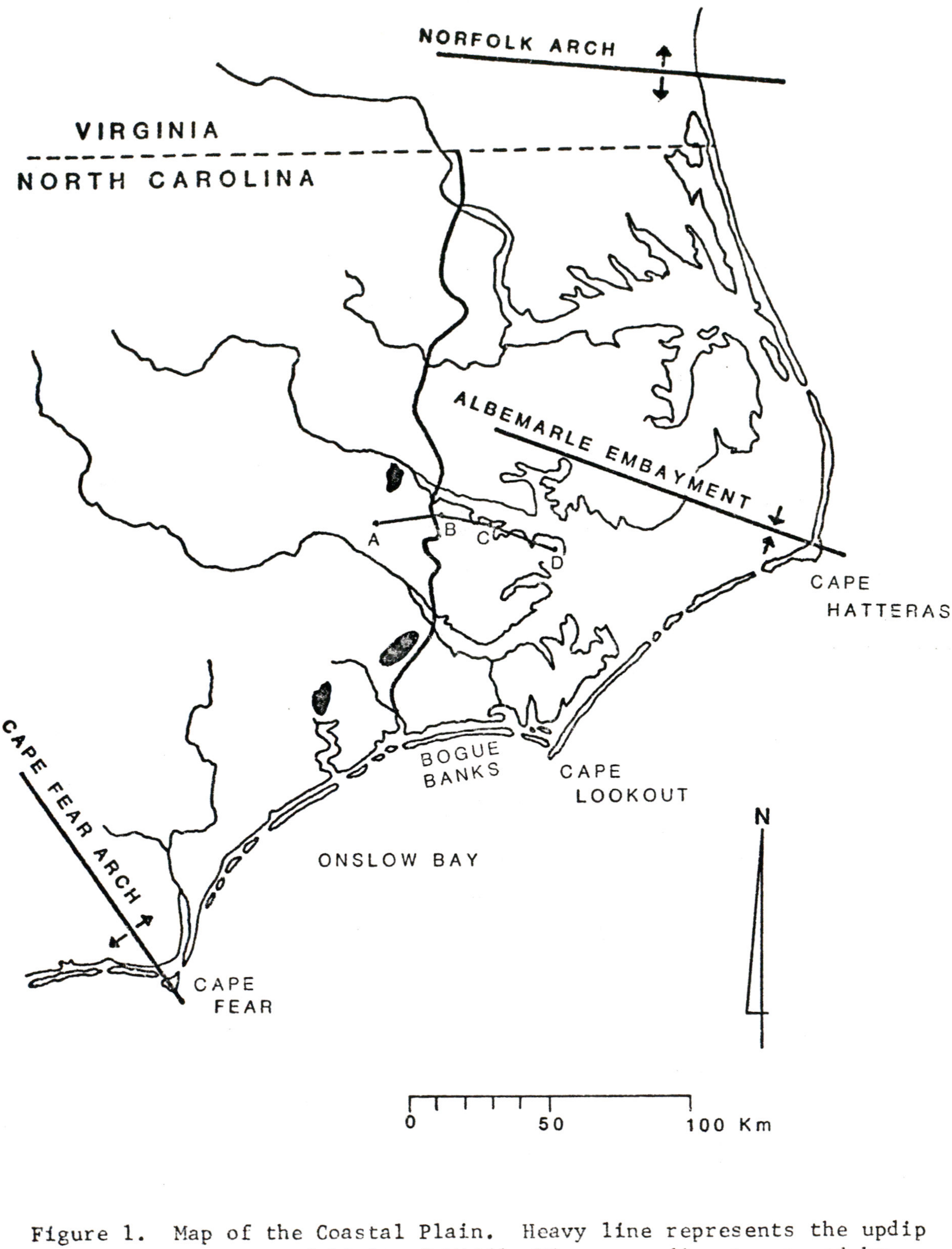


Figure 1. Map of the Coastal Plain. Heavy line represents the updip or westward limit of Middle Miocene sediments mapped by Miller (1971). Line A-D is the traverse of Figure 2. Also shown are the major basement structures, which controlled Tertiary sedimentation, and erosional outliers of the Pungo River Fm. (in black). Data from Miller (1971) and Gibson (1967).

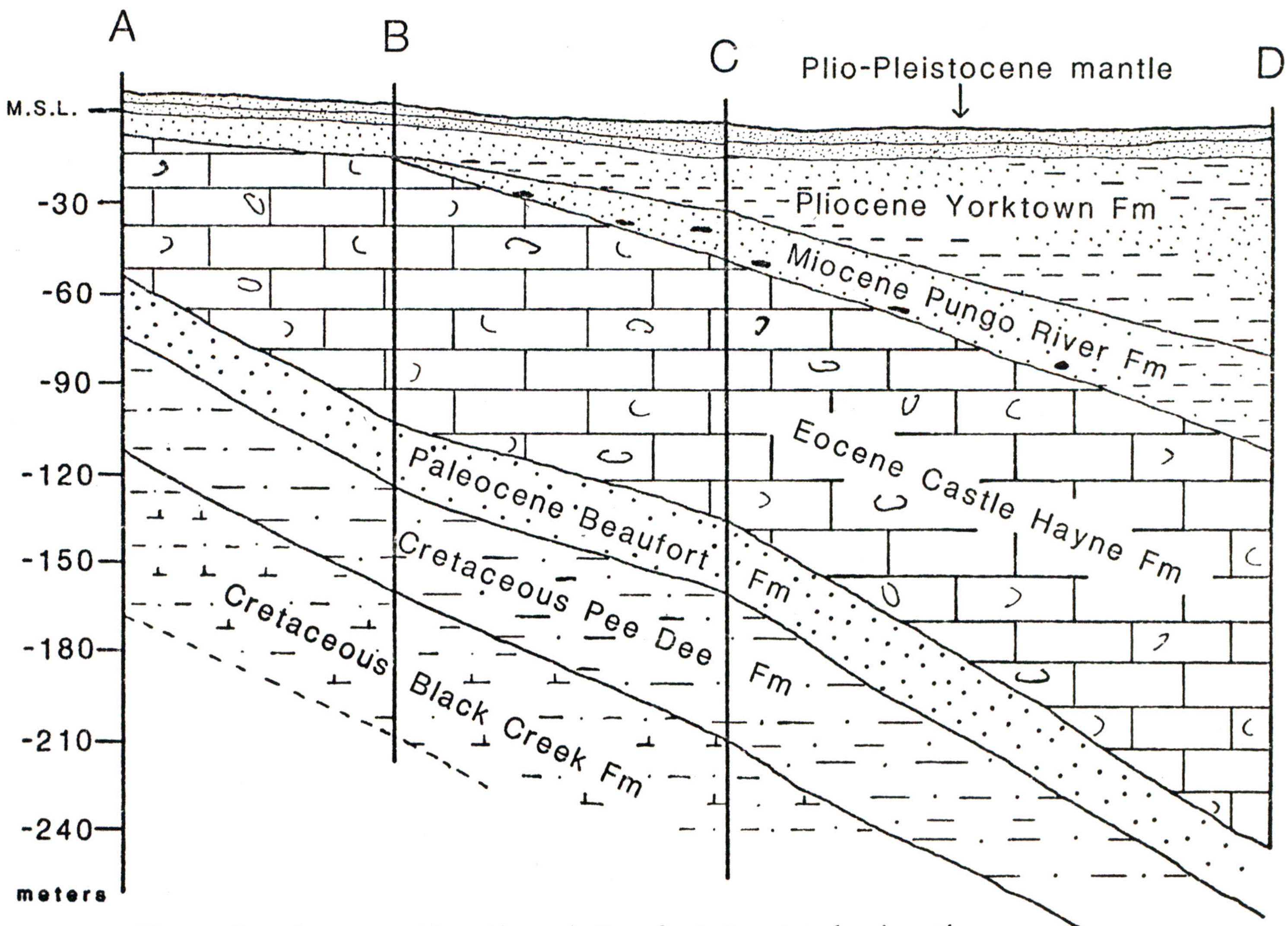


Figure 2. Cross-section through Beaufort County showing the Cretaceous to Pleistocene sediment wedge which underlies the Coastal Plain of North Carolina. Line of section A-D is shown in Figure 1. (Modified from Mauger, 1979).

Post-Pungo River sediments south of the Neuse River are referred to as the Duplin Fm. (Copeland, 1964). Gibson (in press) interprets the Duplin strata as biostratigraphically equivalent to upper portions of the Yorktown Fm. The Pungo River Fm. unconformably overlies rocks of Paleocene, Eocene, Oligocene, or Lower Miocene age, depending on the regional location (Baum et al., 1978; Ward et al., 1978; Miller, 1971).

The Pungo River Fm. is presently being mined for its phosphate content by Texasgulf, Inc. at the Lee Creek Mine, Aurora Area, Beaufort County, North Carolina (Fig. 3). The phosphorite deposit averages 18% P_2O_5 with an estimated phosphate resource totaling 10 billion tons over a 50,000 acre area (Wilson et al., 1976; Rooney and Kerr, 1967). Although the overburden thickness of approximately 25 to 30m is greater than that at other open-pit phosphate mining operations, the thickness and lateral extent of the ore body, and the relatively uniform lithologic characteristics of the formation (including the grain size of the phosphate component) allow Texasgulf to extract between 85 and 90% of the recoverable ore (Caldwell, 1968). These factors have prompted North Carolina Phosphate Corporation to evaluate the possibility of mining the Pungo River Fm. underlying property adjacent to the Lee Creek Mine (Riggs et al., in progress; Riggs et al., 1980).

The study area is located in the east-central portion of the North Carolina Coastal Plain within Beaufort, Pamlico, Craven, and Carteret Counties (Fig. 3). Samples used in this study were obtained from core holes shown in Figure 3. This study will provide additional information concerning the depositional history of an economically valuable sedimentary phosphorite accumulation.

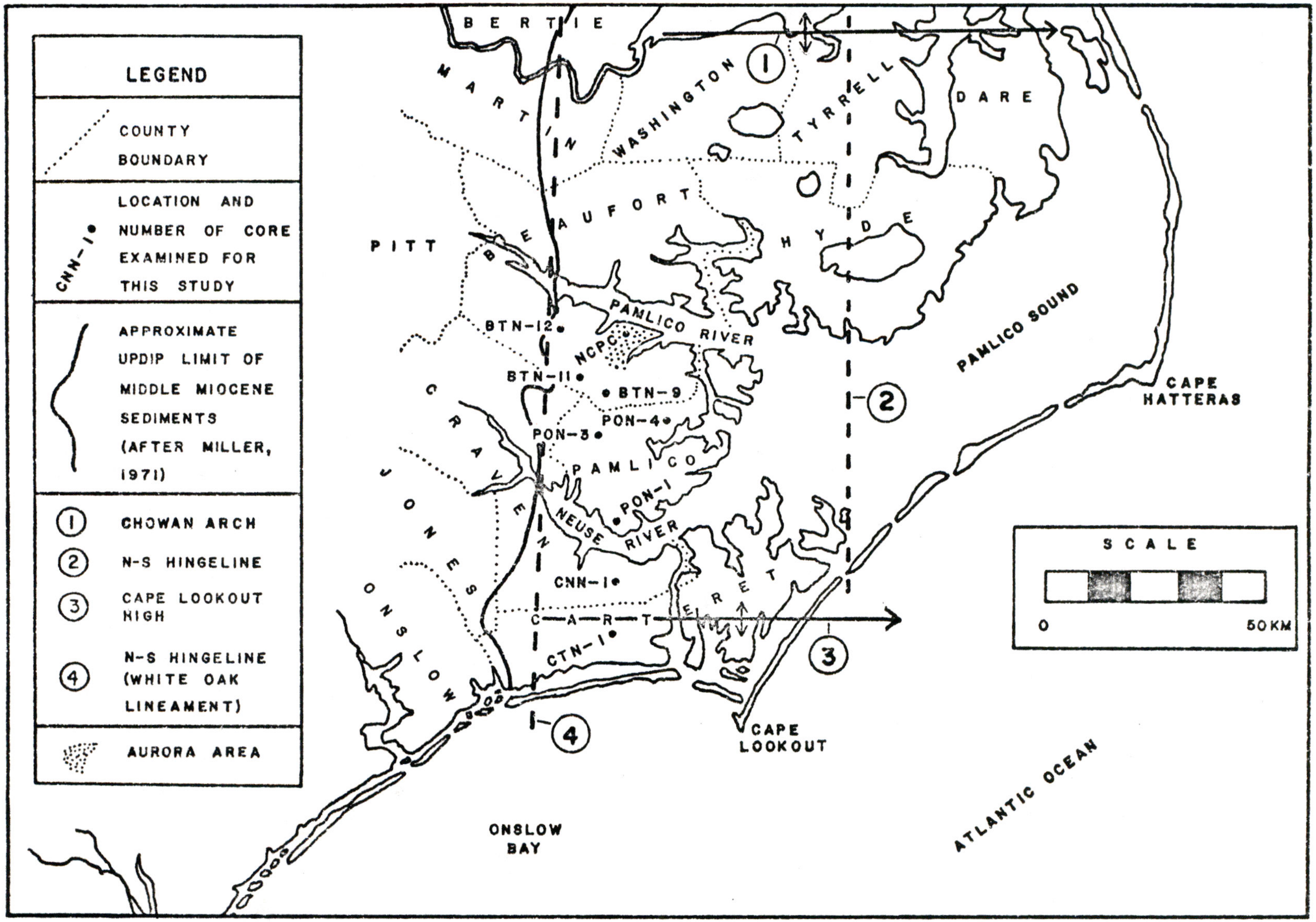


Figure 3. Structural setting of the Aurora Embayment. The embayment is enclosed by structures 1-4. Sources as follows: (1) Miller, 1971; Riggs, 1967b; (2) Brown et al., 1972; Miller, 1971; (3) Snyder et al., in press; and (4) Snyder et al., in press; Brown et al., 1972; Miller, 1971.

PREVIOUS WORK ON THE PUNGO RIVER FORMATION

Geologic Occurance

The phosphatic and phosphorite sediments of the Pungo River Fm. were originally described and correlated with the Middle Miocene Calvert Fm. of Maryland and Virginia on the basis of benthic foraminifera (Brown, 1958). The formation was named by Kimrey (1964). Subsequent work by Gibson (1970, 1967) involving molluscs and benthic foraminifera supports Brown's correlation, but it also extends the lower age limit of the Pungo River Fm. to latest Early Miocene. The work of Katrosh (1981) involving benthic and planktic foraminifera concurs with Gibson's age interpretation. The Pungo River Fm. is also equivalent to portions of the phophatic Miocene Hawthorn Group of Florida (Riggs, 1980, 1979b; Gibson, 1967).

The Pungo River Fm. is found only in the subsurface of eastern North Carolina. Miller (1971) mapped the formation northward to Virginia, and eastward and southward to the continental shelf (Fig. 1). According to Miller, the formation dips and thickens to the east, ranging in thickness from a feather edge along its updip westward limit to +300m near Cape Hatteras. Depths below sea level to the top of the formation range from approximately -8m along the western boundary to more than -90m near Cape Hatteras. The western boundary of the formation coincides with and parallels a major north-south structural hingeline of Miller (1971). This hingeline coincides with the White Oak Lineament defined in the Bogue Banks area by Snyder et al. (in press). The presence of several erosional outliers west of the White Oak

Lineament (Miller, 1971) suggests that primary deposition extended beyond the present updip erosional limit of the formation (Fig. 1). The northern and eastern limits of the formation are unknown. To the south, phosphorite sediments of the Pungo River Fm. have been recovered from holes drilled on Bogue Banks, Carteret County (Steele, 1980), and from vibracores across the continental shelf in Onslow Bay (Lewis et al., in press) (Fig. 3).

Within the study area the Pungo River Fm. unconformably overlies limestones of Eocene and Oligocene age, and shelly quartz arenites of Lower Miocene age (Ward et al., 1978; Baum et al., 1978; Miller, 1971; Gibson, 1967). Due to the controversy concerning the age and stratigraphic assignment of these variable lithologies (Steele, 1980), the underlying units will be referred to as pre-Pungo River sediments. Where the pre-Pungo River limestones are indurated, an undulating, bored and burrowed microsphorite surface is present along the unconformable contact; the limestone may be phosphatized to a depth of 30cm (Riggs et al., in press, 1980; Gibson, 1967).

The Yorktown Fm. of Pliocene age (Mauger, 1979) unconformably overlies the Pungo River Fm. throughout most of the Coastal Plain of North Carolina (Miller, 1971; Gibson, 1967; Copeland, 1964). Steele (1980) notes the presence of Yorktown sediments overlying the Pungo River Fm. in cores from Bogue Banks, and Lewis et al. (in press) have recognized Yorktown sediments overlying the formation in Onslow Bay. The erosional nature of the Pungo River-Yorktown contact is evident in the exposure at the Lee Creek Mine. Small channels or scour holes up to 1m deep have been cut into the Pungo River Fm. These holes are filled with poorly sorted, shelly, phosphate and quartz gravelly, muddy, fine to medium grained phosphatic quartz sands that typify the lower portion of the Yorktown Fm. (Riggs et al., in press; Katrosh, 1981). These sediments have long been interpreted as a transgressive high-energy deposit, formed as a result of erosion and reworking of Pungo River sediments during a Pliocene sea level transgression (Miller, 1971; Gibson, 1967). However, Riggs et al. (in press) postulate that the phosphate component in the lower Yorktown Fm. may be primary, having been produced during a Pliocene phosphogenic transgressive regime.

Structural Controls

The structural features which have traditionally been recognized as controlling Tertiary sedimentation in the Coastal Plain of North Carolina are the Norfolk and Cape Fear Arches, with an associated intervening basinal area called the Albemarle Embayment (Mauger, 1979; Brown et al., 1972; Miller, 1971; Gibson, 1967) (Fig. 1). The thickest sequence of Tertiary sediments was deposited in the axis of the embayment with the sediments thinning or absent over the structural arches.

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 3. The western and eastern margins are delineated by north-south trending hingelines defined by Brown et al. (1972) and Miller (1971). The western hingeline is coincident with the White Oak Lineament as described by Snyder et al. (in press) in the Bogue Banks and Onslow Bay areas. The northern margin is delineated by the east-west trending Chowan Arch of Miller (1971) and Riggs (1967b), which is located just south of Albermarle Sound (Fig. 3). The southern margin is defined by a positive feature located south of the Neuse River which has been recognized by many workers (Snyder et al., in press; Brown et al., 1972; Miller, 1971; Gibson, 1967; Riggs, 1967b). This east-west trending topographic high is called the Cape Lookout High by Snyder et al. (in press). According to Miller (1971) these four structural features created a restricted "Pungo River basin" or Aurora Embayment into which phosphate that was precipitated on the open seaward side of the easternmost hingeline was transported and deposited.

The close relationship of structural elements to phosphorite sedimentation and accumulation has been discussed by Riggs (1980, 1979a, 1979b, 1967b), Miller (1971), and Freas and Riggs (1964). Miller states that "the location of economic or potentially economic phosphate deposits... shows that structural conditions in the basin played a prominent, perhaps dominant, role in deposition and concentration of the phosphate." More specifically, Riggs (1980, 1979a, 1979b) believes that primary phosphorite sedimentaion occurs in the coastal, shallow nearshore shelf, and platform environments associated with structurally positive features such as the Ocala Upland in Florida and the Cape Fear Arch in North Carolina. The phosphate is physicochemically and/or biochemically precipitated as cold phosphate-rich ocean upwelling currents move across the shallow platforms and into the coastal environments. Much of the phosphate and diluent terrigenous sediments are subsequently transported downslope and along the flanks of the structural highs and accumulate in associated "entrapment basins" (Riggs, 1979a, 1979b, 1967a; Freas and Riggs, 1964).

Lithostratigraphy

The lithologic descriptions of the Pungo River Fm. by several authors possess many similarities and are summarized in Table 1. Most of this work has been centered in the Aurora Area of Beaufort County, North Carolina (Fig. 3).

Brown (1958) first described the lithostratigraphy of the Pungo River Fm. in Beaufort County. He identified 4 phosphatic sand units with "4 intercalated calcitic to dolomitic shell limestones" (Table 1). The brown phosphatic sands described by Brown consist of 25 to 55% fine to medium grained, angular to subrounded, water polished quartz sand; 25 to 50% fine to coarse grained, tan to brown to black carbonate fluorapatite spherules and shards; and 15 to 30% brown silt and clay.

Kimrey (1965) described the Pungo River Fm. underlying Beaufort County as a sequence of "interbedded phosphatic sands, silts and clays, diatomaceous clays, and phosphatic and non-phosphatic limestones and silty claystones." In the Aurora quadrangle the formation was subsequently divided into 5 major lithologic zones, each of which contained distinct sublithologies (Table 1). Kimrey (1964, 1965) found that the phosphatic zones of the formation could be distinguished, on the basis of terrigenous content versus phosphate content, and that the phosphate content persistently increased vertically upsection through the formation while terrigenous content decreased. According to Kimrey, the phosphatic sands of the formation are comprised of fine to medium grained carbonate fluorapatite and quartz with varying amounts of silt and clay, and various types of phosphatic fossil material. The phosphate grains are generally brown in color, smooth, glossy and

BROWN, 1958 BEAUFORT COUNTY	
YORKTOWN FM.	INTERBEDDED SHELL BEDS, MARL, SAND, & CLAY
	REWORKED PHOSPHATE
PUNGO RIVER FM.	DOLOMITIC SHELL LIMESTONE
	PHOSPHATIC SAND & DOLOMITIC SHELL LIMESTONE
	PHOSPHATIC SAND
	DOLOMITIC SHELL LIMESTONE
	PHOSPHATIC SAND
	DOLOMITIC SHELL LIMESTONE
	PHOSPHATIC SAND
CASTLE HAYNE LIMESTONE	

KIMREY, 1965 AURORA QUADRANGLE		
YORKTOWN FM.	SHELL MARLS, UNCONSOLIDATED TO INDURATED SANDY SHELL BEDS, MASSIVE CLAYS & INTERBEDDED SAND	
	REWORKED PHOSPHATE	
PUNGO RIVER FM.	ZONE 1	COQUINA
	ZONE 2	HIGH GRADE PHOSPHORITE
	ZONE 4	LOWER GRADE CLAYEY PHOSPHATIC SAND
	ZONE 5	PHOSPHATIC CLAY
CASTLE HAYNE LIMESTONE		

ROONEY & KERR, 1967 LEE CREEK MINE	
UPPER YORKTOWN FM.	MARL
	CALCAREOUS SANDSTONE
	MARL
LOWER YORKTOWN FM.	MARL
	PHOSPHORITE
CALVERT FM.	COQUINA
	PHOSPHORITE & COQUINA
PUNGO RIVER FM.	PHOSPHORITE
	DOLOMITIC LIMESTONE
	PHOSPHORITE
	DOLOMITIC LIMESTONE
	PHOSPHORITE
CASTLE HAYNE LIMESTONE	

GIBSON, 1967 LEE CREEK MINE		
YORKTOWN FM.	UNITS 7-9	VERY FOSSILIFEROUS CLAYEY SAND
	UNITS 3-6	FOSSILIFEROUS CLAYEY SAND
	UNIT 2	PHOSPHATIC CLAYEY SAND
	UNIT 1	CLAYEY SAND & PHOSPHATE PEBBLES
PUNGO RIVER FM.	UNIT 7	YELLOW GREEN SAND & BRYAZOAN HASH
	UNIT 6	YELLOW GREEN SAND & HYDROZOAN HASH
	UNIT 5	MOLDIC LIMESTONE
	UNIT 4	ALTERNATING LIMESTONE & PHOSPHATE
	UNIT 3	PHOSPHATIC SAND
	UNIT 2	DIATOMACEOUS CLAY
	UNIT 1	PHOSPHATIC SANDS BOTTOM OF PIT

RIGGS et al., in press AURORA AREA		
CROATAN FM.		
UPPER YORKTOWN FM.		
LOWER YORKTOWN FM.		
PUNGO RIVER FM.	UNIT D	SHELLY DOLOSILT
	UNIT C	MOLDIC LIMESTONE
		INTERBEDDED
		PHOSPHORITE SAND
	UNIT B	BURROWED DOLOSILT
		MUDDY PHOSPHORITE SAND
	UNIT A	BURROWED DOLOSILT
		MUDDY PHOSPHORITE SAND
CASTLE HAYNE FM.		

Table 1. Lithostratigraphic descriptions of the Pungo River Fm. by previous authors. (From Riggs et al., in press).

spheroidal to ovate in shape. Quartz occurs as clear, bladed, angular to subangular grains. The phosphatic clays are brown to olive green in color while the diatamaceous clays are light gray with up to 90% diatom frustules and fragments in a silt and clay matrix. The calcareous clays and claystones are usually light green to light gray to white. Phosphate content in all of the clay types is less than 10%. The carbonates reported by Kimrey consist of gray to dark gray phosphatic quartz dolosilts and dolomuds and creamy white to light gray coquina which varies in the degree of induration. The dolostones are often moldic and the coquinas are composed of both whole shells and fragments and recrystallized calcite.

Gibson (1967) presented a detailed lithologic description of the formation as it occurred along a pit exposure at the Lee Creek Mine. Gibson recognized seven distinct lithologic units, each having a relatively constant sediment and faunal character, that resemble the sequence described by Kimrey (Table 1),

The most extensive work on the lithology and stratigraphy of the Pungo River Fm. was performed by Miller (1971) when he described and correlated the various facies of the formation throughout the Coastal Plain of North Carolina. Miller concluded that Kimrey's (1965) lithostratigraphic description of the formation from Beaufort County could be applied equally well to the formation as it occurs throughout the Coastal Plain. Miller recognized two major rock types within the formation: light-green, light-weight, diatomaceous, illitic to montmorillonitic clays; and fine to medium grained, clear, angular to subangular quartz sand which contains various amounts of greenish-brown clay and light to dark brown fine to medium grained carbonate fluorapatite. Miller describes the presence of finely crystalline dolomites and dolomitic limestones as thin ($<$1m) intercalations, some of which are laterally continuous. Both the dolomitic rocks and phosphate sands are repeated vertically in the formation. Light gray molluscan-rich limestones, calcareous clays, shell hash units, and white chalk are listed by Miller as minor lithologies of the formation. An increase in phosphate content upward through the formation was also recognized.

Riggs et al. (in press) have presented a comprehensive lithostratigraphic evaluation of the Pungo River Fm. from the Aurora Area. This work is based on sedimentological analyses of many sections observed in the active mine area and hundreds of core holes drilled by two companies. Figure 4 describes the four major vertical sediment sequences (units A, B, C, and D) that comprise the formation in the Aurora Area as identified by Riggs et al. The correlation of these lithostratigraphic units with the units of other workers is shown in Table 1. Riggs et al. (in press) have documented the following mineralogical and textural trends within the formation from the Aurora Area. 1) Within the major sediment units there is an inverse relation between the terrigenous and phosphate contents, both of which are inversely related to the carbonate content. 2) Phosphate content increases upward within each unit until the carbonate appears, then the phosphate decreases as the carbonate increases upward. 3) The carbonate is dolomite in units A, B, and D and calcite in unit C. 4) The upper portion of units A, B, and C show an upward increase in carbonate content which is culminated by an indurated to nonindurated, bored and

COMPOSITE SECTION OF THE PUNGO RIVER FORMATION IN THE AURORA AREA, NORTH CAROLINA

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.

Figure 4. Stratigraphic section of the Pungo River Fm. (From Riggs et al., in press)

burrowed, moldic carbonate sediment cap from 15cm to ~1m thick. 5) The phosphate content generally increases and the terrigenous content decreases upsection from unit A through unit C and is a minor component of unit D. Riggs et al. conclude that these vertical patterns of sedimentation indicate the following. Phosphorite sedimentation began in unit A and increased with a rising sea level, both of which reached maximums during the deposition of unit C. During the major transgression, cyclical phosphorite sedimentation periodically gave way to carbonate sedimentation which formed the caps of units A, B, and C. Unconformable surfaces on top of the moldic carbonates represent minor regressions and periods of nondeposition within the formation and separate the 4 cyclical packages of sediment deposition.

Phosphate Petrology

A detailed petrologic description of the Tertiary phosphorite sediments of Florida has been presented by Riggs (1979a). The classification of macroscopic sedimentary phosphorites which he proposed is shown in Figure 5. Riggs recognizes 4 major classes of authigenic phosphorites; these are the orthochemical, allochemical, lithochemical, and metachemical phosphorites. Petrologic and stratigraphic characteristics used by Riggs to identify these classes include their composition, texture, sedimentary structures, and stratigraphic occurrence.

According to Riggs, orthochemical phosphate mud (microsphorite) is analogous to micrite in carbonates (Folk, 1974). Microsphorite is composed of clay-sized sediments, formed physicochemically or biochemically within the area of deposition, that occur as *in situ* phosphate

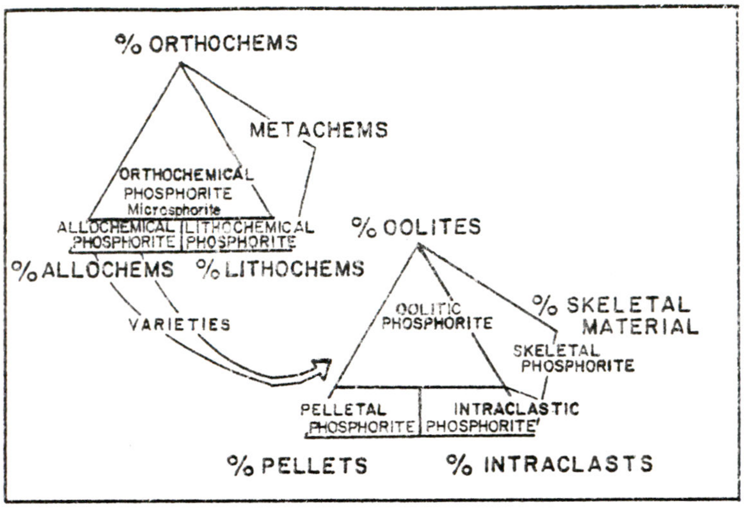


Figure 5. Classification of megascopic sedimentary phosphorites (from Riggs, 1979a).

laminae, organic structures, or mud matrix binding other sediment grains (Fig. 5). The cryptograined carbonate fluorpatite matrix of microsphorite contains inclusions of any macrograined and/or micrograined terrigenous, authigenic, and organic material found within the environment of deposition.

Riggs describes the allochemical phosphate grains as being analagous to carbonate allochems, which are physicochemically or biochemically produced within the area of deposition and subsequently transported within the depositional basin as clastic particles. Allochemical grains can be subdivided into intraclastic, pelletal, skeletal, and oolitic phosphorites based on petrological characteristics (Fig. 5). According to Riggs, intraclastic phosphate grains are irregularly shaped, megascopic ($<63\mu$) fragments of penecontemporaneous microsphorite deposits which have been transported and redeposited within the basin of deposition as discrete phosphate gravel and sand-sized particles. Intraclasts thus possess many of the same characteristics as microsphorite, including matrix composition, laminae, mottles, burrows, borings, terrigenous and allochemical inclusions, and microscopic components. However, the abundance of inclusions and sedimentary structures decreases with continued fragmentation of the grain during transport. Pelletal phosphate grains are generally restricted to the size range of 0.177 to 0.063mm, are extremely well sorted and are ovoid, semispherical, or rod shaped. As in microsphorite and intraclastic phosphate, pelletal forms consist primarily of a cryptograined carbonate fluorapatite matrix. Inclusions are dominated by bacterial rods and rod aggregates, dolomite, and microfossil hash. Terrigenous inclusions are minor (Riggs, 1979a). Thus, the uniformity in size of the pellets, their regular geometric shapes, and the relative paucity of terrigenous inclusions are the main characteristics that distinguish pellets from highly abraded very fine to fine sand-sized intraclasts. Some of the pelletal phosphate grains are considered to be fecal in origin because they commonly occur as clusters cemented by microsphorite and as discrete pellets lining or filling burrow structures (Riggs et al., 1980; Riggs, 1979a, 1979b).

Fossil skeletal material consists primarily of vertebrate bones and teeth, invertebrate shell material, and unknown material such as the "cat's paws" and "unicorn horns" (Riggs, 1979a). True oolitic phosphate grains have not been recognized by Riggs within the Atlantic Coastal Plain phosphorites but "pseudo-oolites," which possess a major nucleus grain but lack well defined concentric laminations, are common.

Lithochemical and metachemical phosphorites are products of secondary processes which alter the composition of the phosphate. Neither of these two classes apply to the primary phosphorite sediments of the Pungo River Fm.

Riggs (1979a, 1979b) also documented the following petrological, stratigraphic, and structural relationships in the phosphorite deposits of Florida. The microsphorite/intraclast phosphate regime existed in the shallow water coastal, nearshore shelf, and platform environments surrounding the major Ocala Arch structure. Microsphorite was produced in the most updip and/or protected portions of the coastal environment where it could accumulate and become indurated. During periods of high energy storm conditions, the microsphorite deposits were eroded, producing intraclasts which were transported downslope and accumulated in entrapment basins and on the flanks of the structural highs. Riggs described the pelletal phosphate sedimentation as being dominant in the higher energy, more open marine environments downslope from the microsphorite/intraclast sediment regime, where loosely suspended, bacteria-rich, orthochemical phosphate muds were ingested and excreted as pellets by detritus and filter feeding benthic varieties of polychaetes and/or arthropods.

OBJECTIVES

The major objective of this thesis is to describe the lithology, stratigraphy, and phosphate petrology of the Pungo River Formation within that portion of the Aurora Embayment extending southward and westward from the Aurora Area into the embayment margins (Fig. 3). More specifically, the objectives are to: 1) define and describe the mineralogy and texture of the lithologic units occurring within the study area; 2) correlate the lithologic units throughout the study area; 3) describe the lateral and vertical variations in the lithologies of the formation through the study area; 4) describe and classify the phosphate grains of the formation according to the scheme presented by Riggs (1979a); and 5) evaluate the environmental and structural controls which led to the accumulation of the Pungo River Formation in the Aurora Embayment.

PROCEDURES

Sampling

Samples representing the Pungo River Fm. were gathered from several sources. The majority of samples were obtained from eight cores drilled by International Mining and Chemical Corporation (IMC) in 1966. Each core was sampled at every major change in lithology (Riggs, 1967b). The eight cores drilled by IMC have a three letter designation, which locates the core by county and state, followed by a number which identifies each core hole within a particular county. Samples of the formation from the Aurora Area were obtained from a core drilled by North Carolina Phosphate Corporation (NCPC) in 1979 (Fig. 3). Subsample locations from each core are indicated on their respective lithologic columns (Appendix B) and by tick marks on the geologic cross-sections (Figs. 8 and 9).

Laboratory Methods

Samples of the Pungo River Fm. and selected samples of overlying and underlying units were analyzed by several methods (Fig. 6). All samples were described using a binocular microscope to determine the mineralogy and texture, to assign a lithologic name, and to identify the megascopic phosphate grain types. The microscopical examination occurred in three stages, each more detailed than the one before (i.e. whole sample, washed sample, and rotapped sample) (Fig. 6). Petrographic examinations of thin sections from selected phosphorite intervals were examined to aid in the identification of phosphate grain

WHOLE SAMPLE

wet sieve to remove $<63\mu$ fraction

thin sections prepared for petrographic studies

petrographic description: mineralogy, and identification of phosphate grain types

various phosphate grains selected for documentation of grain types and analysis by future workers

BINOC. DESCRIPTION: color, mineralogy, grain size, sorting

air dry

weigh and wet sieve through 63μ screen

BINOC. DESCRIPTION (sand and gravel fraction): mineralogy

textural analysis (sand and gravel fraction): rotap using 1ϕ screen interval down to 2.0ϕ, then $1/2\ \phi$ screen interval down to 4.0ϕ

weigh each ϕ fraction: calculate and tabulate size (M_z) using cumulative weight percents of each fraction

BINOC. DESCRIPTION: mineralogy of each fraction, texture of each mineral component, identification and relative abundance of phosphate grain types

calculate and tabulate mineralogical and textural characteristics

ASSIGN LITHOLOGIC NAME

Figure 6. Flow chart of laboratory procedures.

types, and to supplement mineralogical descriptions of the lithologies. A textural analysis of each sample was performed according to the methods outlined by Folk (1974) in order to further characterize the inter-relationships of mineralogy, grain size, and phosphate grain types. The data produced from the above procedures was then used to define and correlate the various lithologies throughout the study area and to interpret the environmental framework under which the Pungo River Fm. was deposited.

RESULTS

Lithologies

Within the study area, the Pungo River Fm. is composed of seven major lithologic units (i.e., lithologies which either pussess laterally persistent mineralogical and textural characteristics or which represent regionally isolated lithologic occurrences). The seven major lithologies (units A, B, C, D, BB, CC, and DD) are described in Figure 7. These descriptions are based primarily on the mineralogical and textural characteristics of each major lithology as tabulated in Appendix A. Units A, B, C, D, and DD each possess regionally persistent lithologic characteristics and are collectively referred to as the central facies (Fig. 7). Although typical of the central facies, units B and D extend eastward and are also present in the eastern facies, which is described below. Lithologies of the central facies form a vertical lithostratigraphic sequence, portions of which are recognized in all holes except CNN-1 (Fig. 3). Table 2 summarizes the mineralogical and textural characteristics of each unit in the central facies. Units BB and CC (Fig. 7) are lithologically distinct from the other units, are restricted in occurrence, and are lateral facies (lithofacies) of units A, B, and C. The calcareous and terrigenous sediments of unit CC are found only in holes PON-1, CNN-1, and CTN-1 and thus are called the southern facies. The daitomaceous sediments of unit BB (hole PON-4) dominate the eastern facies. Discussions of the lithofacies relationships implied in Figure 7 are presented in the following section on lithologic correlations.

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
PUNGO RIVER FM	DD	0-7m		White, slightly phosphatic and quartz sandy, calcareous, bioclastic shell hash (barnacles, bryozoans) with <20% calcite mud			ABSENT	D	0-7m	Yellowish-green, slightly phosphatic and quartz sandy, dolosilty bioclastic shell hash (bryozoans, barnacles, annelid tubes) to shelly dolomite muds
	C	0-9m	0-5m	Cream colored, nonindurated to indurated, fossiliferous and moldic, phosphatic and quartz sandy calcareous mud or limestone interbeds which decrease downward Interbedded, very dark greenish gray, slightly shelly, quartz phosphorite sand which becomes more massive downward	CC	0-17m	White to light gray to light olive green, calcareous silty muds to very shelly, calcareous muddy, sometimes gravelly, slightly phosphatic (<10%) quartz sands	BB	0-11m	Light grayish-green, slightly calcareous, slightly phosphatic and quartz sandy, diatomaceous mud; diatom fragments compose up to 70% of the sediment
			0-6m	Very dark greenish gray, massive, burrowed to mottled, moderately muddy quartz phosphorite sand with minor shell material						
	B	0-12m	0-7m	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						
			0-7m	Dark olive green, massive and mottled, muddy phosphorite quartz sand which is locally gravelly (phosphorite granules) near base				B	0-12m	Dark green, gravelly (phosphorite granules), muddy, phosphorite quartz sand
										?
	A	0-6m	0-1m	Light olive green, indurated to nonindurated, highly burrowed and locally silicified, slightly fossiliferous and moldic, phosphatic and quartz sandy dolomite mud				A		NOT RECOVERED
			0-5m	Moderate olive green, burrowed to mottled, dolomitic, muddy phosphorite quartz sand which is locally gravelly (phosphorite and quartz gravels) near base						

Figure 7. Summary description and correlation of major lithologies, Aurora Embayment.

UNIT	DESCRIPTIVE NAME	LITHOLOGIC CHARACTERISTICS
D/DD	Bioclastic hash in a dolomite or calcite matrix	1) Fragments of dominantly barnacle plates and bryozoans 2) Silty rhombic dolomite matrix (Unit D) or calcite matrix (Unit DD)
C	Interbedded phosphorite sands and phosphatic limestones Fine to medium grained quartz phosphorite sand	1) Upper lithologies are fossiliferous and moldic, calcareous, often indurated, and phosphatic and quartz sandy 2) Calcareous content decreases downward while phosphate content increases 3) Basal lithology is moderately muddy (<20%) and % phosphate sand>% quartz sand 4) % phosphate sand: Unit C>Unit B or A
B	Phosphate and quartz sandy dolomite Fine to medium grained phosphorite quartz sand	1) Upper lithology is dolomitic and often indurated* 2) Dolomite content decreases downward while phosphate content increases* 3) Basal lithology is muddy (>20%) and % quartz sand>% phosphate sand 4) % phosphate sand: Unit B > Unit A
A	Phosphate and quartz sandy dolomite Fine to medium grained dolomitic phosphorite quartz sand	1) Upper lithology is dolomitic and often indurated 2) Dolomite content decreases downward while phosphate content increases 3) Basal lithology is muddy (>20%) and % quartz sand>% phosphate sand** 4) % phosphate sand: Unit A < Unit B or C 5) Contains abundant pelletal allochemical phosphate grains

Table 2. Summary of the mineralogical and textural characteristics of the lithologies in units A, B, C, D and DD (central facies).
*In the Aurora Area (Riggs et al., in press), and hole NCPC
**In holes BTN-12, BTN-11, and BTN-9: % phosphate sand > % quartz sand

The seven major units and the subtle sedimentological variations within each unit (i.e., subunits) are defined and described below in the following order: 1) lithology of the central facies from the base of the formation (unit A) upsection through unit D or DD; 2) the lithology of unit CC (southern facies); and 3) the lithology of unit BB (eastern facies). These descriptions are keyed to the lithologic columns of each core hole presented in Appendix B. Also, the various mineralogical and textural modifiers used in the descriptions are defined in Appendix B. Unless stated otherwise: 1) the phosphate component in all lithologies occurs dominantly as light to dark brown, subrounded to subangular, polished, fine to medium sand-size phosphate intraclasts (see Results--phosphate petrology); 2) quartz occurs dominantly as very clear, bladed, angular to subangular, fine to medium sand-size grains; 3) the mud component ($<63\mu$ fraction) is composed dominantly of illitic to montmorillonitic clay minerals and silt-sized quartz (Miller, 1971; Simmons, 1968; Rooney and Kerr, 1967); and 4) feldspar, heavy minerals, and glauconite each comprise less than 1% of the sediment in the study area. Relative abundances of all mineral and faunal components within each lithology are presented as a percent of the total sediment.

Central Facies

Unit A. Dolomite muddy phosphorite quartz sand to phosphatic and quartz sandy dolomite; holes NCPC, BTN-12, BTN-11, BTN-9, PON-3, and PON-1. This major lithology consists of subunits A1 and A2, and is characterized by a decreasing quartz and phosphate content and a corresponding increase in rhombic dolomite content upward from subunit A1 to subunit A2. The contact between subunit A1 and the underlying pre-Pungo River sediments is sharp and is usually marked by an accumulation of granule and pebble-sized quartz and phosphate intraclasts. The contact between subunits is gradational. The upper surface of subunit A2 is in sharp contact with overlying unit B. Unit A is the only major lithology in the study area that is dominated by pelletal phosphate grains in the very fine to fine sand-sized fraction of the sediment. Much of the pelletal phosphate occurs with quartz sands as burrow fillings and mottles in both subunits. The drilling log for hole PON-1 describes this lithology as calcareous rather than dolomitic, dominantly muddy, and only slightly phosphatic; these lithologic characteristics more closely resemble unit CC. However, the unit is capped by an indurated carbonate sediment and is bounded by gravel accumulations, both of which are characteristic of unit A elsewhere in the study area.

Subunit A1. Dolomite muddy phosphorite quartz sand.

1) Moderate olive green, slightly gravelly to gravelly (<20%), dolomite and terrigenous muddy (20-50%), fine to medium grained, dolomitic (5-20%) phosphorite (10-30%) quartz (10-50%) sand.

2) Holes NCPC, BTN-12, BTN-11, BTN-9, PON-3, and PON-1.

3) Rhombic dolomite occurs as silt and sand-sized crystals and aggregates.

Subunit A2. Phosphatic and quartz sandy dolomite.

1) Light olive green, nonindurated to indurated, slightly fossiliferous and moldic (<10%), phosphatic (<10%) and quartz (10-45%) sandy, dolomite.

2) Holes NCPC, BTN-11, BTN-9, PON-3, and PON-1.

3) Recognizable molds and shells are pectinids.

4) Silicified burrow fillings have been observed in subunit A2 from the Aurora Area.

Unit B. Muddy phosphorite quartz sand to phosphatic and quartz sandy dolomite; holes NCPC, BTN-11, BTN-9, PON-4, PON-3 and PON-1. This major lithology consists of subunits B1, B2, B3, and B4. In the Aurora Area (hole NCPC) the phosphate and quartz content decreases upsection from subunit B1 through subunit B4 while dolomite content increases. Outside of the Aurora Area the dolomite-rich sediments of subunits B3 and B4 are not recognized. The phosphate content of unit B is higher than in unit A. Boundaries between the subunits are gradational, but the contact between unit B and the overlying unit C is sharp.

Subunit B1. Gravelly muddy phosphorite quartz sand.

1) Dark olive green, slightly gravelly to gravelly (5-30%), terrigenous muddy (15-30%), fine to medium grained, slightly dolomitic (~10%) phosphorite (20-40%) quartz (25-40%) sand.

2) Holes NCPC, BTN-11, BTN-9, PON-4, PON-3, and PON-1.

Subunit B2. Muddy phosphorite quartz sand.

1) Moderate olive green, terrigenous muddy (20-45%), fine to medium grained, slightly dolomitic (<10%), phosphorite (20-45%) quartz (35-55%) sand.

2) Holes NCPC, BTN-11, BTN-9, PON-4, PON-3, and PON-1.

3) Diatoms and glauconite are conspicuous in the silt to very fine sand-sized fractions.

Subunit B3. Dolomite muddy phosphorite quartz sand.

1) Moderate olive green, dolomite and terrigenous muddy ($\sim$40%), fine grained, slightly dolomitic ($\sim$10%), phosphorite ($\sim$20%) quartz ($\sim$30%) sand.

2) Hole NCPC.

3) Thus subunit is very similar to subunit A1 but contains a higher phosphate content which is dominated by intraclasts in all sand-sized fractions.

Subunit B4. Phosphatic and quartz sandy dolomite.

1) Light olive green, nonindurated to indurated, phosphatic (20%) and quartz ($\sim$25%) sandy, moldic dolomite.

2) Hole NCPC.

3) This unit is very similar to subunit A2.

Unit C. Quartz phosphorite sand to interbedded phosphorite sands and phosphatic limestones; holes NCPC, BTN-11, BTN-9, PON-3, and PON-1. This major unit and its subunits C1, C2, C3, and C4 possess the same mineralogic and textural trends as units A and B. The phosphate content which is greater in unit C than in units A or B, decreases upward from subunits C1 or C2 to subunits C3 and C4 while carbonate content increases. The carbonate content in unit C is dominantly calcite rather than dolomite. Subunit C4 is a moldic limestone sediment which caps unit C, just as subunits A2 and B4 (in the Aurora Area) cap units A and B respectively. Subunits C2 through C4 are complexly interbedded; they occur as small irregular lenses to laterally continuous beds and vary considerably in thickness and stratigraphic occurrence. Thus, these subunits are collectively referred to as the upper cap rock of unit C, which grades downward into the quartz phosphorite sands of subunit C1. Unit C is in sharp contact with the overlying bioclastic sediments of units D and DD throughout most of the study area but is overlain by the Pliocene Yorktown Fm. in holes BTN-11 and PON-1.

Subunit C1. Moderately muddy quartz phosphorite sand.

1) Very dark greenish gray, slightly gravelly (<10%), moderately terrigenous muddy (<20%), fine to medium grained, quartz (20-40%) phosphorite (40-70%) sand.

2) Holes NCPC, BTN-11, BTN-9, and PON-3.

3) Subunit C1 may contain barnacle shell fragments (~5%) and sand-sized calcite intraclasts (~10%).

4) This subunit is very similar to subunits A1 and B1-B3, but is dominated by sand-sized phosphate intraclasts over quartz, contains less mud, and is finer grained except in hole NCPC.

Subunit C2. Quartz phosphorite sand.

1) Very dark greenish gray, slightly shelly (~5%), calcareous and terrigenous muddy (15-50%), fine to medium grained, quartz (10-15%) phosphorite (65-75%) sand.

2) Holes NCPC, BTN-9, PON-3, and PON-1.

3) Barnacle and pectinid shells and fragments are present.

4) Southward from the Aurora Area the phosphate content decreases from 65-75% to <10% intraclasts in hole PON-1 while quartz content increases from 10-15% to 80% of the total sediment.

Subunit C3. Shelly calcareous muddy phosphorite quartz sand.

1) Dark green to greenish tan, barnacle and bryozoan shelly (<15%), calcareous and dolomitic muddy (30-40%), fine to medium grained, phosphorite (15-30%) quartz (20-30%) sand.

2) Holes NCPC, BTN-11, and PON-3.

Subunit C4. Phosphatic and quartz sandy moldic limestone.

1) Cream to white, nonindurated to indurated, phosphate (~20%) and quartz (~30%) sandy, moldic and shelly (~10%), calcareous mud or limestone.

2) Holes NCPC and PON-1.

3) Shells and abundant molds are dominantly of bivalves and gastropods.

Unit DD. Calcareous muddy phosphate and quarts sandy shell hash; holes BTN-9, PON-3, and CTN-1. Unit DD grades to the north and east from hole BTN-9 into unit D. This unit and unit D, its lateral facies equivalent, are the youngest lithologies of the Pungo River Fm. identified in the study area. Unit DD is in sharp contact with both the underlying units and the overlying Pliocene Yorktown Fm. In holes BTN-9 and PON-3, the phosphate and quartz content decreases upward through the unit while the shell content increases. Unit DD is a white to gray, semi-indurated, calcareous moderately muddy (15-20%), phosphate (~20%) and quartz (~20%) sandy, barnacle and bryozoan shell hash.

Unit D. Phosphate and quartz slightly sandy dolomitic shell hash to shelly dolomite mud; holes NCPC and PON-4. This unit is in sharp contact with underlying units and the overlying Yorktown Fm., and consists of subunits

D1 and D2 which are gradational.

Subunit D1. Dolomite muddy barnacle shell hash.

1) Yellowish green, phosphate (~5%) and quartz (~5%) slightly sandy, dolomite muddy and sandy (~50%), barnacle-rich shell hash.

2) Hole NCPC.

3) Some shell fragments have been partially recrystallized to dolomite.

4) This subunit is very similar to unit DD, but contains a dolomite matrix instead of calcite.

Subunit D2. Shelly dolomite mud.

1) Yellowish green, phosphate (~5%) and quartz (~10%) slightly sandy, barnacle and bryozoan shelly (5-20%), dolomite sandy and silty mud.

2) Holes NCPC and PON-4.

3) Ostracods and annelid worm tubes are common.

Southern Facies

Unit CC. Calcareous silty mud to quartz sand to gravelly shell hash; holes PON-1, CNN-1, and CTN-1. Unit CC is the major lithology which characterizes the Pungo River Fm. in the southern margin of the Aurora Embayment. This unit consists of massive accumulations of terrigenous and calcareous sediments which are only slightly phosphatic (<10%). The sand to gravel-sized quartz grains of this unit are generally subangular to rounded. Fossil material consists of calcareous molds, and slightly to highly fragmented and abraded shells of bryozoans, barnacles, bivalves, gastropods, and echinoids. Contacts between the subunits are gradational; in holes PON-1 and CTN-1 contacts between unit CC and units of the central facies are sharp.

Subunit CC1. Calcareous silty mud.

1) This subunit is described on the drilling log as a light olive green, slightly phosphatic (<5%), calcareous silty (20%), terrigenous mud.

2) Hole PON-1.

3) This lithology is interbedded with subunit B2 of the central facies.

Subunit CC2. Slightly shelly calcareous muddy quartz sand.

1) White to light gray, slightly phosphatic (<5%), slightly shelly (~15%), calcareous sandy (15-25%) and moderately muddy (<20%), fine to medium grained quartz (~50%) sand.

2) Holes CNN-1 and CTN-1.

3) In hole CTN-1 this subunit also contains a significant amount of terrigenous mud (~15%), which imparts a light olive green color to the sediment.

Subunit CC3. Shelly gravelly calcareous quartz sand.

1) White to light gray, quartz gravelly (~10%), calcareous sandy (25%) and slightly muddy (10%), shelly (25%), phosphatic (<10%), medium grained quartz (30%) sand.

2) Hole CNN-1.

Subunit CC4. Calcareous sandy and muddy quartz sandy shell hash.

1) White to light gray, slightly phosphatic (<5%), slightly quartz

gravelly (~5%), calcareous sandy (10-20%) and muddy (10-34%), quartz sandy (5-20%), shell hash.

2) Holes CNN-1 and CTN-1.

3) Shell fragments (40-60%) are of bivalves, barnacles, bryozoans, and gastropods.

Subunit CC5. Shelly calcareous and terrigenous mud.

1) Light olive green, shelly (30%), quartz (~10%) and phosphate (~10%) slightly sandy and silty, calcareous and terrigenous mud.

2) Hole CTN-1.

3) Shell material is dominated by fine sand-sized fragments of barnacles and ostracods.

Eastern Facies

Unit BB. Light grayish green, slightly calcareous, phosphate and quartz slightly sandy, diatomaceous mud; hole PON-4. This unit consists of only one lithology. Unit BB is a massive, highly diatomaceous sediment that is only recognized in hole PON-4. Although Gibson (1967) described a similar lithology in the Aurora Area, the stratigraphic position of his diatomaceous sediment correlates with subunit B4 of the central facies (Table 1). Subunit B4 is a non-diatomaceous moldic dolosilt within the Aurora Area (Riggs et al., in press). Thus, it seems likely that the diatomaceous sediment described by Gibson was very localized and not important from a regional standpoint. Unit BB sharply overlies sediments typical of subunit B2 of the central facies, and is sharply overlain by the dolomitic bioclastic hash of unit D. Unit BB is composed of very fine to fine sand-sized quartz and phosphate intraclasts (~10%), slightly calcareous terrigenous mud (~20%), and diatom frustules and fragments (~70%).

Stratigraphic Correlations

Figures 8 and 9 are geologic cross-sections through the study area which show the stratigraphic correlation of the seven major lithologic units that comprise the Pungo River Fm. The correlations are based in the mineralogical and textural characteristics of each major facies as summarized in Table 2 and Figure 7. Figure 8 is a north-south geologic cross-section from hole NCPC to hole CTN-1 (Fig. 3). A complete section of the central facies (units A, B, C, and D or DD) extends from the Aurora Area southward to hole PON-3 with consistent mineralogical and textural characteristics (Table 2).

The facies change of unit DD to unit D in Figure 8 occurs between holes NCPC and BTN-9. This facies change consists primarily of a change in matrix composition from a calcareous bioclastic-rich sediment in unit DD to a dolomitic bioclastic-rich sediment in unit D. The reason for the matrix change, whether primary or secondary, is not yet understood. Miller (1971) attributes the dolomitization to post-depositional limestone replacement effected by magnesium-bearing waters. Since the elevation of unit D in hole NCPC is slightly less than that of unit DD in hole BTN-9, it seems possible that dolomitization of a primary calcite or micrite matrix occured in a downslope direction due to groundwater or interstitial water movement through the bioclastic sediment. Katrosh (1981) found that foraminifera in unit D are usually highly recrystal-lized to dolomite, whereas the megafossils from this unit are only

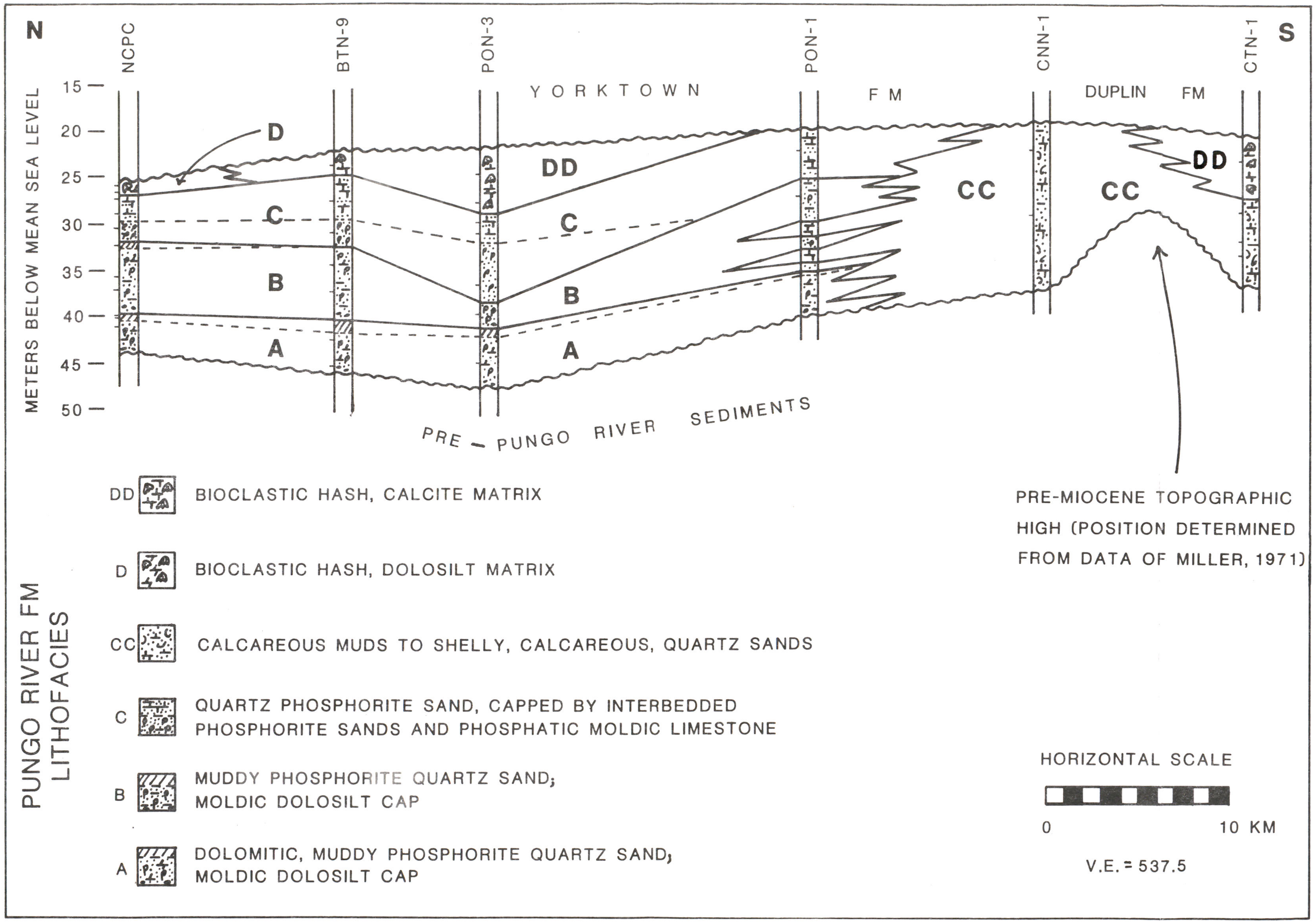


Figure 8. North-south geologic cross-section through the study area.

partially recrystallized. This fact might also be used to argue for secondary alteration of the matrix in unit D.

The thickened section of the Pungo River sediments at hole PON-3 (Fig. 8) 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-3, producing a maximum in the cumulative phosphate content (i.e., % phosphate x thickness) of the formation at hole NCPC (Table 3). On the southern flank of the Aurora Embayment, at hole PON-1, the cumulative phosphate content decreases dramatically due to an increase in terrigenous content of the units and to the absence of the phosphorite subunit C1. The bioclastic sediments of unit DD are also absent.

	CORE HOLES (north)				CORE HOLES (south)
UNITS	NCPC	BTN-11	BTN-9	PON-3	PON-1
C	304	188	214	337	71
B	270	200	228	48	57
A	104	193	134	53	25*
Total	678	581	576	438	153

Table 3. Cumulative Phosphate Content (CPC) values within the study area. CPC values = % phosphate (per sample) X thickness of interval sampled X 100. * % phosphate estimated at ~5% from the drilling log.

On the southern margin of the Aurora Embayment, hole CNN-1 in Figure 8 is dominated by the phosphatic (<10%), shelly, calcareous quartz sands and sandy shell subunits of unit CC. Unit CC comprises the southern facies equivalent of units A, B, and C and was dominated by increased terrigenous and calcareous sedimentation. The benthic foraminifera (Katrosh 1981), the megafossil assemblage, and the mineralogy and texture of the lithologies that comprise unit CC all indicate that this facies was probably deposited in a nearshore shelf, shoaling environment associated with the Cape Lookout High. The increased terrigenous and calcareous sedimentation of unit CC apparently extended northward and downslope to hole PON-1, greatly diluting the phosphate content of units A, B, and C and producing the mud interbeds in unit B.

South of the Cape Lookout High, hole CTN-1 in Figure 8 shows unit DD reappearing. This represents the updip and northern extent of the Pungo River facies deposited in the Onslow Bay depositional system (Lewis et al., in press). The calcareous and terrigenous sediments of unit CC underlie unit DD at hole CTN-1, and, as in hole CNN-1, appear to reflect a sedimentation regime which was directly influenced by the Cape Lookout High.

Figure 9 is a northwest-southeast geologic cross-section through the study area which shows: 1) the major erosional truncation of the vertical lithofacies of the Pungo River Fm. by the Late Miocene unconformity (Riggs et al., in press); 2) the occurrence of the diatomaceous facies in hole PON-4 that is considered equivalent to unit C and the upper portion of unit B; and 3) the facies change of unit DD to unit D between holes BTN-9 and PON-4. Only hole BTN-9 contains a complete

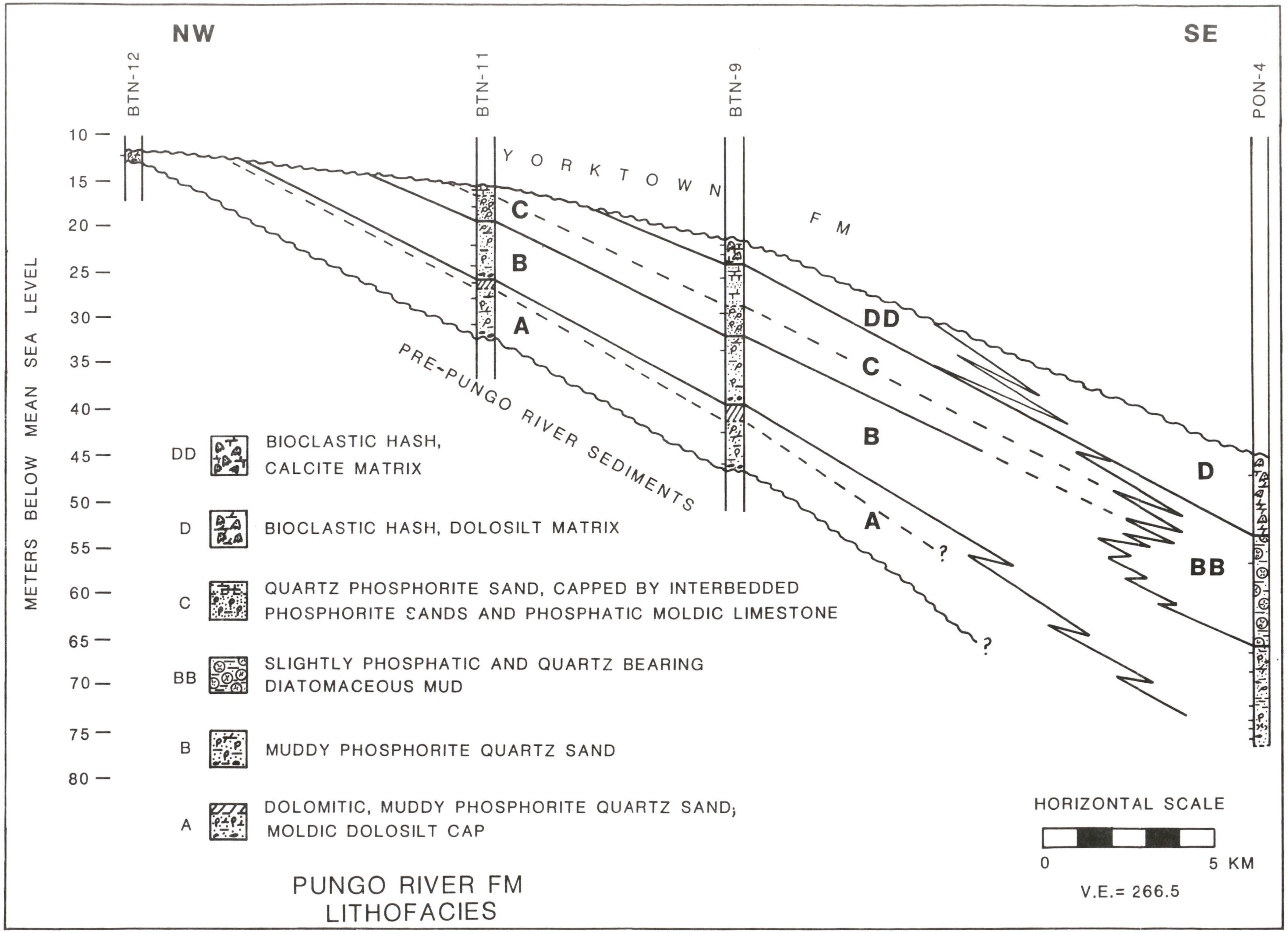


Figure 9. Northwest-southeast geologic cross-section through the study area.

section of the central facies. Updip from hole BTN-9 the units of the central facies are sequentially truncated until, at hole BTN-12, only a thin remnant of unit A is present. Truncation of the formation prior to the deposition of the Pliocene Yorktown Fm. was extensive and severe, eliminating the original western depositional extent of the formation, and producing the erosional outliers noted by Miller (1971) shown in Figure 1. The calcareous matrix of unit DD at hole BTN-9 changes in a downdip direction to dolomite of unit D at hole PON-4.

Hole PON-4 is characterized by a thick accumulation of the slightly sandy diatomaceous mud of unit BB underlying unit D. These diatomaceous sediments are the basinal facies of the phosphate-rich units B and C. Both the phosphate and diatomaceous sediments were probably deposited as a result of the high productivity associated with upwelling currents. The association of upwelling currents and phosphorite sedimentation has been discussed by many authors (Riggs, 1980, 1979b; Miller, 1971; Sheldon, 1964; McKelvey, 1963; and Kazakov, 1938). In the Aurora Embayment, this depositional regime existed during the period of maximum tansgression when the upwelling currents would have extended furthest into the Aurora Embayment, and at which point the phosphorite sedimentation would have been greatest (i.e., unit C).

Vertical and Lateral Trends in Sedimentation

Regional variations in mean grain size (M_z) of the phosphorite sands of units A, B, and C are minor, varying between extremes of 2.6 and 1.3ϕ (fine to medium sand). No meaningful lateral trends in grain size are apparent; the variations are either too small to be of regional significance or too erratic as shown in Figure 10. However, vertically

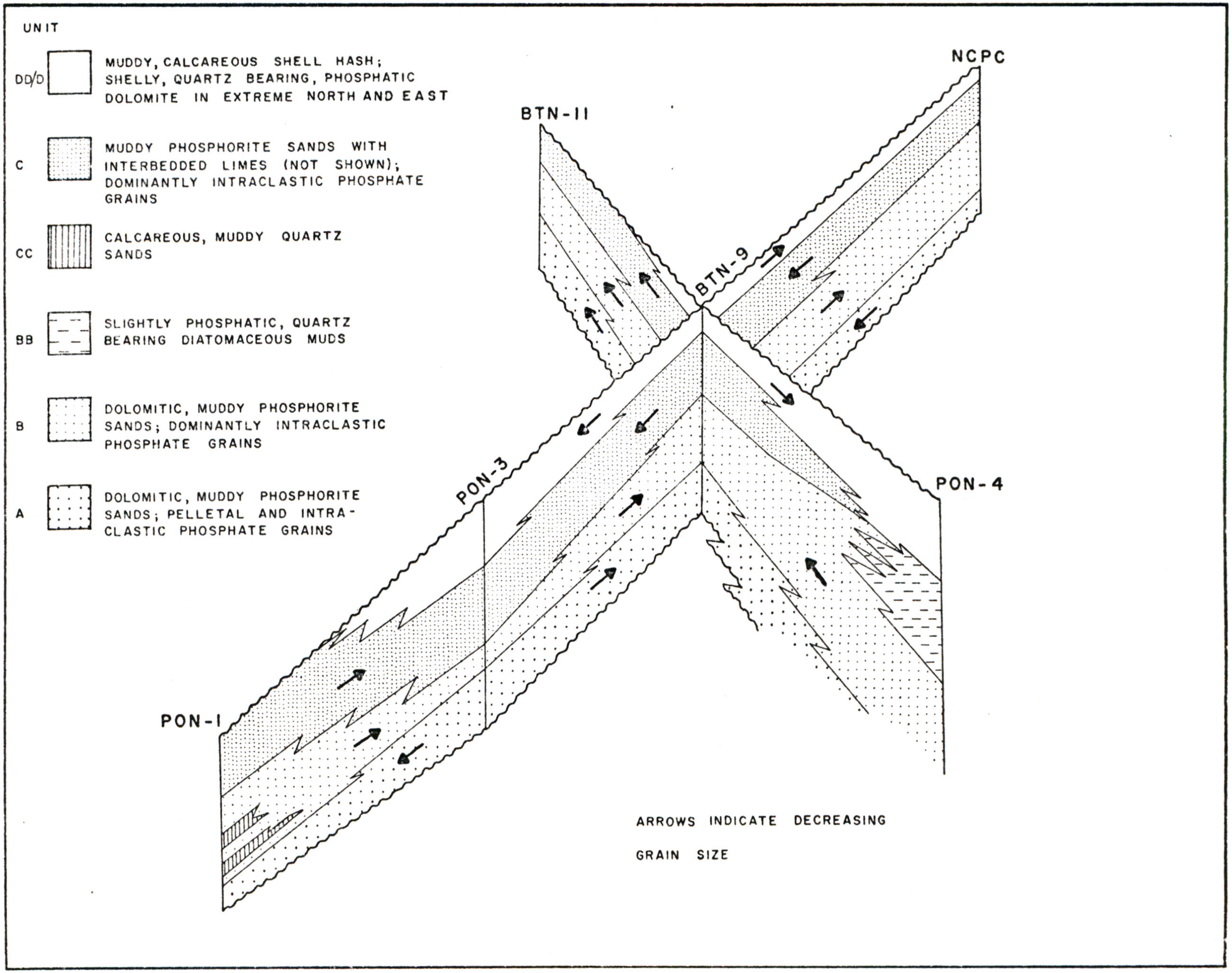


Figure 10. Fence diagram showing trends in grain size for the units in the Pungo River Fm. (From Snyder et al., in press)

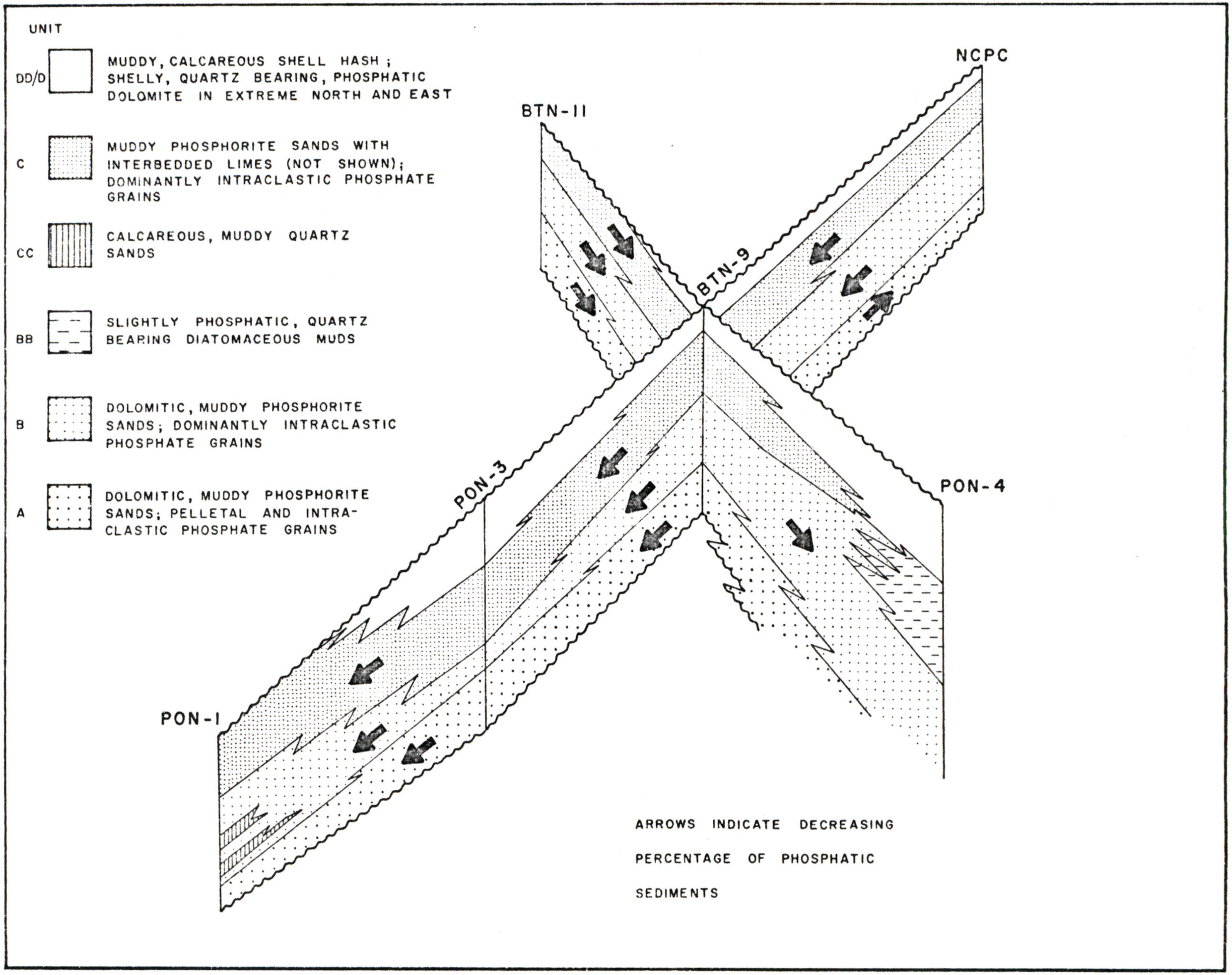


Figure 11. Fence diagram showing trends in phosphatic sediment concentration within each of the phosphorite units of the Pungo River Fm. (From Snyder et al., in press)

	CORE HOLES				
UNIT	NCPC	BTN-11	BTN-9	PON-3	Ave. for study area
C	1.9 m. sand	2.4 f. sand	2.2 f. sand	2.3 f. sand	2.2 f. sand
B	2.1 f. sand	2.2 f. sand	2.1 f. sand	1.9 m. sand	2.0 f.-m. sand
A	2.0 f.-m. sand	2.3 f. sand	2.0 f.-m. sand	1.3 m. sand	2.0 f.-m. sand

Table 4. Grain size variations of the phosphorite units indicating a general fining upward trend. Numbers represent the average phi size of each unit.

within the formation there is a general fining upward trend in the grain size of the phosphorite sands from unit A through unit C (Table 4). Since the phosphorite sands consist of mixed terrigenous and authigenic sediments, the grain size variations are only used to indicate the relative amount of energy in the depositional environments of the units. The fining upward trend from unit A through unit C suggests deposition in increasingly deeper water further from the shoreline (i.e., deposition during a relatively rising sea level). This is consistent with the interpretations of Riggs et al. (in press) and Katrosh (1981).

Several regionally persistent trends in the mineralogy of the phosphorite units A, B, and C are recognized. The phosphate component of all three units is most abundant in hole BTN-11 or in the Aurora Area (hole NCPC) and decreases to the south and east (Fig. 11). This suggests that the optimum environment for phosphate accumulation and possibly genesis existed in the northwestern portion of the study area, which is consistent with the interpretations of Snyder et al. (in press). Two regionally persistent vertical trends occur in the mineralogy of the phosphorite units A, B, and C. First, there is a decrease in phosphate and terrigenous content (i.e., quartz and mud) and an increase in carbonate content upward within each of the phosphorite units, except in unit B which lacks a carbonate cap rock outside of the Aurora Area. Second, there is an increase in phosphate content upsection from unit A through unit C, followed by a dramatic decrease in the phosphate content of units D and DD (Fig. 12 and Table 2).

Phosphate Petrology

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 described by Riggs (1979a). These characteristics were summarized in the section on previous work. The intraclasts of the Pungo River Formation consist of a cryptocrystalline carbonate fluorapatite matrix (Rooney and Kerr, 1967), terrigenous and authigenic mineral inclusions, laminae, mottles, and bored and burrowed surfaces (Plate 1). Intraclasts, which comprise approximately 80% of the phosphate grains in the formation (Appendix A), are angular to subrounded and irregular in shape, especially in the coarse sand and gravel-sized fractions (Plate 1). The surface texture of most grains is polished, but dull and pitted surfaces are common. Rounding and sphericity increase with decreasing grain size although some irregularity in shape can be recognized even in the very fine sand-sized fraction (Plate 1). 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 contained in the intraclasts of the Pungo

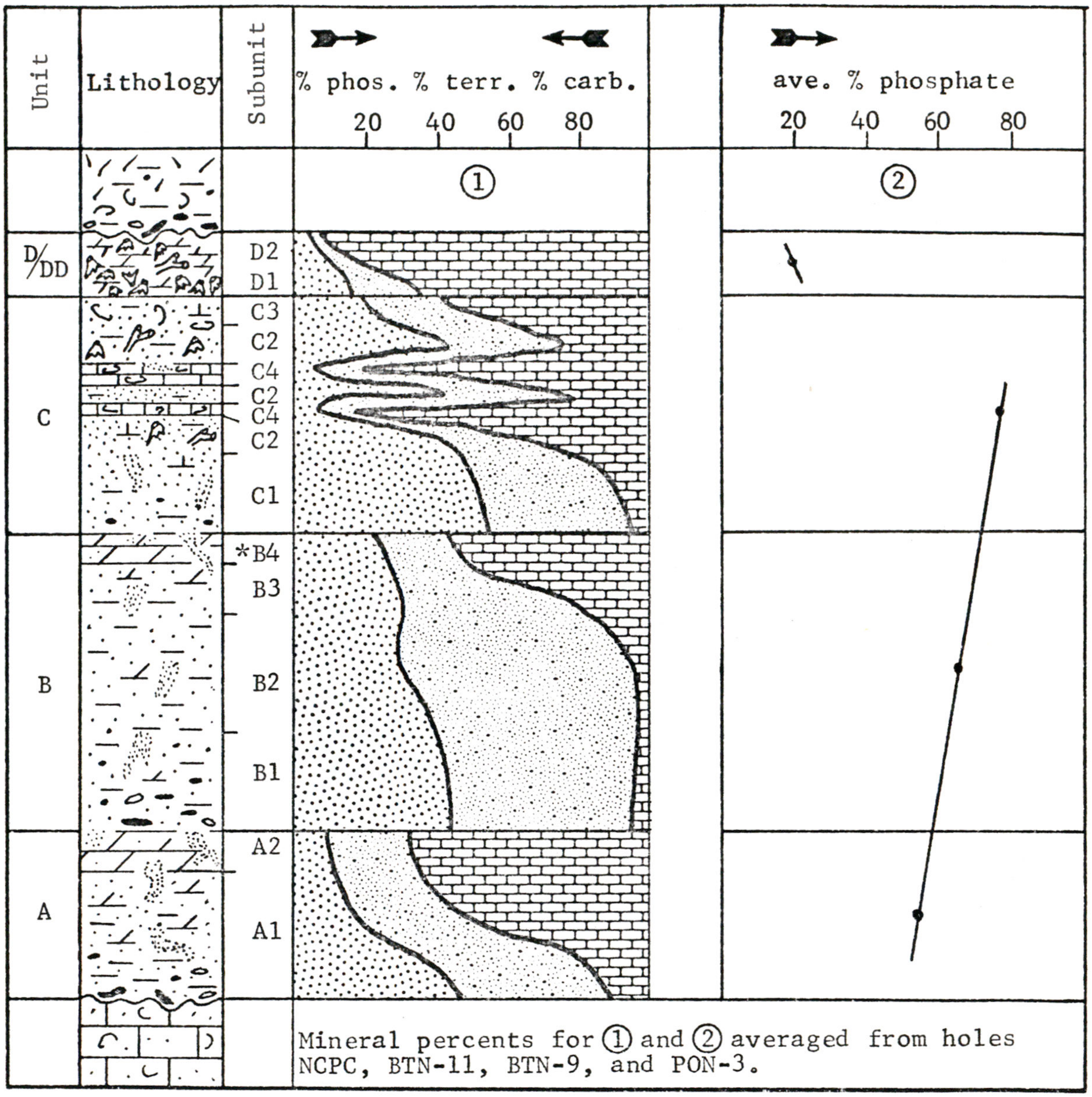


Figure 12. Mineralogical trends - vertically through the Pungo River Fm.

① Increase in carbonate content and decrease in phosphate and terrigenous content upward within each unit. *Subunit B4 is present in hole NCPC only.

② Increase in phosphate content upwards from unit A to unit C, and decrease in units D and DD.

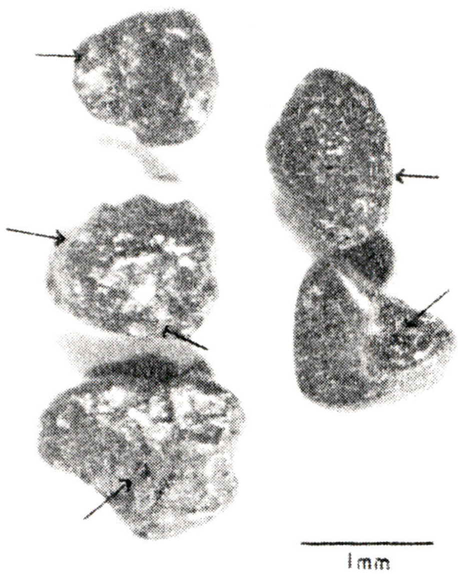
Plate 1

A. Coarse sand to very coarse sand-sized phosphate intraclasts. Notice the inclusions (see arrows) of clear quartz and subangular to subrounded and irregular texture of the intraclast.

B. Fine to medium sand-sized phosphate intraclasts. Notice the variety in grain shape and texture. Elongate cylindrical grains are often internal molds of echinoid spines.

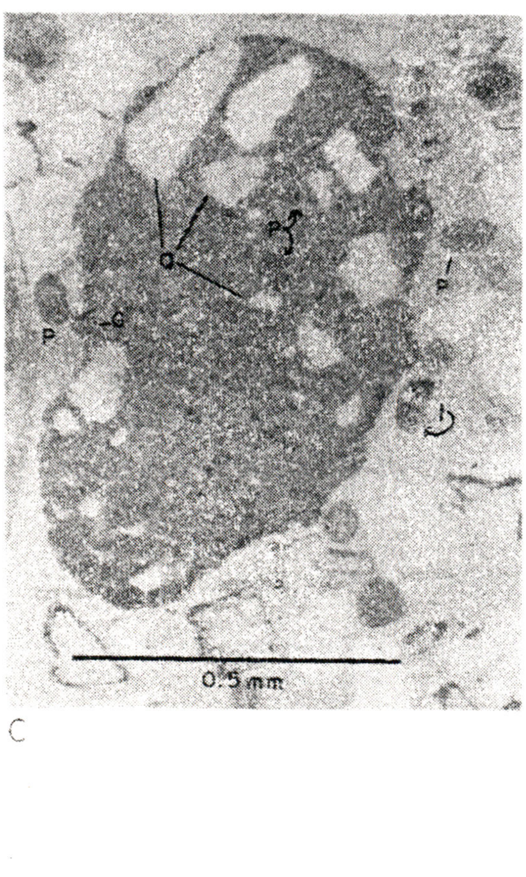
C. Thin section of a coarse sand-sized phosphate intraclast. The disseminated inclusions are dominated by bladed to angular, silt to fine sand-sized quartz grains (Q). Two very fine sand-sized phosphate pellets (P) and a glauconite grain (G) are also present as inclusions. Note the irregular surface of the intraclast which is partially due to the breaking out of inclusions from abrasion during transport. Also note the very fine sand-sized phosphate pellets (P) and intraclast (I) next to the coarse sand-sized intraclast.

D. Thin section of silt to medium sand-sized phosphate intraclasts. Notice the quartz and phosphate inclusions in the medium sand-sized intraclast (I), and the irregular geometric shapes of even the very fine sand-sized intraclasts.



A

B



C

D

River Fm. include detrital grains of quartz, feldspar, and clay clasts; authigenic phosphate and calcite allochems, dolomite rhombs, glauconite, and pyrite; and organic skeletal matter such as teeth, bone fragments, spicules, and microfossil fragments of diatoms, radiolarians, and foraminifiera. Approximately 50% of all inclusions found in the very fine to coarse sand-sized intraclasts consist of silt to very fine sand-sized, angular to bladed, quartz grains (Plate 1). Silt and very fine sand-sized phosphate allochems comprise approximately 10% of the inclusions, and glauconite grains of this same size comprise approximately 5%. Approximately 30% of all inclusions consist of microfossil fragments. Feldspar, clay clasts, calcite, dolomite, and pyrite each comprise approximately 1% of all inclusions. The inclusions occur as disseminated particles throughout the carbonate fluorapatite matrix of the intraclasts (Plate 1).

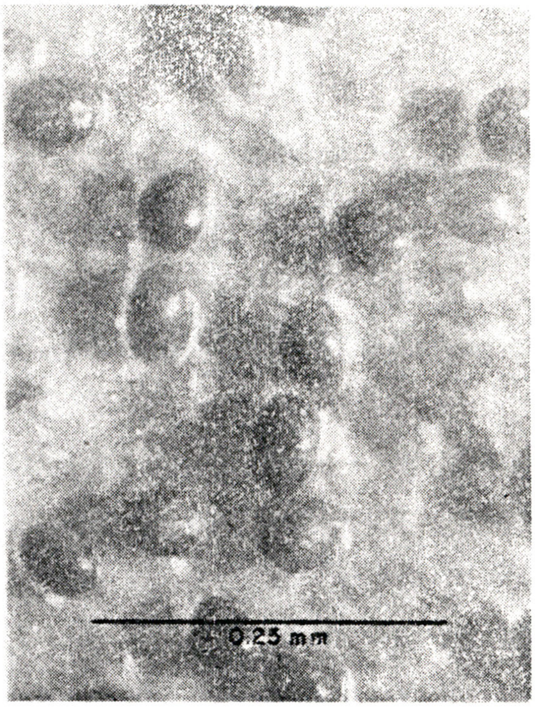
Pelletal allochems comprise the second major group of phosphate grain types found in the Pungo River Fm. (Plate 2). The petrological and textural characteristic of pellets as described by Riggs (1979a) apply to approximately 10% of the phosphate grains in the Pungo River Fm. (Appendix A). The pelletal phosphates are moderate to dark brown in color, polished, extremely well sorted, and are ovoid, ellipsoidal, and rod shaped. The pelletal grains are dominantly very fine to fine sand-sized particles (0.177 to 0.063mm), as are the pelletal grains described by Riggs (1979a). Pelletal forms consist primarily of a cryptograined phosphate matrix with varying amounts of inclusions that are dominated by microfossil fragments and include minor amounts (<10%) of terrigenous material (Plate 2).

Plate 2

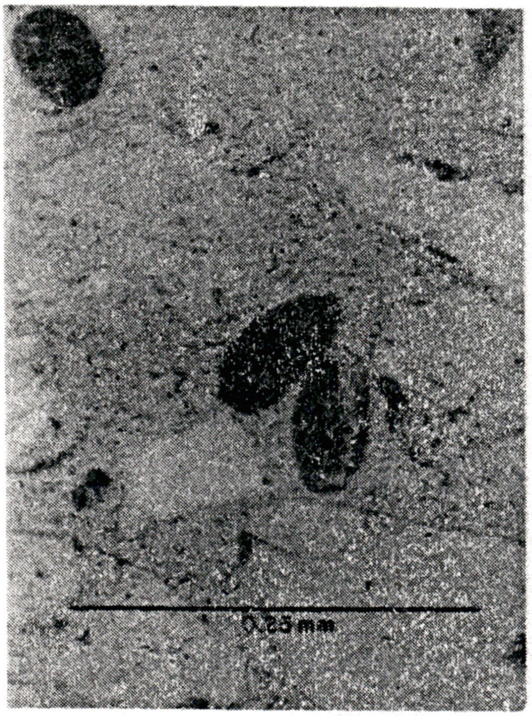
A and B. Very fine to fine sand-sized phosphate pellets. Upper grain in A consists of three pellets cemented by microsphorite. All grains illustrate the smooth and polished texture and the ovoid to spherical shape of pelletal forms.

C and D. 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 and rod aggregates and microfossil remains) contained within the carbonate fluorapatite matrix (Riggs, 1979a).

A



B



C

D

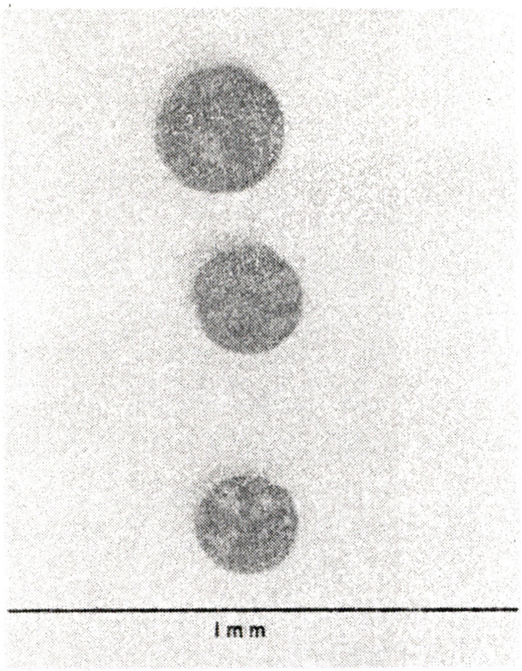
Plate 3

A. Fine sand-sized discoid phosphate grains. Surface structures on these grains resemble the surface structures of disc-shaped diatoms present in the Pungo River Fm. The light colored portions of these grains are siliceous, and probably represent original test material. The grains are interpreted as microsphorite molds of diatoms. Grains of this sort are commonly present in the fine sand-sized fraction of the phosphorite sands in the formation and have also been recognized in the Hawthorn phosphorites of Florida (Riggs, 1979a).

B. Fine to medium sand-sized microsphorite internal molds of foraminifera. Microsphorite molds of foraminifera, diatoms, radiolarians, ostracods, and echinoid spines and shell fragments have been recognized in all units of the formation, but generally comprise 5% of the phosphate grains.

C. Thin section of a very fine sand-sized "pseudo-oolite." This grain contains an angular silt-sized quartz nucleus; organic inclusions are arranged in a vaguely concentric fashion.

D. Thin section of a medium sand-sized skeletal phosphate grain infilled with microsphorite. The microsphorite mold contains abundant quartz and allochemical phosphate inclusions. If released from the skeletal fragment, the mold would be classified as an intraclast.



A

B

C

D

Invertebrate and vertebrate skeletal material generally constitutes less than 15% of the phosphate macrograins in any given sample with a range of 5 to 20%. Indirect evidence of fossils in the form of phosphatic molds and casts of pelecypods, ostracods, echinoid spines, diatoms, radiolarians, and foraminifera are also minor components (<10%) of most samples (Plate 3). Less than 1% of any given sample consists of unknown phosphate grain types such as the "cat's paws" and "unicorn horns" of Riggs (1979a). An occasional oolitic grain was recognized in thin-section; however, "pseudo-oolites," which possess a nucleus grain but lack well-defined concentric laminations, may comprise up to 5% of any given sample (Plate 3).

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 is characterized by abundant pelletal allochems which comprise 10 to 30% of the total phosphate component, and often constitute greater than 50% of the phosphate grains in the very fine to fine sand-sized range. In units B and C pellets account for less than 10% of the total phosphate grains (Appendix A) and up to 20% of the phosphate grains in the very fine to fine sand-sized range. The lack of observable concentric layering within the pellets, and the common occurrence of pelletal grains clustered in what appear to be burrow fillings, strongly suggests a fecal origin (Riggs et al., 1980; Riggs, 1979a).

SUMMARY AND CONCLUSIONS

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 north-south hingeline of Miller (1971) or the White Oak Lineament (Snyder et al., in press). Up to 30m of phosphorites and phosphatic sediments of the Pungo River Fm. were deposited in the eastern portion of the Aurora Embayment. The formation thins westward to less than 1m and pinches out at the White Oak Lineament. The formation thins southward to less than 16m over the Cape Lookout High.

Seven major lithologic units (units A, B, C, D, BB, CC, and DD) comprise the Pungo River Fm. 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 collectively comprise the central facies. These units are erosionally truncated eastward of the White Oak Lineament. Units A, B, and C are the major phosphorite facies of the formation.

Unit BB is an 11m thick diatomaceous facies, which contains up to 70% diatom fragments, that occurs in the eastern portion of the embayment. Facies BB is considered to be the downbasin equivalent of the mid-slope phosphorite sands of units B and C. The apparent contemporaneous deposition of the diatomaceous sediments in the east-central embayment area with the greatest development of phosphorite sedimentation in the mid-slope area to the west suggests that both the phosphorite and diatomite sediments were deposited in response to increasing productivity. Such a depositional regime could reflect an increasing influence of upwelling currents upsection and westward through the embayment in response to the Middle Miocene transgression as described by Riggs et al., (in press). The transgression culminated with maximum deposition of phosphate and diatoms in units B, C, and BB when upwelling currents could have extended furthest into the Aurora Embayment (Fig. 13).

Unit CC is a shelly calcareous fine to medium grained quartz sand facies that was deposited in the southern margin of the Aurora Embayment, its deposition occurring contemporaneously with that of the phosphorite sediments of units A, B, and C in the central portion of the embayment. Deposition of the dominantly terrigenous and calcareous sediments on and near the flanks of the Cape Lookout High suggests major chemical and physical changes in the environment of sedimentation. These changes effectively diminished and diluted major phosphate sedimentation south of hole PON-1 (Fig. 8).

Lateral variations in grain size of the phosphorite units are minor. However, the following regional trends in mineralogy and texture of the phosphorite units A, B, and C are recognized: 1) phosphate content within each of the phosphorite units increases from south to north through the study area; 2) phosphate and quartz content decreases and carbonate content increases upward within each of the phosphorite units, except where the carbonate cap of unit B is absent; 3) phosphate content increases upsection from unit A through unit C; and 4) there is a decrease in grain size upsection from unit A through unit C.

The phosphate component of the Pungo River Fm. is dominated by intraclastic allochemical grains. This suggests that there was contem-

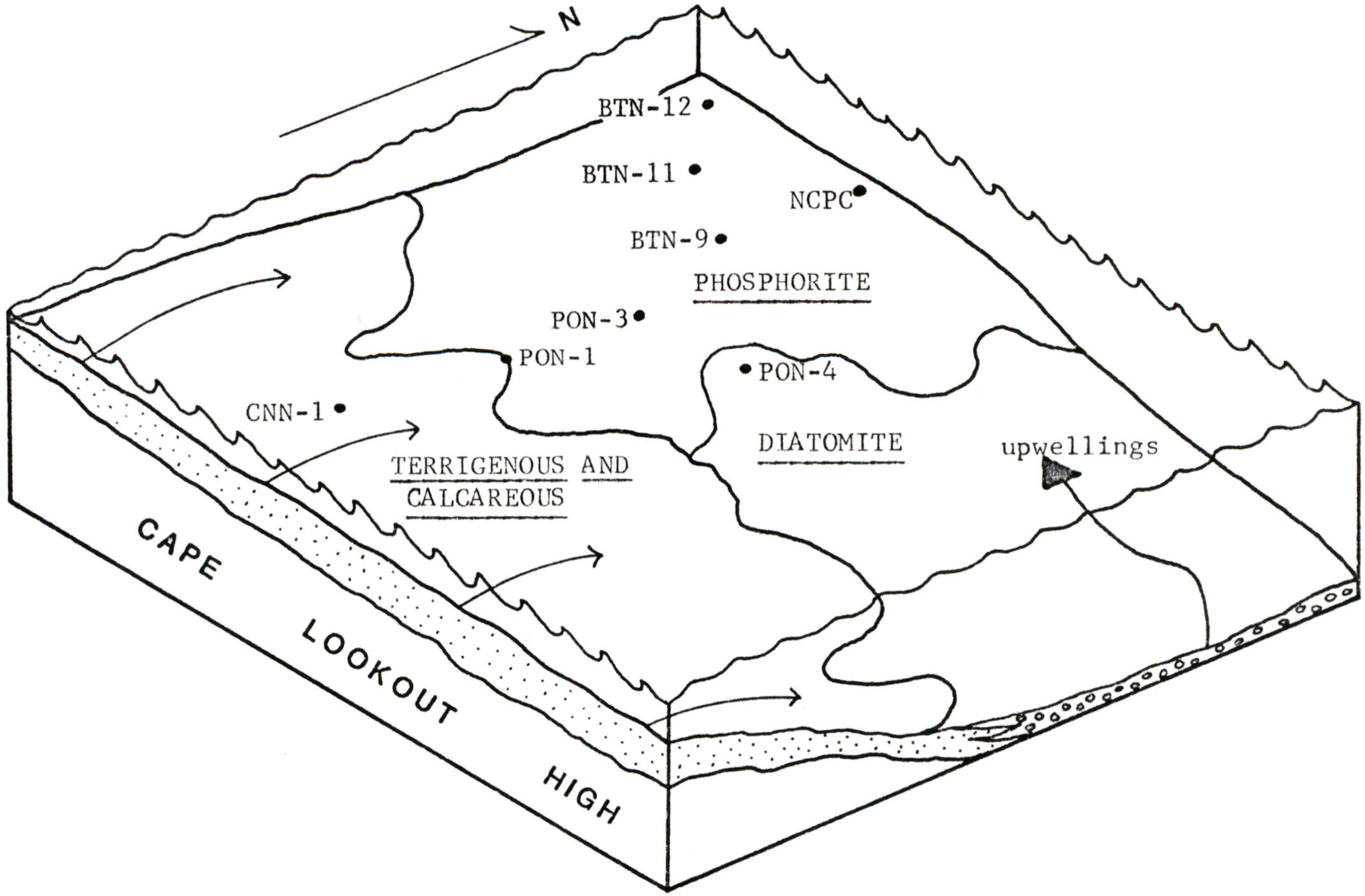


Figure 13. Depositional regimes during the period of maximum Middle Miocene sea level transgression. PHOSPHORITE (unit C), DIATOMITE (unit BB), TERRIGENOUS and CALCAREOUS (unit CC)

poraneous formation of microsphorite upslope of and possibly within the study area; the microsphorite was simultaneously fragmented, transported, and deposited as intraclasts within the Aurora Embayment. Unit A, however, contains a significant concentration of pelletal phosphate grains, which indicate a partially orthochemical environment where the phosphate mud was biogenically extracted from the water, concentrated, and excreted as fecal pellets. This interpretation is support for the *in situ* deposition of the phosphorite of units A and B, as described by Snyder et al. (in press).

There is a distinct portion of the study area where optimum phosphate formation and/or deposition took place; this locus occurs about mid-slope on the west-central embayment margin (Fig. 14). Updip to the west each facies has been sequentially truncated and eliminated by post-Pungo River erosion (Fig. 9). Downdip to the east, and in the southern embayment margin, there are major facies changes within the formation. Consequently, the primary area of potentially economic phosphate concentration is found in the west-central mid-slope portion of the Aurora Embayment where the maximum thickness of units A, B, and C are present.

Riggs et al. (in press) have proposed that units A, B, and C each represent third-order transgressive-regressive depositional sequences that are part of the major Middle Miocene transgression of Vail and Mitchum. (1979). Each depositional sequence was capped by carbonate deposition that was followed by a minor hiatus. The absence of the moldic carbonate subunit B4 south of the Aurora Area, and the thin occurrence of unit B in the depositional axis of the Aurora Embayment

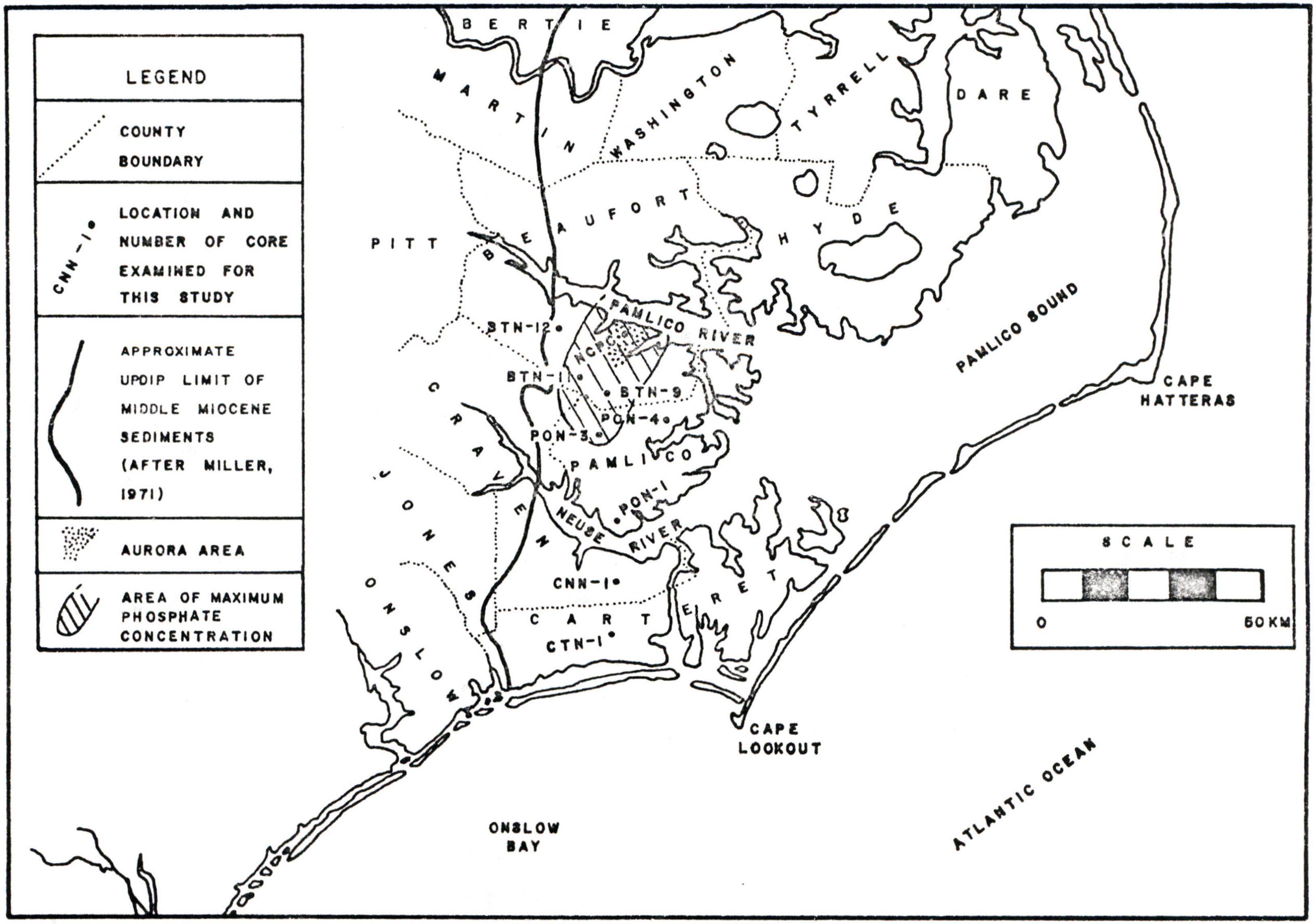


Figure 14. Map showing the area of maximum phosphate concentration within the study area (refer to table 3).

(hole PON-3, Fig. 8) suggests that some erosion accompanied the hiatuses. This erosional "subbasin" within the Aurora Embayment was subsequently infilled by the phosphorite sediments of unit C during the following period of maximum transgression. Riggs et al. (in press) interpret unit D as having been deposited at the beginning of the regressive phase of the Middle Miocene transgression, which resulted in the limited occurrence and the low phosphate content of unit D. The barnacle- and bryozoan-rich sediments of unit D possess a dolomitic matrix and grade laterally into the barnacle and bryozoan-rich sediments of unit DD. Unit DD has a calcareous matrix and occurs in the central portion of the study area (Figs. 8 and 9). According to Zullo (1979), barnacle-rich sediments are most frequently produced in moderate to high energy environments where hard substrata are found. Zullo states that barnacle remains are often concentrated above the diastems and disconformities. Thus, units D and DD may represent a higher energy environment than the underlying phosphorite units; the barnacle and bryozoan fragments could have originally been attached to the carbonate hardground surface of the underlying subunit C4.

The regionally persistent nature of the lithologies, the lateral and vertical facies relationships and the sedimentation trends exhibited by the Pungo River Fm. within the Aurora Embayment, the basinal geometry of each of the lithologies, and the subsequent erosional modification of the sediment units all support the following interpretation. Units A, B, and C represent phosphate deposition through a relatively rising sea level which culminated in the deposition of the rich phosphorite of unit C, the diatomite of unit BB, and the quartz sands of unit CC. Deposition of the phosphorite sediments was periodically interrupted by regional increases in carbonate sedimentation, non-deposition, and/or erosion. Deposition of units D and DD occurred on the following regression which culminated in a major erosional period and severe truncation of the Pungo River sediments across the western margin of the embayment and across the Cape Lookout High. This post-Pungo River erosional truncation has produced an apparent offlap geometric configuration of Pungo River sediments which acutally represent a transgressive or onlap depositional sequence.

REFERENCES CITED

Baum, G.R., Harris W.B., and Zullo, V.A., 1978, Stratigraphic revision of the exposed Middle Eocene to Lower Miocene formations of North Carolina: Southeastern Geol., v. 20, p. 1-19.

Brown, P.M., 1958, The relation of phosphorites to groundwater in Beaufort County, North Carolina: Econ. Geology, v. 53, p. 85-101.

Brown, P.M., Miller, J.A., Swain, F.M., 1972, Structural architecture, geologic framework, and regional permeability distribution network of the Atlantic Coastal Plain: U.S. Geol. Survey Prof. Paper 796, 65p.

Caldwell, A.B., 1968, TGS Lee Creek Complex: Engineering and Mining Journal: McGraw-Hill, New York, New York, 82p.

Copeland, C.W., 1964, Eocene and Miocene foraminifera from two locations in Duplin County, North Carolina: Bull. Amer. Paleontology, v. 47, 324p.

Folk, R.L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Pub. Co., 182p.

Freas, D.H., and Riggs, S.R., 1964, Geologic guides to exploration for sedimentary phosphate deposits: unpubl. tech. rept. for International Minerals and Chemical Corp., Skokie, Illinois, 27p.

Gibson, T.G., in press, key foraminifera species from Upper Oligocene to Lower Pleistocene strata for the Central Atlantic Coastal Plain: Smithsonian Contr. Paleobiology, n. 41.

_____, 1970, Late Mesozoic-Cenozoic tectonic aspects of the Atlantic Coastal Margin: Geol. Soc. America Bull., v. 81, p. 1813-1822.

_____, 1967, Stratigraphy and paleoenvironment of the phosphatic Miocene strata of North Carolina: Geol. Soc., America Bull., v. 78, p. 631-650.

Katrosh, M.R., 1981, Foraminiferal paleoecology and biostratigraphy of the Yorktown and Pungo River Formations: Beaufort, Pamlico, Craven, and Carteret Counties, North Carolina: unpubl. thesis, East Carolina University, Greenville, North Carolina, 198p.

Kazakov, A.V., 1937, The phosphorite facies and the genesis of phosphorites, in Geological Investigations of Agricultural Ores: Trans. Sci. Inst. Fertilizers Insecto-Fungicides, no. 142, p. 95-113.

Kimrey, J.D., 1965, Description of the Pungo River Formation in Beaufort County, North Carolina: N.C. Div. Mineral Resources Bull. 79, 131p.

Kimrey, J.D., 1964, The Pungo River Formation, a new name for Middle Miocene phosphorites in Beaufort County North Carolina: Southeastern Geology, v. 5, p. 195-205.

Lewis, D.W., Riggs, S.R., Snyder, S.W.P., Hine, A.C., Snyder, S.W., and Waters, V., in press, Preliminary report on the Pungo River Formation in Onslow Bay, continental shelf, North Carolina: Fla. Bureau Geology Spec. Publ.

Mauger, L.L., 1979, Benthic foraminiferal paleoecology of the Yorktown Formation at Lee Creek Mine, Beaufort County, North Carolina: unpubl. thesis, East Carolina University, Greenville, North Carolina, 198p.

McKelvey, V.E., 1963, Successful new techniques in prospecting for phosphate deposits: in U.S. Dept. State Nat. Resources -- Minerals and mining, mapping, and geodetic control; Geneva, United Nations Conf.; Applications of Science and Technology for the Benefit of Less Developed Areas, U.S. Paper, v.2, p. 169-172.

Miller, J.A., 1971, Stratigraphic and structural setting of the Middle Miocene Pungo River Formation of North Carolina: unpubl. Ph.D. dissert., University of North Carolina, Chapel Hill, North Carolina, 82p.

Riggs, S.R., 1980, Tectonic model of phosphate genesis, in Sheldon, R.P., and Burnett, W.E., eds., Fertilizer mineral potential in Asia and the Pacific: East-West Resource Systems Institute, East-West Center, Honolulu, Hawaii, 190p.

_____, 1979a, Petrology of the Tertiary Phosphorite System of Florida: Econ. Geol., v. 74, p. 195-220.

_____, 1979b, Phosphorite sedimentation in Florida; a model phosphogenic system: Econ, Geol., v. 74, p. 285-314.

_____, 1967a, Phosphorite stratigraphy, sedimentation, and petrography of the Noralyn Mine, Central Florida Phosphate District: Ph.D. dissert., University of Montana, Missoula, Univ. microfilm no. 67-13, 473, Ann Arbor, Michigan, 268p.

_____, 1967b, Geological exploration and evaluation of the North Carolina and Virginia Coastal Plains for phosphate: unpubl. tech. rept. for International Minerals and Chemical Corp., Skokie, Illinois, 28p.

Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Snyder, S.W., in press, Cyclic deposition of the Upper Tertiary phosphorites of the Aurora Area, North Carolina, and their possible relationship to global sea level fluctuations: Fla. Bureau Geology Spec. Publ.

Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Ellington, M.D., in progress, Stratigraphic analysis of the 1980 NCPC drilling program: tech. rept. for North Carolina Phosphate Corp. Washington, North Carolina.

Riggs, S.R., Lewis, D.W., and Scarborough, A.K., 1980, Sedimentologic and stratigraphic analysis of the 1979 NCPC drill holes: unpubl. tech. rept. for North Carolina Phosphate Corp., Washington, North Carolina, 34p.

Rooney, T.P., and Kerr, P.F., 1967, Mineralogic nature and origin of phosphorite, Beaufort County, North Carolina: Geology Soc. America Bull., v. 78, p. 731-748.

Sheldon, R.P., 1964, Paleolatitudinal and paleogeographical distribution of phosphorite: U.S. Geol. Survey Prof. Paper 501-C, p. C106-C113.

Simmons, W.B., 1968, Mineralogy of South Georgia and North Carolina phosphorite: Unpubl. thesis, University of Georgia, Athens, Georgia, 77p.

Snyder, S.W.P., Hine, A.C., and Riggs, S.R., in press, Miocene seismic stratigraphy, stuctural framework and global sea level cyclicity: North Carolina Continental Shelf: Fla. Bureau Geology Spec. Publ.

Snyder, S.W., Riggs, S.R., Katrosh, M.R., Lewis, D.W. and Scarborough, A.K., in press, Synthesis of sediment faunal relationships within the Pungo River Formation: paleoenvironmental implications: Fla. Bureau Geology Spec. Pub.

Steele, G.A., 1980, Stratigraphy and depositional history of Bogue Banks, North Carolina: unpubl. thesis, Duke University, Durham, North Carolina, 201p.

Vail, P.R., and Mitchum, R.M., Jr., 1979, Global cycles of relative changes of sea level from seismic stratigraphy, <u>in</u> Geological and geophysical investigations of continental margins, <u>eds</u>. Watkins, J.S., Montadert. L., and Dickerson, P.W.: Am. Assoc. Pet. Geol. Mem. 29, p. 469-472.

Ward, L.W., Lawrence, D.R., and Blackwelder, B.W., 1978, Stratigraphic revision of the Middle Eocene, Oligocene, and Lower Miocene -- Atlantic Coastal Plain of North Carolina: Geol. Survey Bull., 1457-F, 23p.

Weaver, C.E., and Beck, K.C., 1977, Miocene of the SE United States: A model for chemical sedimentation in a peri-marine environment: Elsevier, Amsterdam, 234p.

Wilson, W.F., Carpenter, P.A., and Conrad, S.G., 1976, North Carolina geology and mineral resources: a foundation for progress: Mineral Resources Section Educational Series No. 4, North Carolina Department of Natural and Economic Resources Division of Resource Planning and Evaluation, 78p.

Zullo, V.A., 1979, Biostratigraphy of Eocene through Miocene Cirripedia, North Carolina Plain, <u>in</u> Baum, G.K., Harris, W.B., and Zullo, V.A., eds., Structural and stratigraphic framework for the Coastal Plain of North Carolina: Field Trip Guide Book, Carolina Geological Society, p. 73-85.

APPENDIX A. Lithologic characteristics of the Pungo River Fm.

Hole NCPC															phosphate types			
subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite / % heavies	CPC*	% skeletal	% intraclasts	% pellets	% microsphorite molds and U/I types
D_2	22	1.2	3	20	77 D	2.1	tr	tr	14	0	8	/ tr	<1	5	87	6	2
D_1	23	0.6	2	45	53 D	1.0	tr	2	tr	0	45	/ tr	<1	7	89	3	1
C_2	24	1.3	1	85	14 T,C	1.8	74	11	0	tr	1	0	96	22	77	1	<1
C_2	25	0.8	tr	83	17 T	1.9	67	16	0	0	0	0	54	20	79	<1	1
C_1	26	2.2	tr	86	14 T	1.9	70	16	0	0	0	tr /	154	10	89	<1	<1
B_4	27	0.5	15	38	47 D	2.2	23	25	5	0	0	tr /	12	16	80	2	2
B_2	28	4.1	2	78	20 T	2.2	36	44	tr	0	0	tr /	148	18	76	2	4
B_1	29	2.9	14	68	18 T	2.0	38	44	tr	0	0	tr /	110	17	75	5	3
A_2	30	0.4	** 50	29	21 D	~1.9	11	43	27	0	0	0	4	24	56	20	<1
A_2	31	1.0	2	81	17 D,T	1.7	18	50	15	0	0	0	15	29	48	22	1
A_1	32	3.4	1	74	25 T,D	2.0	25	48	2	0	0	tr /	85	18	67	13	2

Table A1. Hole NCPC.

* CPC= % phosphate x thickness x 100

** Dominantly dolomite intraclasts

Hole BTN-12														phosphate types			
subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite % heavies	CPC*	% skeletal	% intraclasts	% pellets	% microspherite molds and U/I types
A_1	7	0.8	20	57	23 D,T	2.6	34	18	23	tr	tr	tr	27	27	53	20	tr
Hole BTN-11																	
C3	7	1.2	8	60	32 C,T	2.1	30	21	tr	3	13	tr	36	8	89	2	1
C_1	8	3.1	tr	80	19 T	2.4	49	30	tr	tr	1	tr	152	19	79	1	1
B_2	9	3.5	1	78	21 T	2.4	27	50	tr	tr	tr	tr-1/tr	94	9	83	1	7***
B_1	10	2.2	28	57	15 T	2.0	48**	30	5	0	0	tr	106	14	66	8	12***
A_2	11	1.0	tr	21	79 D	3.2	10	5	5	tr	tr	tr	10	21	59	18	2
A_1	12	2.6	1	47	53 D,T	2.6	25	14	8	0	0	tr	65	15	63	21	1
A_1	13	2.8	7	73	20 T,D	2.1	42	24	10	0	3	tr	118	14	66	18	2

Table A2. Holes BTN-12 and BTN-11.
* As in Table A1
** Includes 25% gravel-sized phosphate intraclasts
*** Dominated by discoid forms (see Plate 3)

Hole BTN-9																phosphate types			
subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite % heavies	CPC*			% skeletal	% intraclasts	% pellets	% microsphorite molds and U/I types
DD	11	0.9	15	71	14 C	~0.5	8	6	tr	tr	70	tr	7			5	90	5	tr
DD	12	0.9	4	81	15 C	~1.9	28	20	tr	tr	35	tr	25			10	78	10	2
C_3	13	3.2	tr	56	44 C,T,D	2.1	27	21	3	3	1	tr	86			15	77	6	2
C_1	14	2.4	7	80	12 T,D	2.2	42	32	1	8	3	tr	101			12	79	6	3
B_2	15	3.6	1	79	20 T,D	2.2	35	36	7	0	1	tr	126			17	73	6	4
B_1	16	3.5	4	71	25 T,D	1.9	29	37	9	0	tr	tr-1 / tr	102			11	68	9	12**
A_1	17	3.5	tr	37	63 D,T	3.1	17	5	14	0	tr	tr	60			13	59	24	4
A_1	18	1.7	19	59	22 T,D	0.9	44	16	12	0	tr	tr	75			14	65	17	4

Table A3. Hole BTN-9.

* As in Table A1

** Dominated by discoid forms (see Plate 3)

Hole PON-4															phosphate types			
subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite % heavies	CPC*		% skeletal	% intraclasts	% pellets	% microsphorite molds and U/I types
D_1	13	8	5	65	30 D	2.5	3	7	39	0	21	tr	24		8	88	4	tr
BB	14	11.2	tr	30	70 T,C	3.5	8	7	0	tr	15	tr	90		11	80	9	tr
B_2	15	1.0	3	77	20T,D	2.0	34	44	2	tr	1	tr	34		19	71	8	2
B_2	16	6.4	5	75	20T,D	2.0	36	46	2	tr	tr	tr	23		18	72	7	3
B_2	17	1.6	tr	40	60T	2.8	16	24	tr	tr	tr	tr	25		15	79	6	tr
B_1	18	0.9	30	40	30T,D	1.5	33	35	2	0	0	tr	30		17	78	5	tr
B_1	19	0.8	50	40	10T	2.0	7	27	tr	5	49	tr	6		10	87	3	tr
B_1	20	0.6	20	30	50T	1.2	18	27	3	tr	tr	tr	11		12	78	7	3

Table A4. Hole PON-4.
* As in Table A1

subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite % heavies	CPC*	% skeletal (phosphate types)	% intraclasts (phosphate types)	% pellets (phosphate types)	% microphorite molds and U/I types (phosphate types)
Hole PON-3																	
DO	11	5.4	12	73	15 C	~0.8	3	12	0	0	70	tr	16	3	89	8	tr
DO	12	2.0	23	61	16 C	~2.2	19	25	0	9	0	tr	38	22	71	4	3
C_2	13	1.6	4	72	24 C,T	1.9	29	31	tr	10	4	tr	46	21	65	12	2
C_3	14	1.6	8	54	39 C,T,D	1.5	14	26	tr	7	14	tr	22	16	70	11	3
C_1	15	6.1	7	75	18 T	2.3	44	25	tr	12	1	tr	269	14	75	8	3
B_2	16	2.1	7	48	45 T	1.9	23	27	3	tr	1	tr	48	10	77	9	4**
A_1	17	4.4	25	53	22 T,D	1.3	12	26	5	24	10	tr	53	8	74	16	2
Hole PON-1																	
C_4	8	3.0	39	45	16 C	1.7	18	27	11	17	11	tr	54	10	80	9	1
C_2	9	2.4	tr	88	12 C	2.3	7	77	1	2	1	tr	17	24	67	7	2
B_2	10	3.0	8	64	28 T	1.9	19	48	3	0	0	tr	57	15	76	8	1

Table A5. Holes PON-3 and PON-1.
* As in Table A1
** Dominated by discoid forms (see Plate 3)

Hole CNN-1														phosphate types			
subunit	sample	thickness of unit sampled (in meters)	% gravel	% sand	% mud D=dolomite C=calcite T=terrigen.	M_z (ϕ)	% phosphate	% quartz	% dolomite	% calcite	% shell	% glauconite % heavies	CPC*	% skeletal	% intraclasts	% pellets	% microsphorite molds and U/I types
CC_3	8	1.8	37	53	10 C	1.5	7	31	1	26	23	tr	13	12	85	3	tr
CC_2	9	7.6	10	73	17 C	1.7	2	48	tr	25	8	tr	15	18	82	tr	tr
CC_4	10	7.0	70	20	10 C	—	tr	20	tr	10	59	tr	<10	10	90	tr	tr
Hole CTN-1																	
OO	10	6.8	33	49	18 C	1	tr	1	0	0	81	0	<7	2	98	tr	tr
CC_5	11	3.2	tr	32	68 C,T	3.5	1	1	tr	0	30	tr	3	21	71	1	tr
CC_4	12	1.3	5	61	34 C	2.1	1	6	tr	18	40	tr	1	33	61	5	1
CC_2	13	4.6	1	64	35 C,T	1.7	2	46	tr	17	1	tr	9	10	88	1	1
CC_2	14	2.1	2	66	32 C,T	2.5	1	46	0	9	11	tr	2	28	71	tr	1

Table A6. Holes CNN-1 and CTN-1.
* As in Table A1

APPENDIX B. Lithologic columns of the Pungo River Fm.

KEY

Terms:

phosphatic- phosphate grains comprise <10% of the sediment
phosphorite- phosphate grains comprise >10% of the sediment

Symbols

barnacle plates and fragments

diatoms

bryozoan fragments

echinoid spines and shell frag.

bivalve shells and fragments

gastropod shells and fragments

terrigenous mud

rhombic dolomite crystals (silt to sand-sized) and aggregates

calcite mud and sand to gravel-sized intraclasts

fine to medium grained sand

pebbles (phosphate in black, quartz is clear)

Abbreviations

f. (F.) = fine

m. (M.) = medium

c. (C.) = coarse

v. = very

sli. = slightly

mod. = moderate

abun. = abundant

frag. = fragments

grav. = gravelly

indur. = indurated

calc. = calcareous

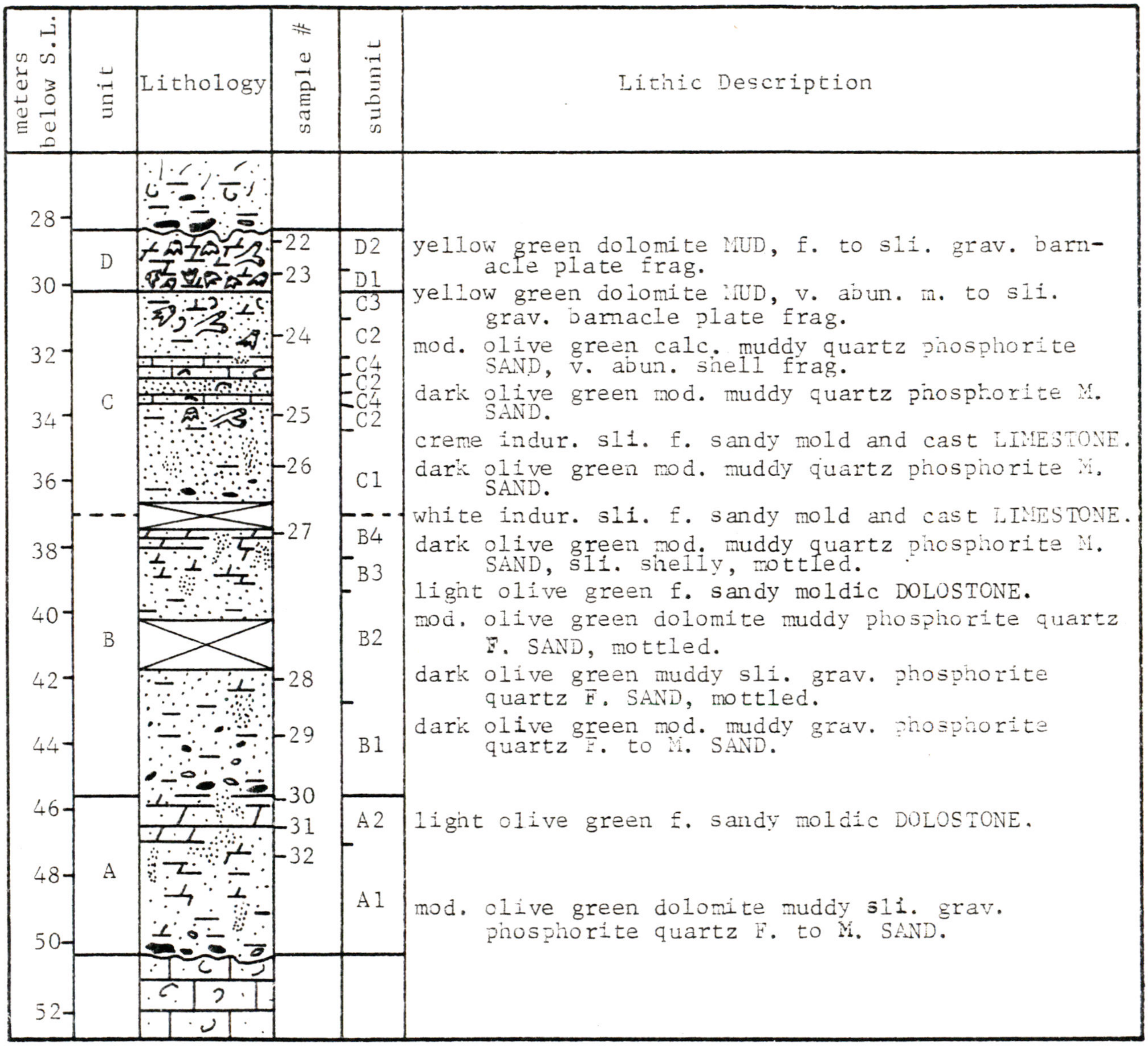


Figure B1. Hole NCPC.

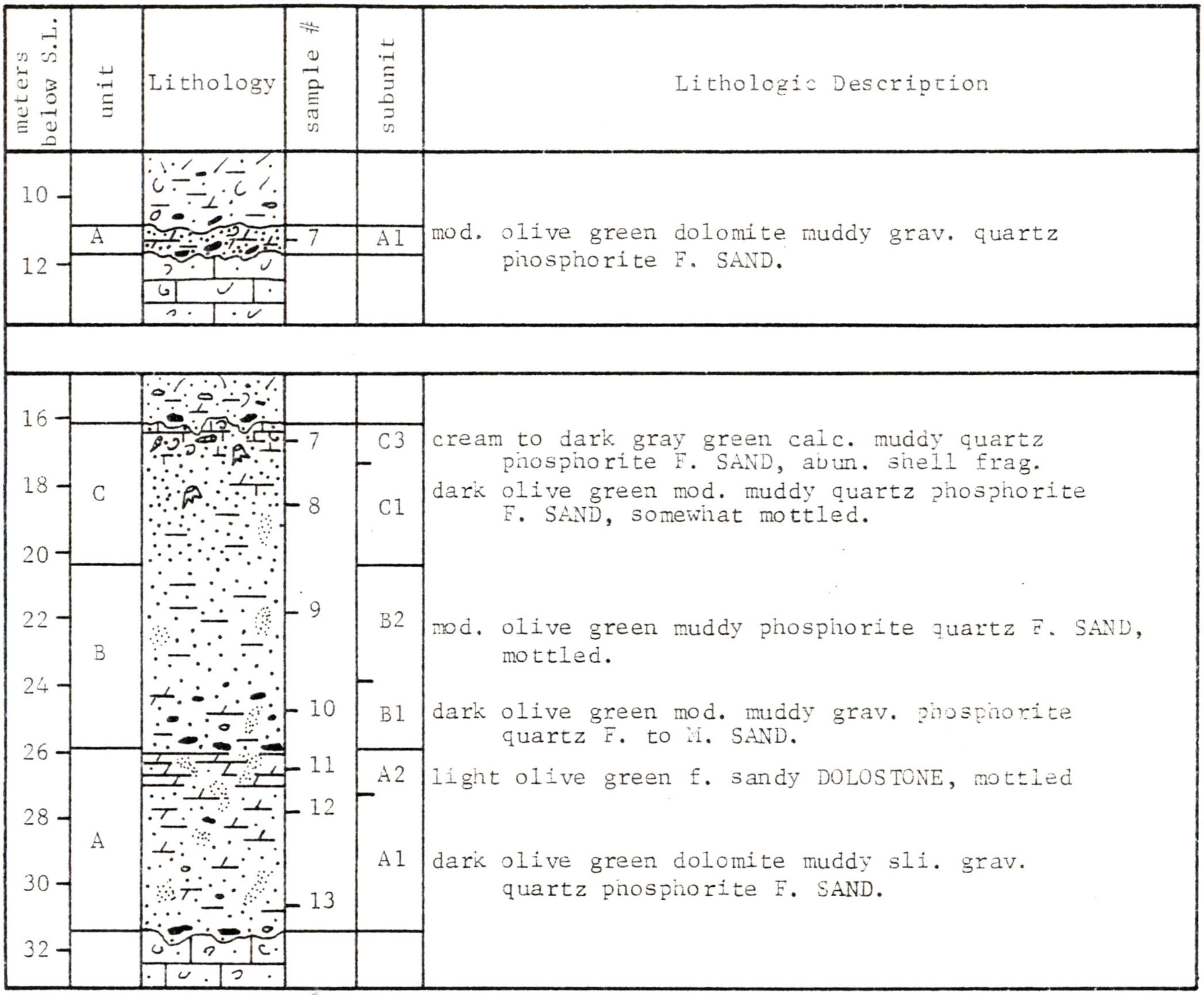
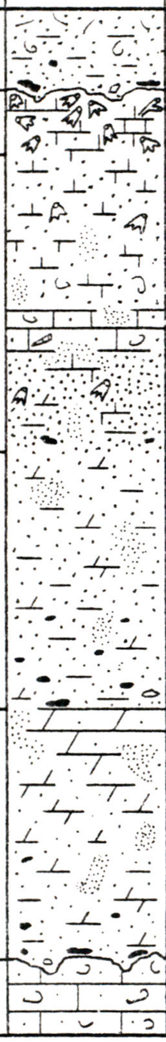


Figure B2. Holes BTN-12 (upper column) and BTN-11 (lower column).



meters below S.L.	unit	sample #	subunit	Lithologic Description
22				
	DD	11	DD	creme mod. muddy sli. c. sandy grav. barnacle SHELL HASH.
24		12		
	C		C3	creme mod. muddy sli. grav. v. barnacle shelly quartz phosphorite M. SAND.
26		13		mod. olive green calc. muddy sli. shelly sli. dolomitic quartz phosphorite F. SAND, mottled.
28				
			C4	creme indur. moldic and shelly LIMESTONE.
30		14	C1	v. dark green brown mod. muddy sli. grav. sli. shelly sli. calc. and dolomitic quartz phosphorite F. SAND.
32	B			
34		15	B2	dark green muddy sli. dolomitic phosphorite quartz F. SAND, mottled.
36				
38		16	B1	dark green muddy sli. grav. to grav. sli. dolomitic phosphorite quartz F. SAND, mottled.
40	A		A2	light olive green v. v. sandy DOLOSTONE.
42		17	A1	light olive green v. f. sandy DOLOMUD.
44				
46		18		mod. olive green dolomite muddy grav. quartz phosphorite C. SAND.

Figure B3. Hole BTN-9.

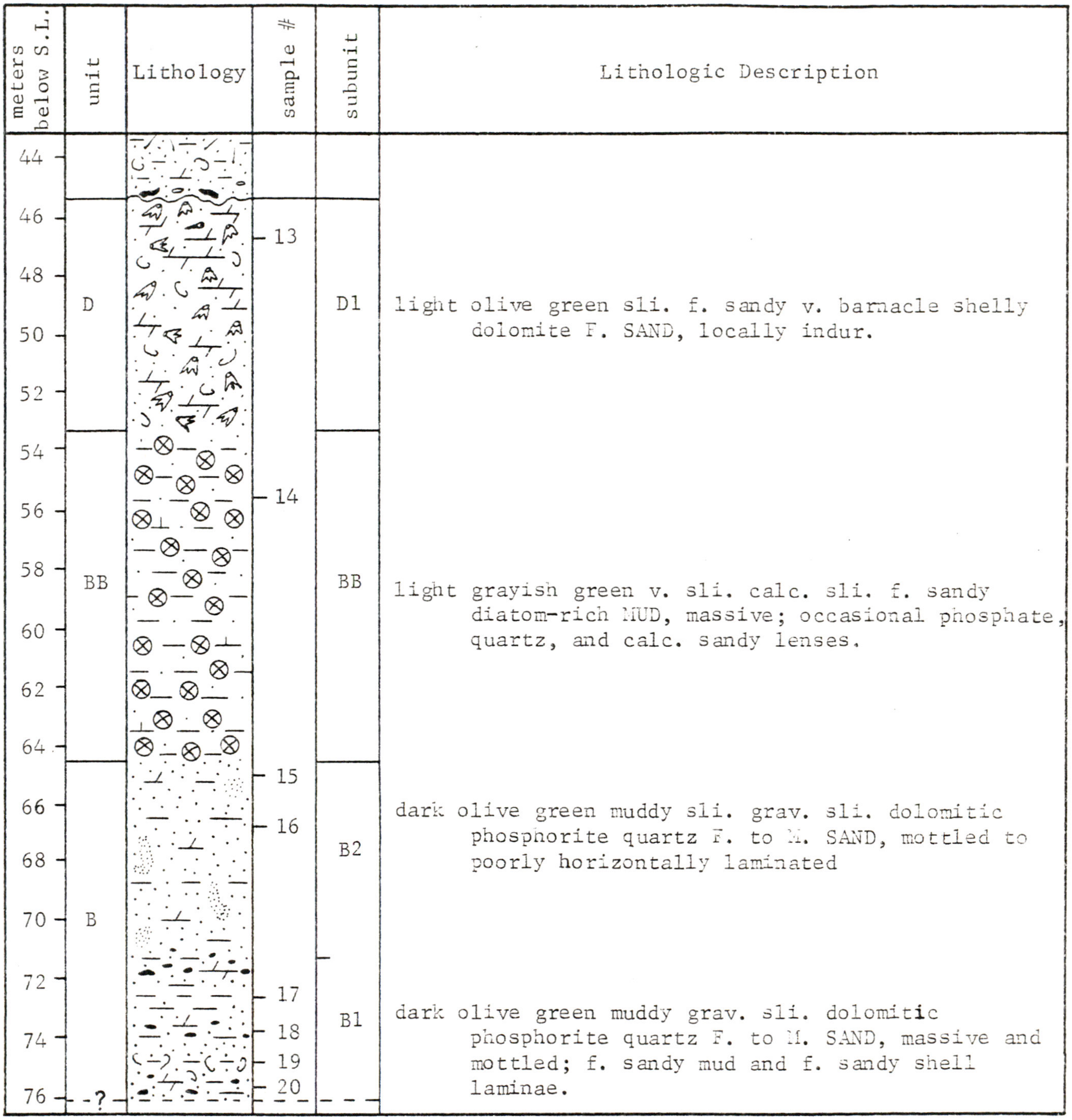


Figure B4. Hole PON-4.

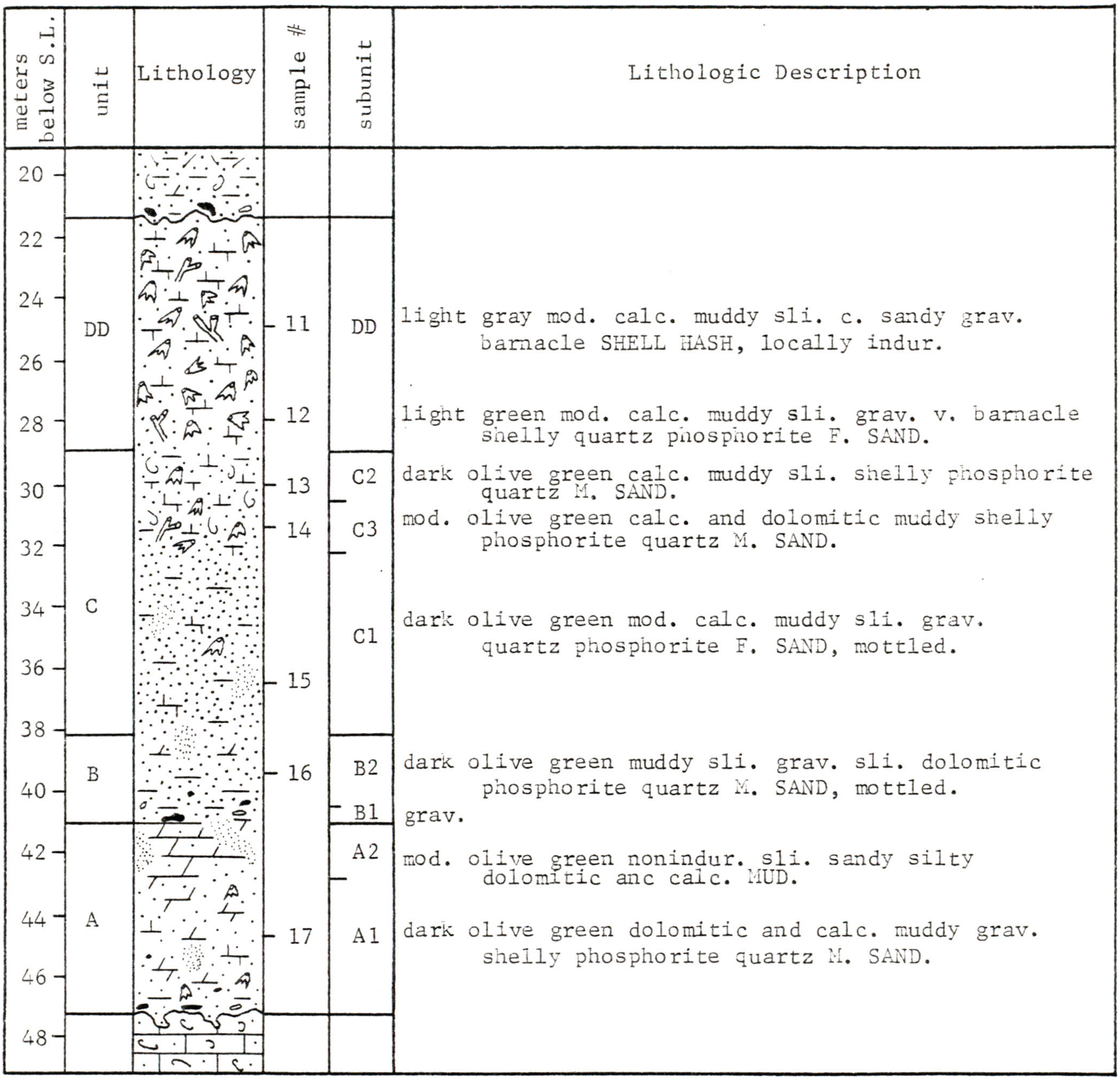


Figure B5. Hole PON-3.

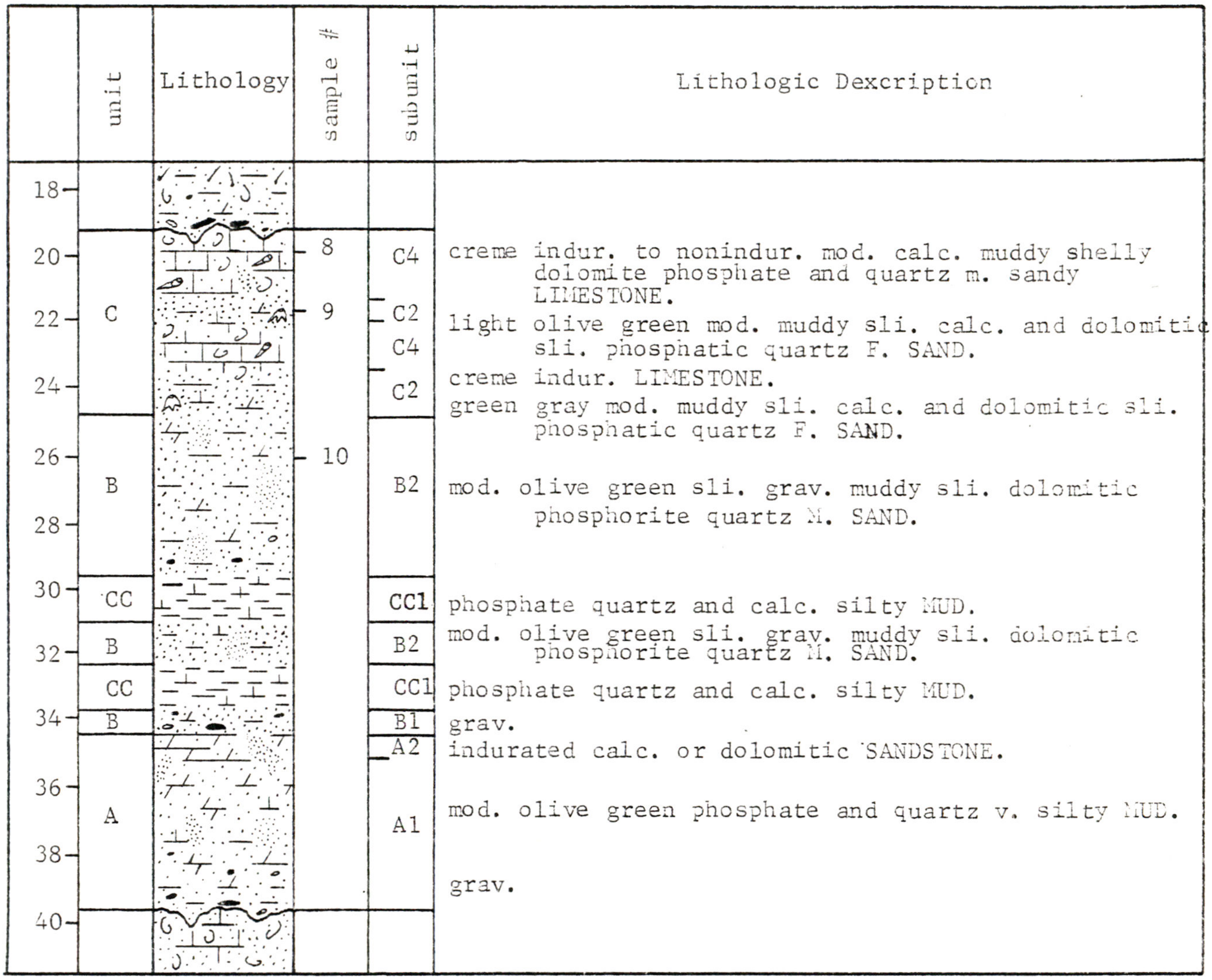


Figure B6. Hole PON-1.

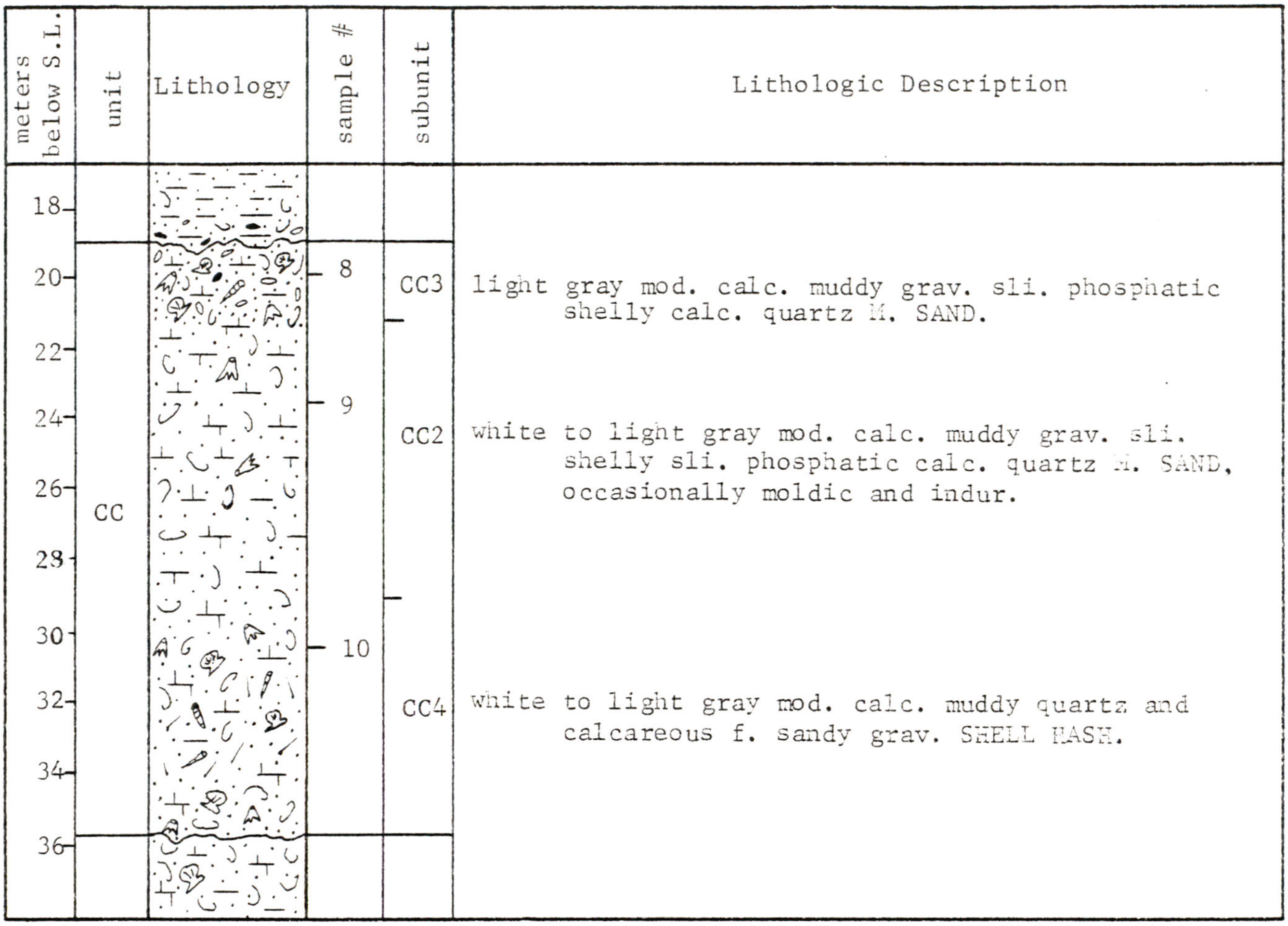


Figure B7. Hole CNN-1.

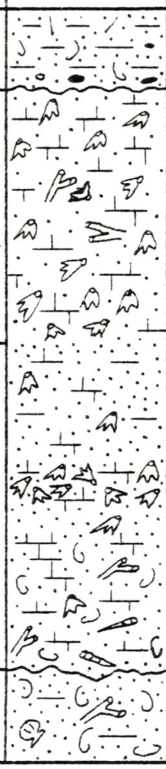
meters below S.L.	unit	Lithology	sample #	subunit	Lithologic Description
18					
20, 22, 24, 26	DD		10	DD	white to gray mod. calc. muddy v. sli. phosphate and quartz sandy grav. barnacle SHELL HASH.
28	CC		11	CC5	light olive green v. sli. phosphate and quartz sandy v. shelly calc. MUD.
30			12	CC4	olive green v. sli. phosphate and quartz sandy calc. sandy and muddy sli. grav. SHELL HASH.
32, 34			13, 14	CC2	gray to olive green calc. sandy and muddy sli. phosphatic shelly quartz F. to M. SAND.
36					

Figure B8. Hole CTN-1.