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

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ABSTRACT

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

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

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

INTRODUCTION

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

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

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

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

OBJECTIVES

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

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

STUDY AREA

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

LOWER PUNGO RIVER PHOSPHORITES

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

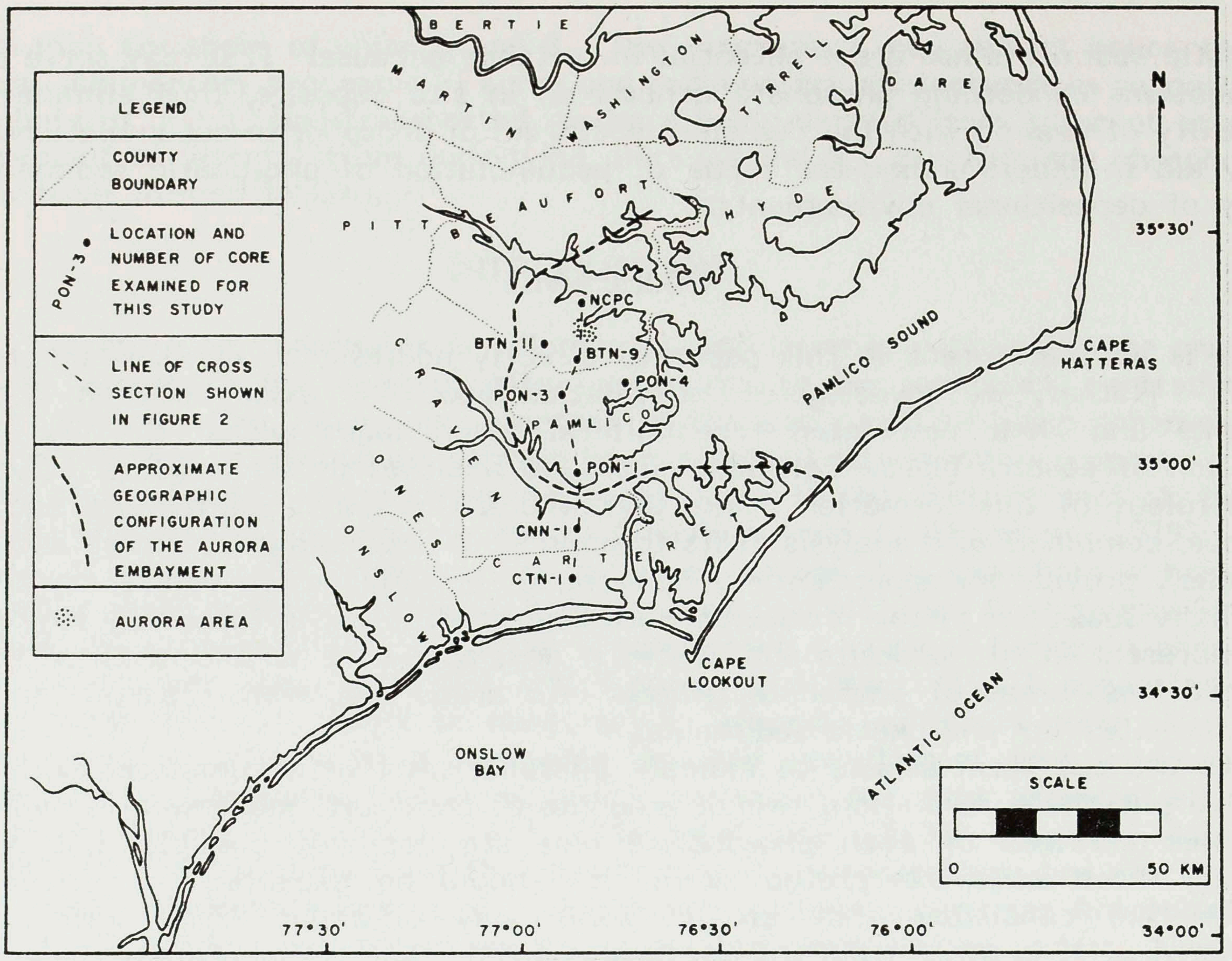

Figure 1. Map of study area showing location of cores.

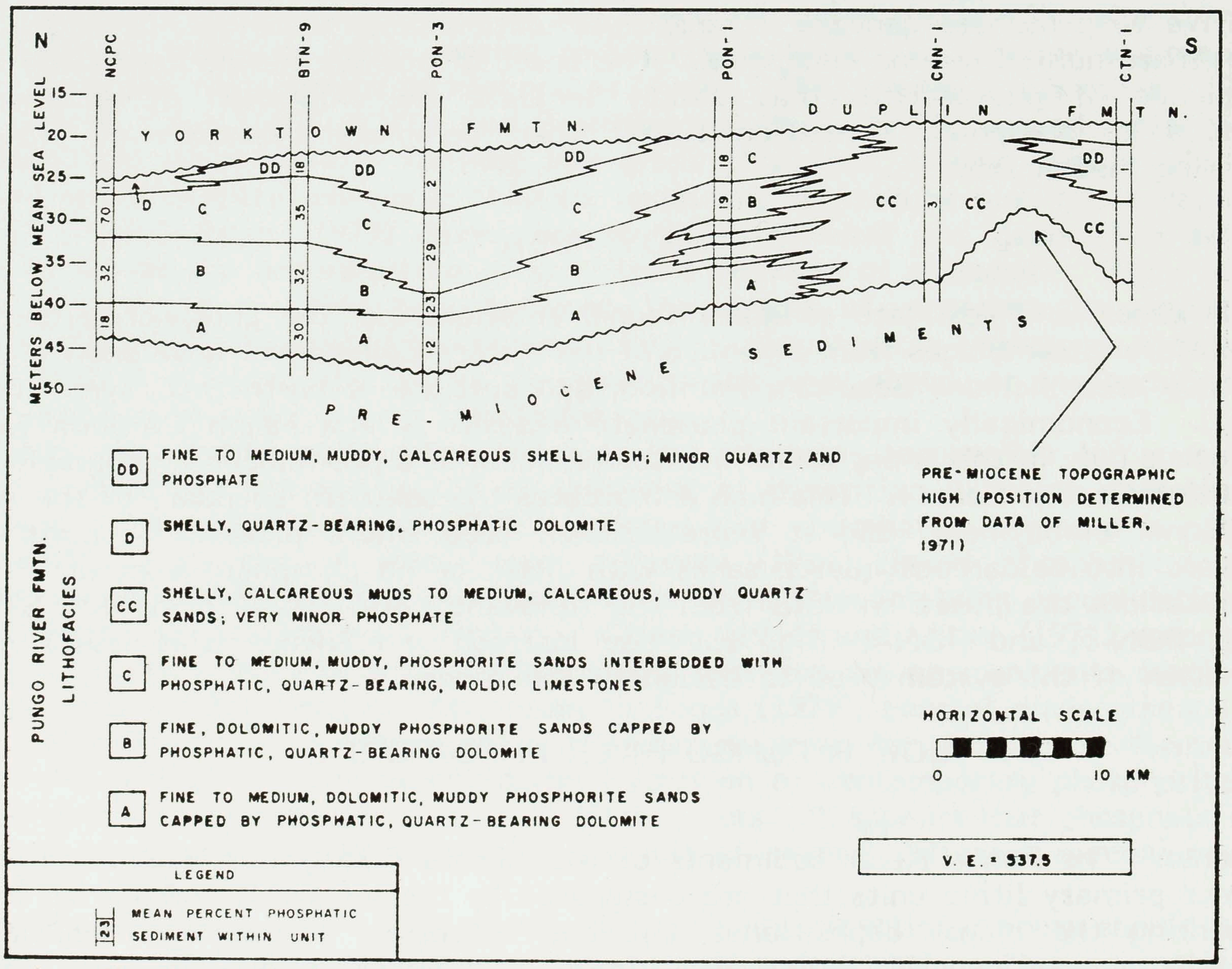

Figure 2. North-south distribution of lithologic units within the Aurora Embayment (core NCPC through core PON-1).

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

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

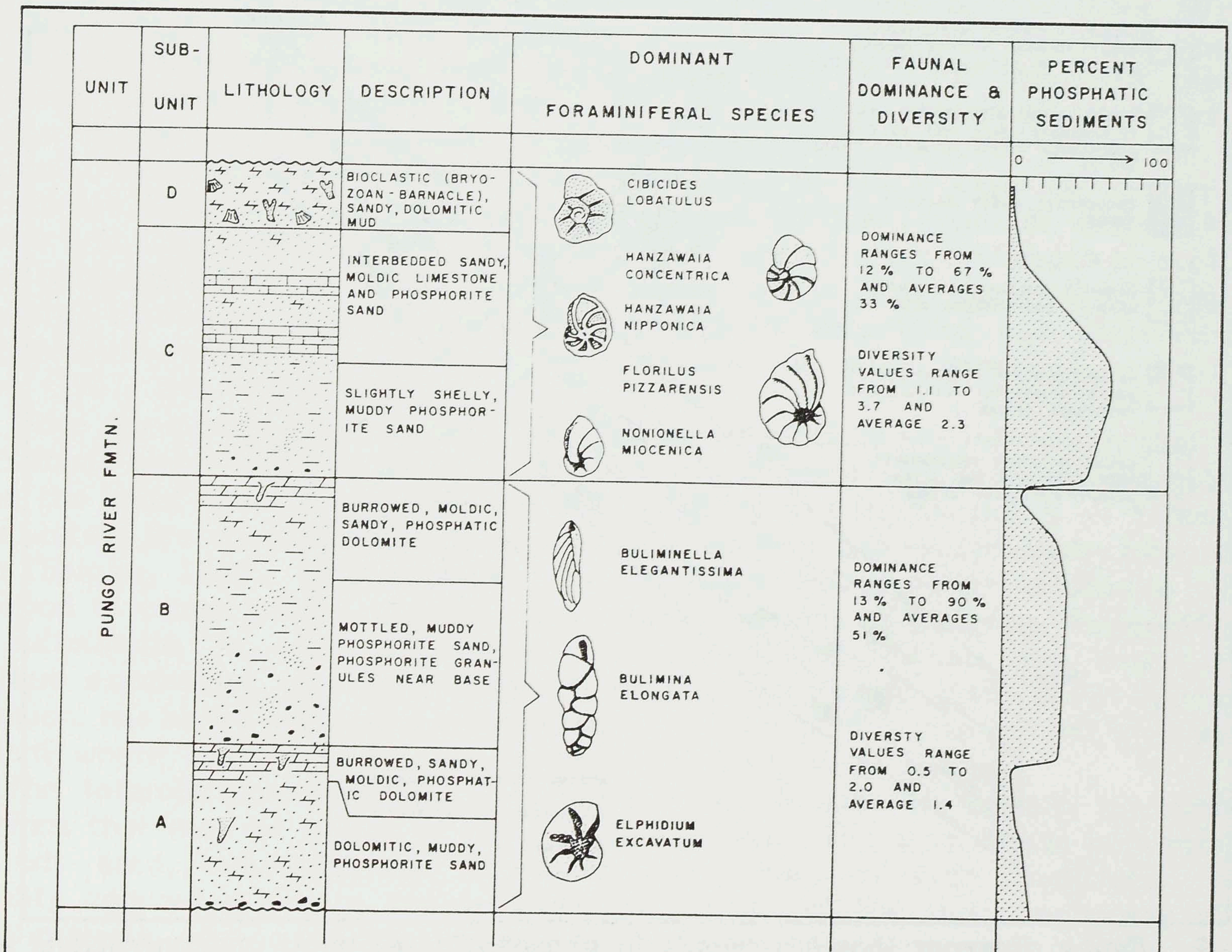

Figure 3. Composite section of the Pungo River Formation in the Aurora area.

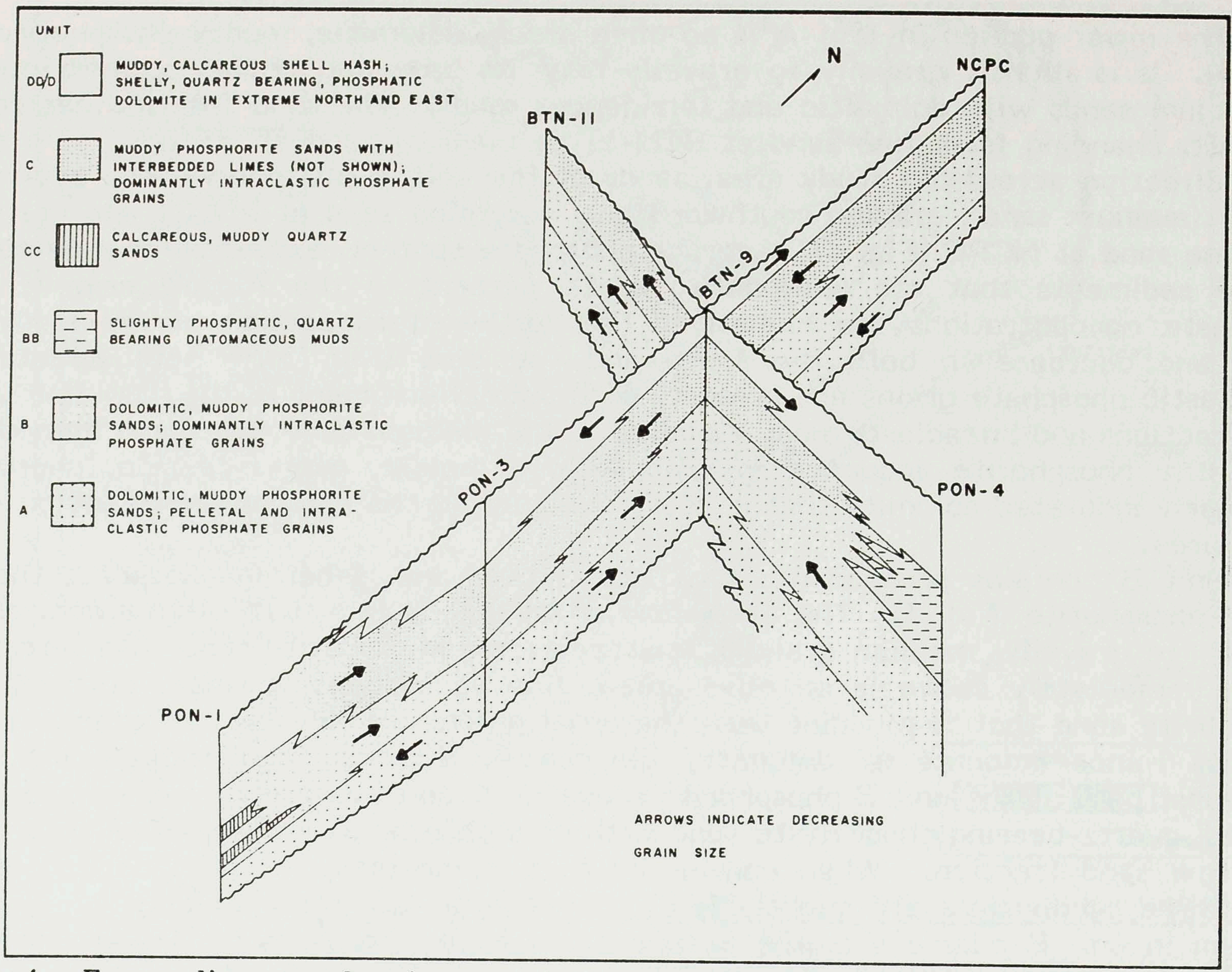

Figure 4. Fence diagram showing trends in grain size for each of the phosphorite units in the Pungo River Formation.

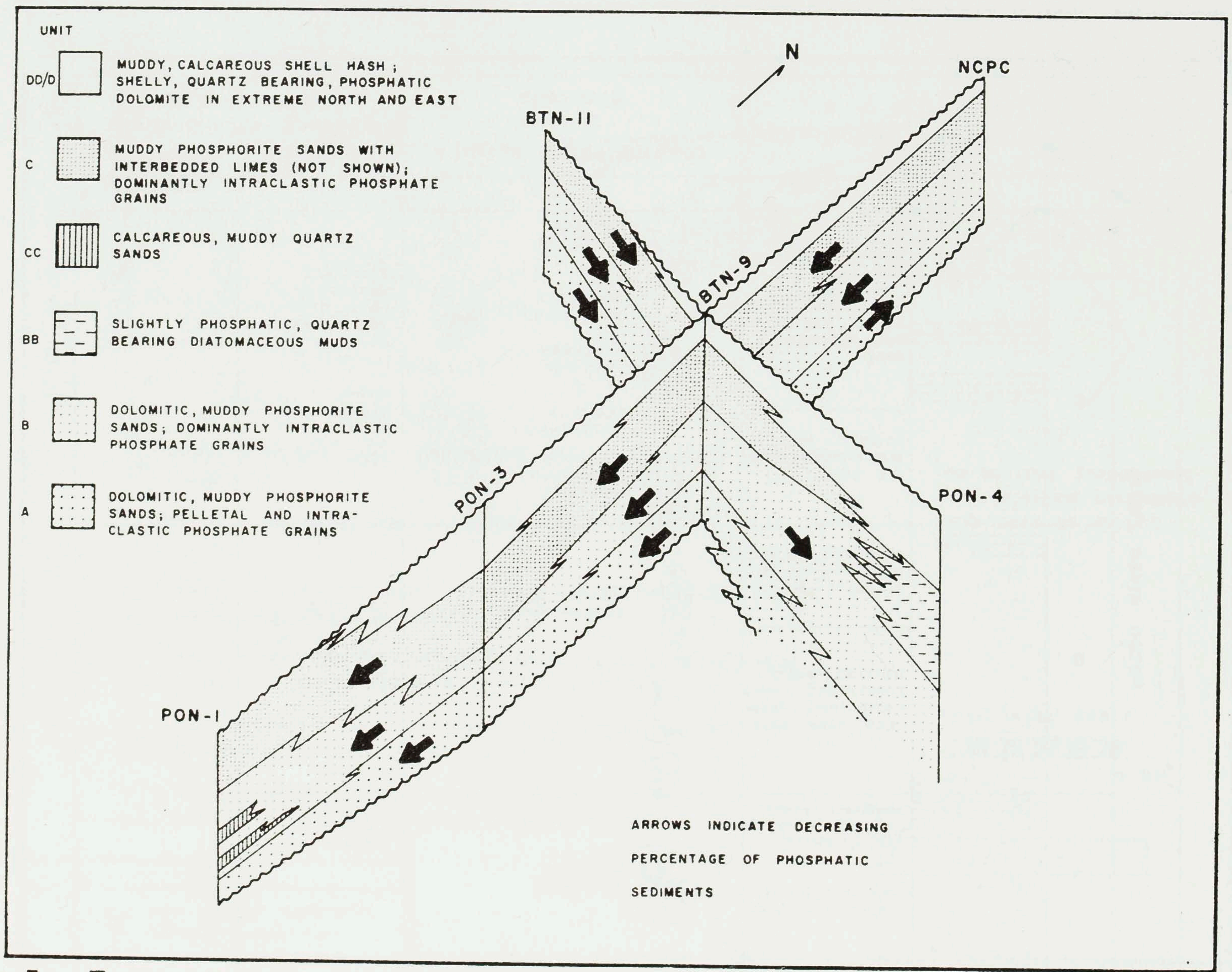

Figure 5. Fence diagram showing trends in phosphatic sediment concentrations within each of the phosophorite units of the Pungo River Formation.

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

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

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

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

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

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

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

UPPER PUNGO RIVER PHOSPHORITES

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

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

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

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

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

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

DISCUSSION

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

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

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

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

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

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

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

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

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

CONCLUSIONS

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

1) The in situ deposition of unit A phosphorites.

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

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

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

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

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

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

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

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

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

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

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

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

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REFERENCES CITED

Ames, L. L., 1959, The genesis of carbonate apatites: Econ. Geology, v. 54, p. 829-841.

Baturin, G. N., 1971, Stages of phosphorite formation on the ocean floor: Nat. Phys. Science, v. 232, p. 61-62.

Blow, W. H., 1969, Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy: First Internatl. Conf. Planktonic Microfossils, Proc., v. 1, p. 199-422.

Bremner, J. M., and Willis, J. P., 1975, Glauconite and phosphorites from southwest Africa: Proc. Electron Microscopy Soc. Southern Africa, v. 5, p. 127-128.

Brongersma-Sanders, M., 1957, Mass mortality in the sea, *in* Hedgepeth, ed., Treatise on Marine Ecology and Paleoecology: Geol. Soc. America Mem. 67, v. 1, p. 941-1010.

Bushinskii, G. I., 1966, Ancient phosphorites of Asia and their genesis: Tr. Geol. Inst., SSSR, v. 149, 192 p.

Cook, P. J., 1967, Winnowing--an important process in the concentration of the Stariway Sandstone (Ordovician) phosphorites of central Australia: Jour. Sed. Petrology, v. 37, p. 818-828.

Cook, P. J., 1976, Sedimentary phosphate deposits, *in* Wolf, ed., Handbook of Strata-Bound and Strataform Ore Deposits: Elsevier, p. 505-535.

Culver, S. J., and Buzas, M. A., 1980, Distribution of Recent benthic foraminifera off the North American Atlantic coast: Smithsonian Contributions to Mar. Sci., n. 6, 512 p.

Culver, S. J., and Buzas, M. A., 1981, Distribution of Recent benthic foraminifera in the Gulf of Mexico: Smithsonian Contributions to Mar. Sci., n. 8, v. 1 and 2, 898 p.

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

Gibson, T. G., in press, Key foraminiferal species from upper Oligocene to lower Pleistocene strata of the central Atlantic Coastal Plain: Smithsonian Contributions to Paleobiology, n. 41.

Katrosh, M. R., and Snyder, S. W., 1982, Diagnostic foraminifera and paleoecology of the Pungo River Formation, central Coastal Plain of North Carolina: Southeastern Geology, v. 23 (this issue).

Kazakov, A. V., 1937, The phosphorite facies and the genesis of phosphorites, *in* Geological Investigations of Agricultural Ores: Trans. Sci. Inst. Fertilizers Insecto-Fungicides, n. 142, p. 95-113.

Kazakov, A. V., 1938, The phosphorite facies and the genesis of natural phosphates: Sovetskaya Geologiya, v. 8, p. 33-47.

Manheim, F. T., and Gulbrandsen, R. A., 1979, Marine phosphorites, *in* Marine Minerals: Min. Soc. America Short Course Notes, v. 6, p. 151-173.

Manheim, F. T., Rowe, G. T., and Jipa, D., 1975, Marine phosphorite formation off Peru: Jour. Sed. Petrology, v. 45, p. 243-251.

Mansfield, G. R., 1940, The role of fluorine in phosphate deposition: Am. Jour. Sci., v. 238, n. 12, p. 833-879.

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 National 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 [unpub. Ph.D. dissertation]: Chapel Hill, Univ. North Carolina.

Penrose, R. A. F., 1888, Nature and origin of deposits of phosphate of lime, with an introduction by N. S. Shaler: U.S. Geological Survey Bull. 46, 143 p.

Pevear, D. R., 1966, The estuarine formation of United States Atlantic Coastal Plain phosphorite: Econ. Geol., v. 61, p. 251-256.

Phleger, F. B., and Soutar, A., 1973, Production of benthic foraminifera in three east Pacific oxygen minima: Micropaleontology, v. 19, p. 110-115.

Pinet, P. R., and Popenoe, P., 1982, Blake Plateau: Control of Miocene sedimentation patterns by large-scale shifts of the Gulf Stream axis: Geology, v. 10, p. 257-259.

Poag, C. W., 1981, Ecological Atlas of Benthic Foraminifera of the Gulf of Mexico: Woods Hole, Massachusetss, Mar. Sci. Internatl., 174 p.

Riggs, S. R., 1979, Phosphorite sedimentation in Florida--a model phosphogenic system: Econ. Geology, v. 74, p. 285-314.

Riggs, S. R., 1980, Tectonic model of phosphate genesis, *in* Sheldon, R. P., and Burnett, W. C., eds., Fertilizer Mineral Potential in Asia and the Pacific: Honolulu, Hawaii, East-West Center, East-West Resource Systems Inst. Pub., p. 159-190.

Riggs, S. R., Lewis, D. W., Scarborough, A. K., and Snyder, S. W., 1982, Cyclic deposition of Neogene phosphorites in the Aurora Area, North Carolina, and their possible relationship to global sea-level fluctuations: Southeastern Geology, v. 23 (this issue).

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

Scarborough, A. K., Riggs, S. R., and Snyder, S. W., 1982, Stratigraphy and petrology of the Pungo River Formation, central Coastal Plain of North Carolina: Southeastern Geology, v. 23 (this issue).

Schafer, C. T., and Cole, F. E., 1982, Living benthic foraminifera distributions on the continental slope and rise of Newfoundland, Canada: Geol. Soc. America Bull., v. 93, p. 207-217.

Schnitker, D. F., 1971, Distribution of foraminifera on the North Carolina continental shelf: Tulane Stud. Geology Paleontology, v. 8, n. 4, p. 169-215.

Seeley, H., 1866, The rock of the Cambridge Greensand: Geol. Mag., v. 3, p. 302-307.

Seiglie, G. A., 1968, Foraminiferal assemblages as indicators of high organic carbon content in sediments and of polluted waters: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 2231-2241.

Stainforth, R. M., Lamb, J. L., Luterbacher, H., Beard, J. H., and Jeffords, R. M., 1975, Cenozoic planktonic foraminiferal zonation and characteristics of index forms: Univ. Kansas Paleontol. Contr., art. 62, p. 1-425.

Todd, R., 1979, Depth occurrences of foraminifera along the southeastern United States: Jour. Foram. Research, v. 9, n. 4, p. 277-301.

Vail, P. R., Mitchum, R. M., Todd, R. G., Widmier, J. M., Thompson, J., Sangree, J. B., Bubb, J. N., and Hatfield, W. C., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C. E., ed., Seismic Stratigraphy--Applications to Hydrocarbon Exploration: Am. Assoc. Petroleum Geologists Mem. 26, p. 49-212.

Walton, W. R., 1964, Recent foraminiferal ecology and paleoecology, *in* Imbrie and Newell, eds., Approaches to Paleoecology: John Wiley and Sons Inc., p. 151-237.

Weaver, C. E., and Beck, K. C., 1977, Miocene of the southeast United States, *in* Developments in Sedimentology: Elsevier, 234 p.