Upper Cenozoic Geology of the Onslow Bay and Aurora Embayments,

North Carolina: Compilation of Published Abstracts From the Literature

North Carolina Geological Survey - Information Circular 28
Division of Land Resources
Department of Environment, Health, and Natural Resources

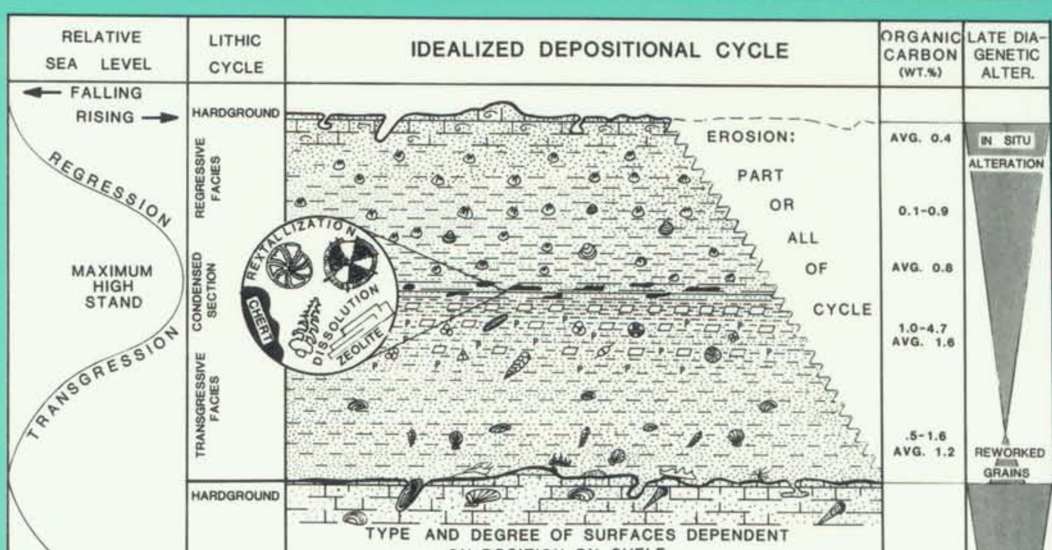


FIGURE CAPTIONS FOR COVER PLATE

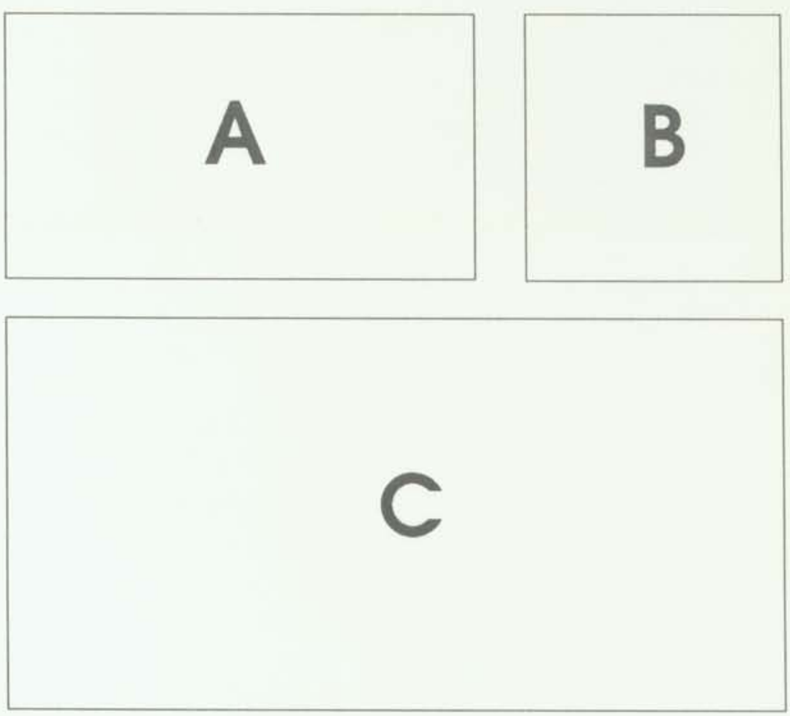
FIGURE A. Top Left. The R/V CAPE HATTERAS, a National Science Foundation oceanographic research vessel operated by the Duke/University of North Carolina Oceanographic Consortium, Beaufort, North Carolina.

FIGURE B. Right. Vibracoring in Onslow Bay aboard the R/V CAPE HATTERAS.

FIGURE C. Bottom Left. Idealized lithologic cycle common to some of the Miocene depositional units within the Aurora and Onslow Embayments of the Carolina Phosphogenic Province. This figure shows the following features:

1. mixed fining upward sequence lithofacies (FUSL) through the various stages of one fourth-order sea-level cycle;
2. associated organic carbon content;
3. erosional potential of the deposited unit due to subsequent submarine and subaerial processes; and
4. late diagenetic alteration patterns resulting from submarine exposure and development of a condensed section during the maximum sea-level highstand and hardground development during the sea-level lowstand. The downward decrease in size of the pattern in the column entitled diagenetic alteration indicates decreasing degree of *in situ* late diagenesis down-section from the hiatal surfaces. Note the basal zone of diagenetically altered grains that have been reworked from the erosion of the preceding hardground surface.

Figure is from Riggs and Mallette, 1990.



UPPER CENOZOIC GEOLOGY OF THE ONSLOW BAY AND AURORA EMBAYMENTS, NORTH CAROLINA: COMPILATION OF PUBLISHED ABSTRACTS FROM THE LITERATURE

edited by

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INFORMATION CIRCULAR 28

NORTH CAROLINA GEOLOGICAL SURVEY
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UPPER CENOZOIC GEOLOGY OF THE ONSLOW BAY AND AURORA EMBAYMENTS OF NORTH CAROLINA

by

Stanley R. Riggs

PURPOSE AND SCOPE OF THIS PUBLICATION

This compilation of published abstracts from the literature concerns the Upper Cenozoic geology of the Onslow and Aurora Embayments on the North Carolina continental margin as indicated in Figure 1. This study area is the Carolina Phosphogenic Province as defined by Riggs (1979, 1984) and represents the focus of an extended research program entitled GENESIS OF THE UPPER CENOZOIC DEPOSITIONAL SEQUENCES OF THE MID-ATLANTIC CONTINENTAL MARGIN with Stanley R. Riggs, Albert C. Hine, Scott W. Snyder, Stephen W. Snyder, and William J. Showers as co-principal investigators of various portions of the research. This extended research program began in 1979 and is still in progress, although at a slower pace than during the past decade. The published abstracts compiled in the present volume represent the products of this research program on the Carolina Phosphogenic Province.

The abstracts presented in the first three sections of this publication (M. Monographs, Book Chapters, and Journal Articles; T. Theses and Dissertations; and A. Abstracts) are based on research funded by the National Science Foundation (NSF) and the University of North Carolina Sea Grant College Program (UNCSGCP) of the National Oceanographic and Atmospheric Administration (NOAA). Specific research grants during the period of 1979 through 1990 are listed below.

1. **National Science Foundation Research Grants:**
   - OCE-7908949 to S.R. Riggs and A.C. Hine
     Submarine phosphorites in Onslow Bay, North Carolina: evaluation of an exploration model.
   - OCE-8110907 to S.R. Riggs and A.C. Hine
     Submarine phosphorites in Onslow Bay, North Carolina: evaluation of an exploration model.
   - OCE-8118164 to S.R. Riggs and A.C. Hine
     Genesis of the phosphorite sediment sequence on the mid-Atlantic continental margin.
   - OCE-8342777 to A.C. Hine, Stephen W. Snyder, and S.R. Riggs
     Seismic stratigraphy of the North Carolina estuarine system.
   - OCE-8400383 to S.R. Riggs, A.C. Hine, and Scott W. Snyder
     Genesis of the phosphorite sediment sequence on the mid-Atlantic continental margin.
   - OCE-8540985 to S.R. Riggs and A.C. Hine
     Geologic and biologic impacts of Hurricane Diana on the outer continental shelf, Frying Pan Shoals region, North Carolina.

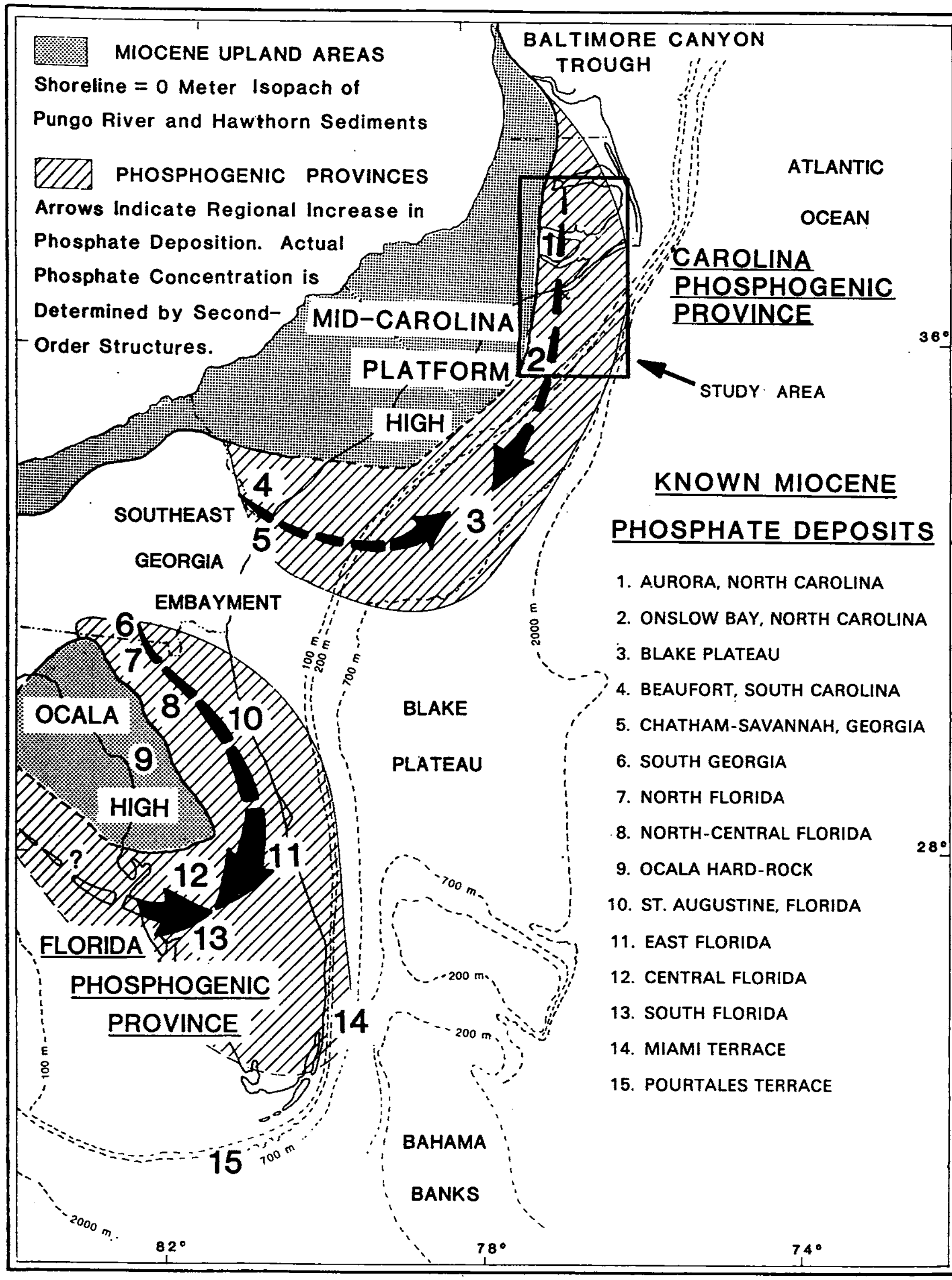

FIGURE 1. Map of the southeastern United States showing: 1) major first-order structural features which controlled Miocene phosphate sedimentation; 2) regional distribution of cumulative phosphate formed during the Miocene; and 3) location of major phosphate deposits. Modified from Riggs (1984).

OCE-8609161 to S.R. Riggs, A.C. Hine, and Scott W. Snyder:
Genesis of the phosphorite sediment sequence on the mid-Atlantic continental margin.

OCE-8709429 to S.R. Riggs
Isotopic composition of the Miocene phosphorite sediment on the Carolina continental margin: a detailed record of glacio-eustatic sea-level cyclicity.

OCE-8710311 to W.J. Showers
Isotopic composition of the Miocene phosphorite sediment on the Carolina continental margin: a detailed record of glacio-eustatic sea-level cyclicity.

2. **University of North Carolina Sea Grant College Program of the National Oceanographic and Atmospheric Administration Research Grants:**

NA83AA-D-00012 to Scott W. Snyder and S.R. Riggs
Micropaleontological characterization and correlation of the continental shelf phosphorites, Onslow Bay, North Carolina.

NA85AA-D-SG022 to 1) Scott W. Snyder and S.R. Riggs
Relationship of microfauna to post-depositional changes in cyclical Neogene sedimentary sequences of Onslow Bay.

NA85AA-D-SG022 to 2) S.R. Riggs, A.C. Hine, and Scott W. Snyder
Carbonate hardgrounds in Onslow Bay, North Carolina.

3. Preparation and publication of this specific document is the result of a grant from the **U.S. Department of Interior, Minerals Management Service** to S.R. Riggs with the assistance of the **North Carolina Department of Environment, Health, and Natural Resources; Division of Land Resources, Geological Survey Section.**

Personnel associated with this multi-institutional project include many senior researchers from numerous universities and government agencies, as well as students, who have produced 25 M.S. theses and 2 Ph.D. dissertations, from the five institutions listed below.

1. East Carolina University, Greenville, North Carolina.
2. North Carolina State University, Raleigh, North Carolina.
3. University of South Florida, St. Petersburg, Florida.
4. University of North Carolina--Chapel Hill, North Carolina.
5. Duke University, Durham, North Carolina.

Publications resulting directly from this extended research project include 54 peer-reviewed manuscripts appearing in professional journals, monographs, and as chapters in technical books, and 88 abstracts appearing in abstract volumes. Several synthesis papers are being prepared for publication during the next few years. In fact, this long-term research project continues, but with a slightly different focus that considers the following:

1. Isotope stratigraphy (including strontium age dating of various sediment components) within the Upper Cenozoic;
2. Isotope and trace element geochemistry (including oxygen, carbon, and neodymium isotopes) of the phosphate sediment component; and

3. Quaternary history and role of hardbottoms in biological productivity on the continental shelf.

The publications resulting from this extended research program have been published in many different places and formats. Consequently, a literature search to determine what has been done, by whom, and where to locate it would be a major undertaking. Hence, the purpose of this publication is to summarize under one cover all published information resulting from the research program entitled GENESIS OF THE UPPER CENOZOIC DEPOSITIONAL SEQUENCES OF THE MID-ATLANTIC CONTINENTAL MARGIN, including the following:

1. copy of each abstract;
2. complete bibliographic citation;
3. complete author listing of publications; and
4. general listing of publications by geologic subject.

In general, all abstracts have been reproduced as they were published in the literature. However, those abstracts that were originally published as stand-alone contributions in abstract volumes have occasionally been edited with minor corrections made for geological and grammatical errors.

This publication is intended to chart the evolution of scientific thought and understanding, and to serve as a reference for future research and development within this important geologic province. Because the science has evolved through time, beginning with the most recent publications and backtracking is recommended.

ORGANIZATION AND USER'S GUIDE FOR THIS PUBLICATION

The abstracts and their accompanying bibliographic citations within the text are listed under four major categories.

CODE	TYPE OF PUBLICATION
M.	Monographs, Book Chapters, and Journal Articles
T.	Theses and Dissertations
A.	Abstracts
P.	Pertinent Selected Articles by Other Authors

Within categories M, T, and P, each citation is listed in alphabetical order by the senior author and assigned a code. The code includes a letter (M, T, or P) that indicates the type of publication, and a number reflecting the alphabetical sequence according to senior author. However, within category A (Abstracts), each citation is first listed by the year of publication and then by alphabetical sequence of the senior author. The code includes the letter A, the last two digits of the year published, and then a number reflecting the alphabetical sequence of the senior author during that specific year.

This bibliography of published literature is indexed in two ways: by author(s) and geologic subject. The author index provides a breakdown of the bibliography by the first two authors, year of publication, index number indicating the type of publication, and page number within the text where the indicating the type of publication, and page number within the text where the complete citation and abstract are located. The subject index provides a breakdown of key geologic subjects and lists the publications by first two authors, year of publication, index number indicating the type of publication, and page number within text where the complete citation and abstract are located. The subject index includes the following categories.

General Geologic Overview
Lithostratigraphy
Biostratigraphy
Seismicstratigraphy
Sedimentation
Phosphate Mineralogy/Petrology
Carbonate Mineralogy/Petrology
Clay Mineralogy/Petrology
Major/Trace Element Geochemistry
Isotope Geochemistry
Economic Geology
Paleoceanography/Paleoecology
Modern Shelf Processes

To use this bibliography, the reader can pursue any one of four different tacks, working either through the table of contents or the indices.

CONTENTS:

1. To locate a specific type of publication (M. Manuscripts, Book Chapters, and Journal Articles; T. Theses and Dissertations; or P. Pertinent Selected Articles by Other Authors), go directly to that publication category in the text. Then proceed through the alphabetical listing by senior author.

2. To locate a specific abstract contribution to an abstract volume (A), go directly to that publication category in the text. Then proceed to the year of publication and through the alphabetical listing by senior author within that year.

AUTHOR INDEX:

3. To identify the works of a specific author, proceed to the author index, which lists alphabetically the first two authors, date of publication, index number indicating type of publication, and the page in the text for complete citation and abstract.

SUBJECT INDEX:

4. To investigate a specific geologic subject, proceed to the subject index, which lists alphabetically the first two authors, date of publication, index number indicating type of publication, and the page in the text for complete citation and abstract.

SUMMARY OF THE GEOLOGIC FRAMEWORK

The North Carolina Coastal Plain and continental shelf are parts of a coherent geologic province on a passive plate margin that have responded as an integral unit to changing environmental conditions through time. The large-scale structural framework and patterns of sediment accumulation during the Cenozoic were produced by the early tectonic history of the Atlantic Ocean. The decreasing influence of structural subsidence during the Cenozoic (Parsons and Sclater, 1977) believe that 95% of the total subsidence had occurred by the end of the Cretaceous), have resulted in a relatively thin Cenozoic section. The small-scale and detailed depositional histories of Upper Cenozoic stratigraphic units resulted from cyclical paleoclimatic and paleoceanographic conditions interacting with the continental margin, rather than regional tectonism and structural processes. The resulting sediment sequences are complex products of climatically controlled processes of glaciation, deglaciation, and rapid glacio-eustatic sea-level fluctuations interacting with the oceanographic currents and shelf-slope morphology.

The pre-Cenozoic structural framework of the North Carolina continental margin is a product of continental break-up that produced an irregular boundary consisting of a series of first-order structural promontories or platforms and re-entrants or basins (Dillon et al., 1979; Grow et al., 1979; Klitgord and Behrendt, 1979; Popenoe, 1985; Schlee, 1982). Figure 1 generally outlines these first-order structural features that include the Carolina Platform High and the surrounding basins: Southeast Georgia Embayment to the south, Baltimore Canyon Trough to the north, and Carolina Trough to the east. Deposited upon this rifted terrain is a Mesozoic and Cenozoic sedimentary wedge that is 8 to 12 km thick in the basins and thins and disappears as it onlaps onto the adjacent platforms.

Figure 2 demonstrates that the Carolina Platform was the major structural feature that controlled the deposition and concentric distribution pattern of apparent offlapping Upper Cenozoic units throughout the continental margin of both Carolinas (Riggs and Belknap, 1988; Riggs et al., 1985, 1990; Stephen W. Snyder, 1982). These sediment units are displaced seaward in northern South Carolina and southern North Carolina as a result of deposition around the Carolina Platform (Riggs et al., 1990). The topographically highest portion of this basement feature has historically been called the Cape Fear Arch; more recent literature refers to it as the Mid-Carolina Platform High. The Upper Cenozoic section in North Carolina occurs as a seaward thickening sedimentary wedge deposited off the northeastern flank of the Carolina Platform as it dips into the Carolina Trough as reflected in the isopach map for the Miocene sediments in (Figure 3).

Deposition and distribution of specific sediment facies, such as the Miocene phosphate, on the Carolina continental margin (Riggs, 1979, 1984) were controlled locally by second-order paleotopographic features. Upper Cenozoic sediments were deposited on a large, open continental shelf-slope system off the east flank of the Carolina Platform (Figures 2 and 3). Figure 4 shows the location of the Cape Lookout High, an east-west oriented, late Oligocene and Miocene, paleotopographic high that subdivided the North Carolina shelf into two embayments (Popenoe, 1985; Riggs, 1984; Riggs et al., 1982, 1985, 1990; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1982, 1990). North of Cape Lookout

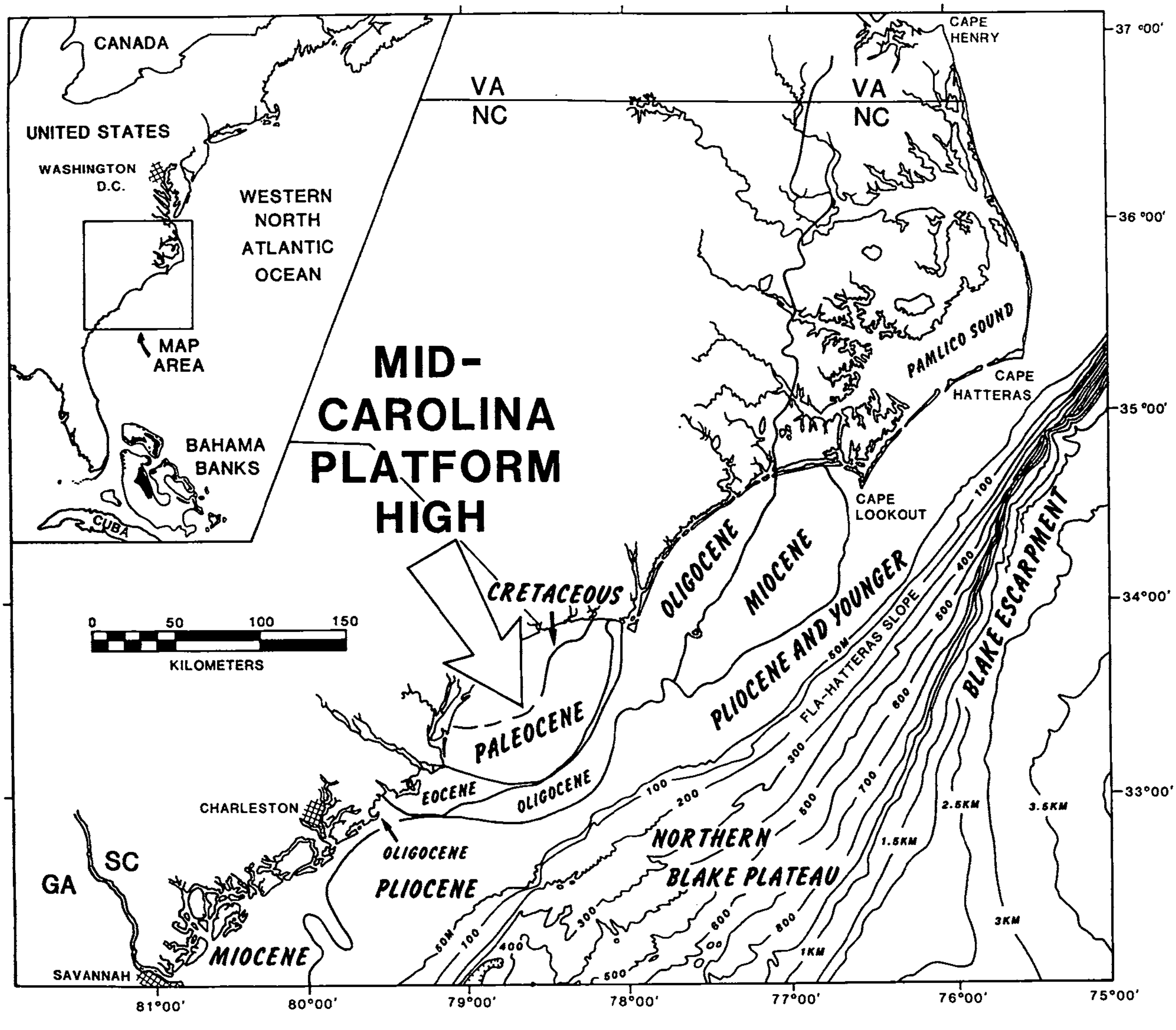

FIGURE 2. Distribution of outcropping Cenozoic and Cretaceous sequences within the continental shelf of the Carolinas as mapped from chronostratigraphic correlations via seismic-reflection studies of Stephen W. Snyder (1982), Idris (1983), and Popenoe (1985). Note that Miocene sequences only crop out on the seafloor across the limbs of the Mid-Carolina Platform High and are partially missing from the nose of this first-order paleotopographic feature; the remaining Miocene sediment has been buried by Pliocene and Quaternary shelf-margin sediments. Modified from Stephen W. Snyder (1982).

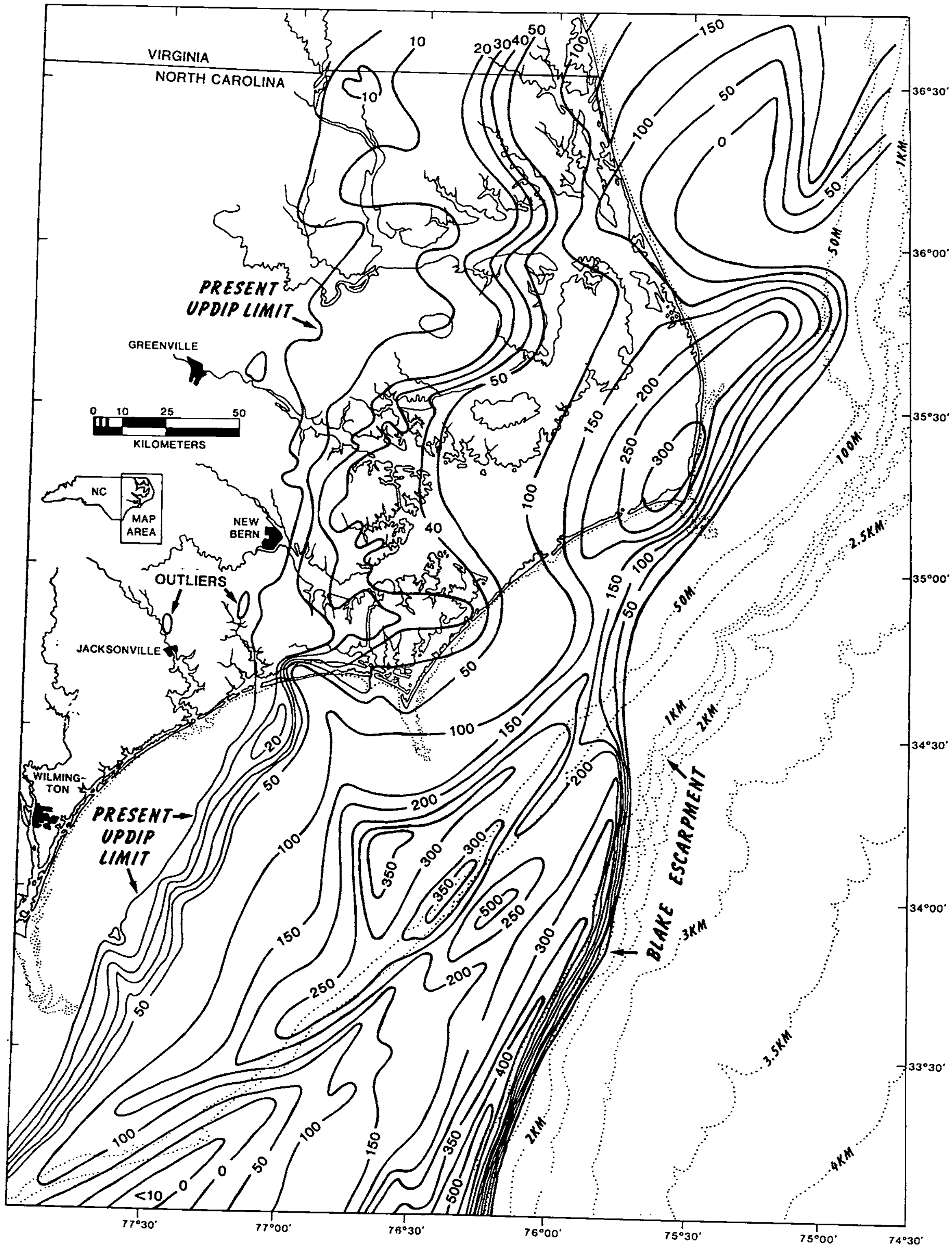

FIGURE 3. Isopach map (in meters) of the Miocene Pungo River Formation in the North Carolina continental margin. This map was produced from seismic-reflection data of Stephen W. Snyder (1982) and Popenoe (1985) and drill hole data of Miller (1982). Notice how the formation thickens seaward to between 300 and 500 m and is abruptly terminated. Modified from Riggs et al. (1985).

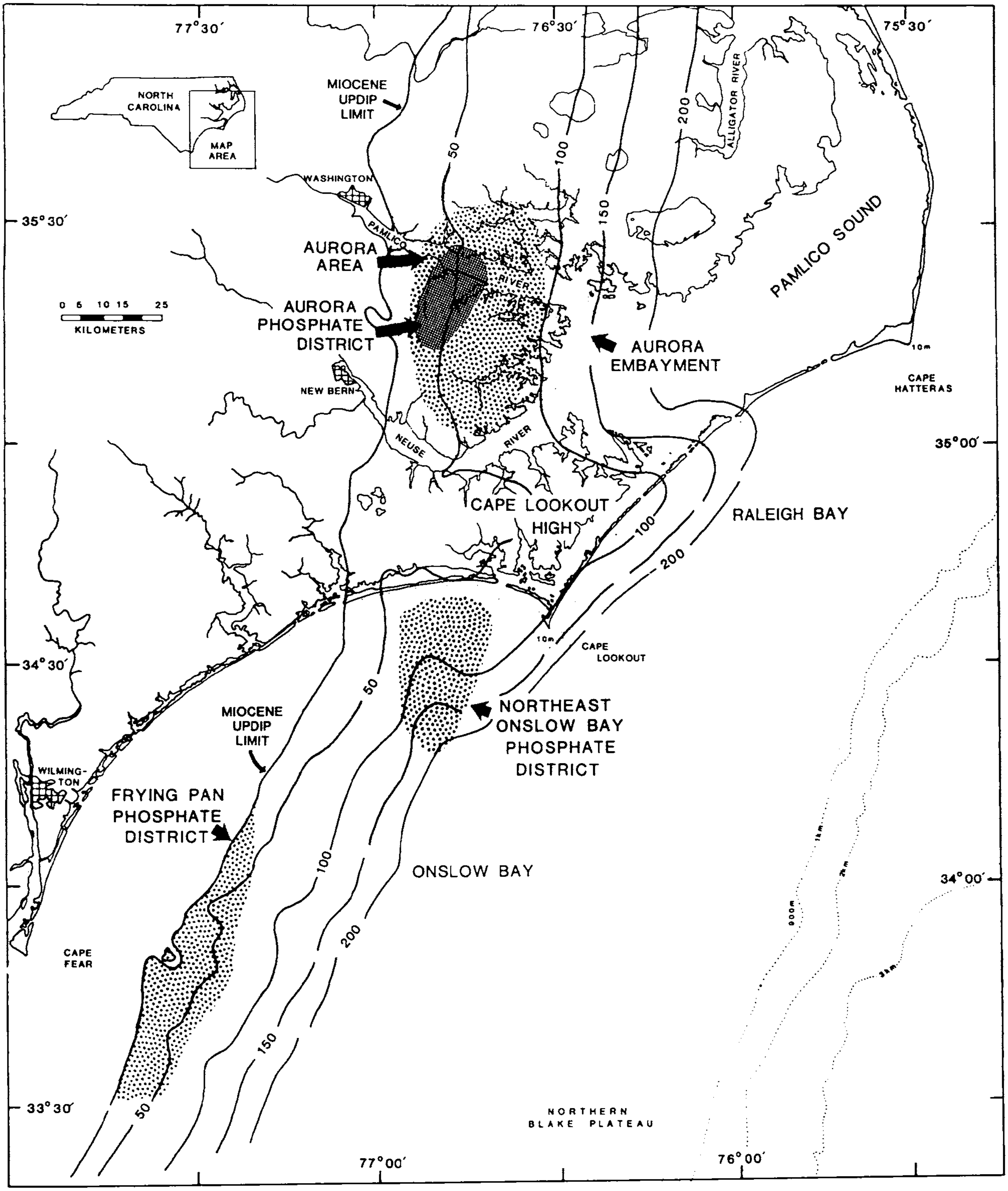

FIGURE 4. Structural contour map (in meters) on the base of the Miocene Pungo River Formation along the North Carolina Coastal Plain and Continental Shelf. The map delineates the 1) location of the Aurora, Northeast Onslow Bay, and Frying Pan Phosphate Districts; and 2) Cape Lookout High, a paleotopographic feature on top of Oligocene sediments that defines the Miocene Aurora Embayment on the north and Onslow Embayment on the south. Modified from Riggs et al. (1985).

High is the Aurora Embayment, which underlies the outer coastal plain of northeastern North Carolina and contains a major producing phosphate mine near Aurora (Figure 4). South of Cape Lookout High is Onslow Embayment, which underlies the modern continental shelf in Onslow Bay and contains two recently discovered phosphate deposits (Figure 4) in northeastern Onslow Bay and the Frying Pan areas (Powers et al., 1990; Riggs, 1984, 1989; Riggs and Manheim, 1988; Riggs et al., 1985). Formation of specific lithofacies within each depositional sequence was controlled by the location in each embayment with dramatic sedimentologic changes in response to cyclical sea-level oscillations, changing current patterns, and fluctuations in chemical environments (Riggs, 1984; Riggs and Belknap, 1988; Riggs and Mallette, 1990; Riggs et al., 1982, 1985, 1990; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1982, 1990).

The resulting Upper Cenozoic sediment record is characterized by cyclical sediment units composed of extremely variable lithologies with complex geometries that have been extensively dissected by unconformities (Hine and Stephen W. Snyder, 1985; Riggs, 1984; Riggs and Mallette, 1990; Riggs et al., 1982, 1985, 1990; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1982, 1990). The Miocene units on the North Carolina margin, and to a much lesser extent the Pliocene and Quaternary units, are dominated by three distinctive characteristics. First, they contain abnormally high concentrations of authigenic minerals including phosphate, dolomite, opaline silica, glauconite, magnesium-rich clay, and clinoptilolite. Second, they occur in specific sequential depositional patterns of siliciclastic-rich, phosphate-rich, and carbonate-rich facies. Third, each depositional sequence is significantly modified by both contemporaneous and subsequent erosional processes by oceanographic processes during sea-level highstands (i.e., Gulf Stream dynamics) and by subaerial processes (i.e., weathering and fluvial dynamics) during sea-level lowstands.

During the Neogene, widespread stratigraphic units were formed in response to two second-order marine transgressions (Haq et al., 1987; Vail and Mitchum, 1979), one in early to middle Miocene and one in the Pliocene. The major Miocene transgression produced the Pungo River Formation, which is approximately contemporaneous with the Miocene portion of the Hawthorn Group in southeastern United States (Riggs, 1979, 1984; Riggs and Belknap, 1988). Hawthorn sediments and their stratigraphic equivalents extend from southern Florida into southern South Carolina. In northern South Carolina and southern North Carolina (Figure 2), these sediments crop out on the continental shelf in Long and Onslow Bays and extend northward on the North Carolina Coastal Plain where they are called the Pungo River Formation. This group of sediments extends into Virginia with a major decrease in phosphate and increase in glauconite and diatomite and constitutes the Calvert and lower portion of the Choptank Formations of Virginia through Delaware (Gibson, 1982, 1983; Ward and Strickland, 1985).

Throughout the late Miocene, North Carolina received little or no deposition. Widespread deposition resumed during the major Pliocene marine transgression, which inundated pre-existing paleotopographic lows and produced the Yorktown Formation in the northern portion of North Carolina and the Duplin Formation in the southern portion (Gibson, 1983; Ward and Strickland, 1985). Regression during the late Pliocene produced a widespread unconformity throughout the Atlantic margin (Blackwelder, 1980). This was followed by the very complex depositional patterns of the surficial Pleistocene sediments. The Pleistocene record consists of multiple sequences that are generally thin with highly variable lithologies and characterized by extensive erosion and truncation. Due largely to difficulties in differentiating and correlating this complex sequence of similar Pleistocene sediment units, the stratigraphic nomenclature is confusing and to a major extent, remains unresolved (Riggs and Belknap, 1988).

The Upper Cenozoic stratigraphic units generally strike from north to north-northeast and dip from east to southeast off the flank of the Mid-Carolina Platform High. For example, the isopach map for the Miocene Pungo River Formation in Figure 3 shows that the unit thickens from the western, erosional updip limit on the flanks of the High to over 500 m on the eastern margin along the modern continental slope where it has been abruptly truncated. Miocene sediments occur only in the subsurface on the Coastal Plain, whereas they crop out or occur in shallow subcrop across the continental shelf in Onslow Bay. In the Aurora Embayment, the Pungo River Formation is underlain by Eocene fossiliferous and sandy limestones and is overlain by the extensive Pliocene Yorktown Formation and a complex sequence of highly dissected and discontinuous, terrigenous sand and mud units of Pleistocene age. In the Onslow Embayment, the Pungo River Formation is underlain by Oligocene sandy calcarenites and is overlain by a complex sequence of highly dissected and discontinuous marine carbonates of Pleistocene age dominated by fluvial channel structures (Hine and Stephen W. Snyder, 1985). The latter units generally lap over Miocene sediments in eastern and southern portions of Onslow Bay, forming major rock units along the shelf-slope break. A Holocene sand sheet forms a thin and discontinuous cover on older sediments throughout the continental shelf in Onslow Bay.

Miocene phosphorites and associated sediments formed in distinctive depositional environments that occurred within specific portions of the depositional cycles as they moved across the continental margin (Riggs and Mallette, 1990; Baker and Allen, 1990). Major phosphate deposits that occur on the emerged Coastal Plain (Figure 4) are geologically well known. Many workers, included in this bibliography, have studied the Pungo River Formation since Brown (1958) first described subsurface phosphorites from Beaufort County. However, these Coastal Plain deposits represent only the updip limit of a much larger Miocene section that extends seaward beyond the Coastal Plain to form a thick sediment wedge underlying most of the modern continental shelf and upper slope (Figure 3). Offshore phosphorites (Figure 4) were first noted by Luternauer and Pilkey (1967) and Pilkey and Luternauer (1967) and have been the object of numerous studies ever since as indicated by the extensive number of citations in this bibliography.

Figure 5 summarizes the results of extensive high-resolution seismic, lithologic, and biostratigraphic analysis of the Upper Cenozoic section on the continental margin. The Pungo River Formation consists of three third-order and at least 18 fourth-order depositional sequences (Figure 5). The biostratigraphic resolution of these third- and fourth-order seismic sequences and associated unconformites (Scott W. Snyder, 1988) is depicted in Figure 5. These seismic units have also been mapped throughout Onslow Bay (Hine and Riggs, 1986; Riggs et al., 1985, 1990; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1982) and their geologic distribution pattern is presented in Figure 6. Within the three third-order Miocene seismic sequences, at least 18 or more fourth-order

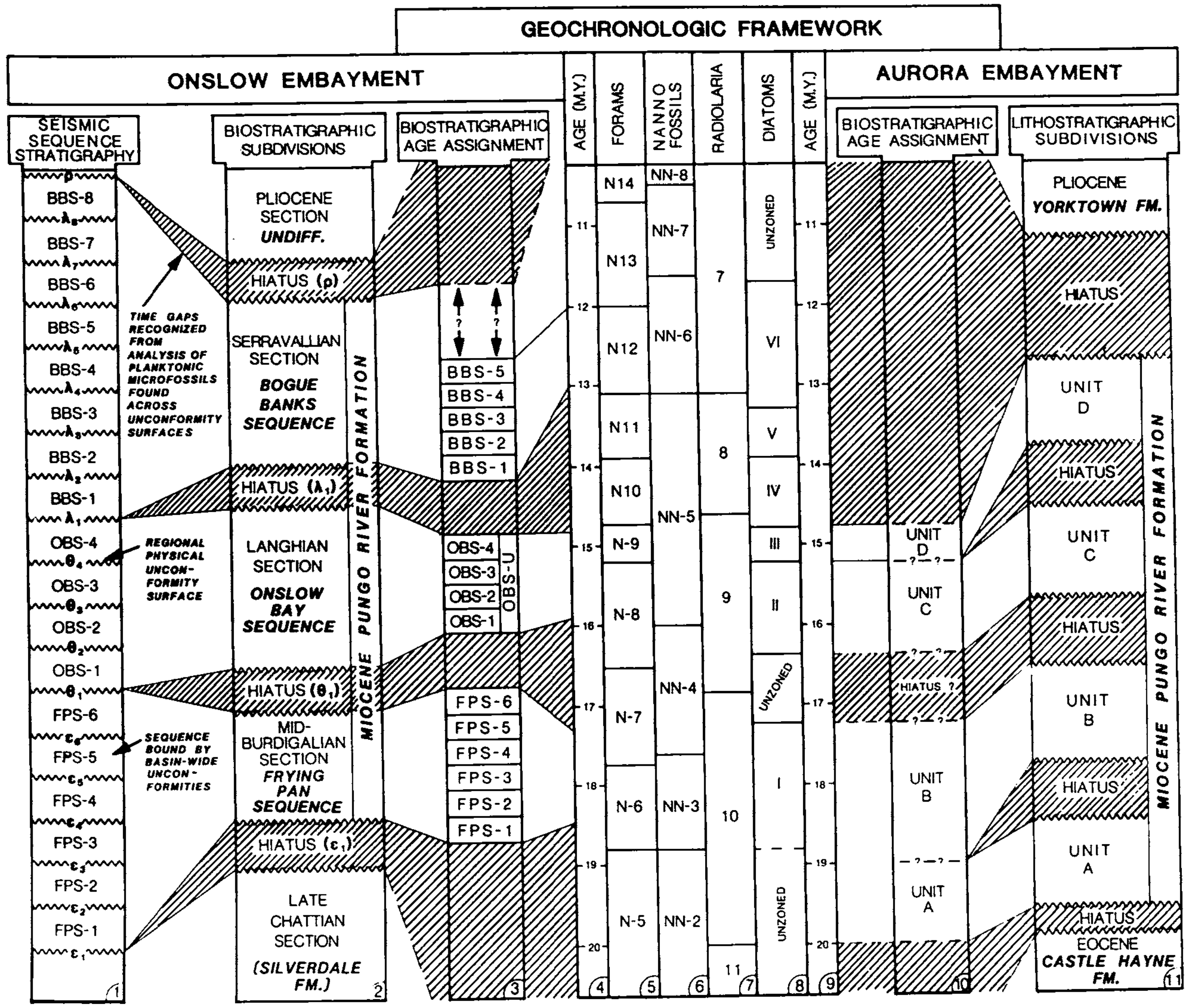

FIGURE 5. Three stratigraphic columns depicting the relationships between sequence stratigraphy, biostratigraphy, and geochronology of the composite Miocene chronostratigraphic framework of North Carolina. 1) Relative chronostratigraphic framework generated by identification of physical unconformities from seismic-reflection profiles (from Stephen W. Snyder, 1982). 2) Biostratigraphic sections for Onslow Bay and associated time-stratigraphic unconformities identified using planktonic microfossils (from Scott W. Snyder, 1988). 3) Biostratigraphic sections for Aurora Phosphate District and associated time-stratigraphic unconformities identified using diatoms (from Powers, 1987). 4) Geochronology of Miocene sequences and unconformities using microfossils to correlate to global planktonic biochrons and thereby place the sequences on the calibrated time scale of Haq et al. (1987) (from Stephen W. Snyder, 1982 and Scott W. Snyder, 1988). Modified from Riggs et al. (1990).

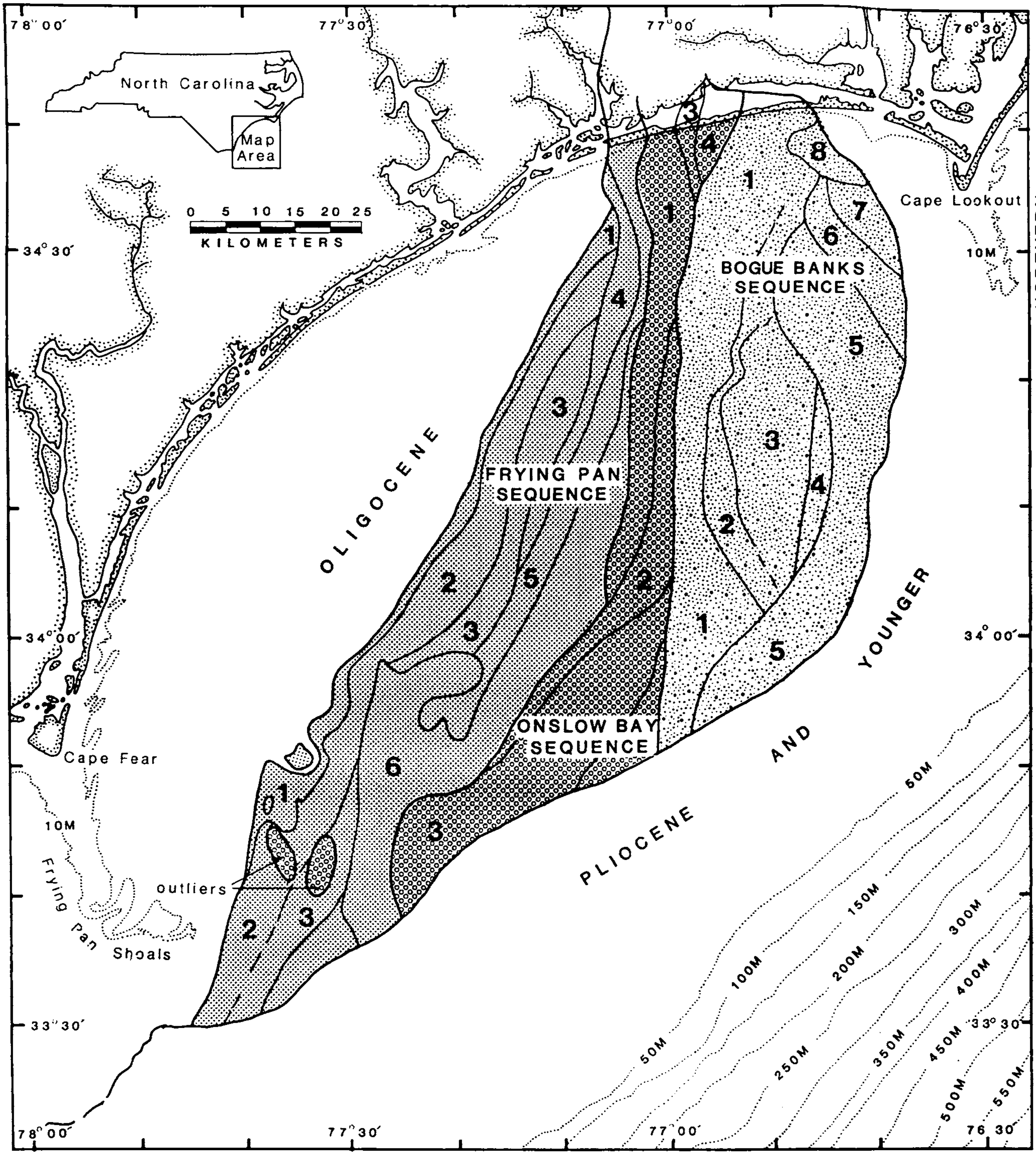

FIGURE 6. Outcrop distribution map of Onslow Bay, North Carolina showing 16 (of the 18 or more) fourth-order seismic sequences of the Miocene Pungo River Formation. Additional fourth-order seismic sequences have been mapped in the subsurface but do not crop out. Also, shown on the map are the three third-order seismic, biostratigraphic, and depositional sections referred to as the Frying Pan (FPS), Onslow Bay (OBS), and Bogue Banks Sections (BBS) of Mid-Burdigalian, Langhian, and Serravallian ages, respectively. Modified from Stephen W. Snyder (1982) by Mallette (1986)

depositional sequences have been mapped across the continental shelf as depicted in Figure 6. These fourth-order Miocene depositional sequences extend northward over and around the Cape Lookout High and into the Aurora Embayment. However, due largely to the lack of seismic control and very limited regional stratigraphic drilling, only four similar depositional sequences have been recognized beneath the Coastal Plain (Figure 5), and those are in the Lee Creek Mine of the Aurora Phosphate District (Riggs, 1984; Riggs et al., 1982; Scarborough et al., 1982).

Figure 7 integrates the final synthesis of physical stratigraphic relationships from seismic data with the biostratigraphic constraints. The relative Miocene sea-level curve for the North Carolina continental margin consists of a series of short-pulsed, high amplitude, fourth-order seismic cycles that are not biostratigraphically resolvable, superimposed on three, third-order biochronostratigraphic sections and their associated unconformities. Figure 7 correlates the third-order sequences with the second- and third-order Miocene eustatic sea-level cycles proposed by Haq et al. (1987). The pattern of third-order cycles appears to follow the general rise and fall of the second-order supercycle (Figure 7); the mid-Burdigalian section (FPS) is situated on the transgressive side, the Langhian section (OBS) is correlative to maximum highstand, and the Serravallian section (BBS) falls on the regressive side of the TB2 supercycle.

Synthesis of seismic, lithologic, and biostratigraphic data has lead to development of a proposed relative sea-level curve for the higher-order seismic sequences of the Miocene on the Carolina margin (Stephen W. Snyder et al., 1990). These complex fourth-order seismic sequences are interpreted to be the sedimentological and paleoecological responses to high-frequency climatic and oceanographic cycles. If this hypothesis is correct, the biogenic and authigenic sediments in these seismic sequences should contain the detailed records of continental margin paleoceanographic conditions through early to middle Miocene glacio-eustatic sea-level cycles. This hypothesis is presently being tested with the ongoing trace element and isotope geochemical studies.

SUMMARY OF THE MINERAL RESOURCES

The existing mineral industry of the Coastal Plain consists of two major types of resources. First are the surficial deposits of sand, gravel, shell, and crushed limestone used for either construction aggregate or for agricultural lime. For the most part, these deposits have low unit values and require modest, if any, beneficiation prior to use in local markets. Consequently, most mining operations are small scale, short term, low budget, and dependent on local economies.

The second major mineral resource that is recovered from the Coastal Plain is phosphate. The phosphate mining industry is part of a major world economic resource. Combined with the deposits in Florida, these resources constitute the world's largest phosphate producing district which supplies about 90% of total United States phosphate production and about 40% of total world production (Cathcart, et al., 1984). Because there is only one very large operating mine

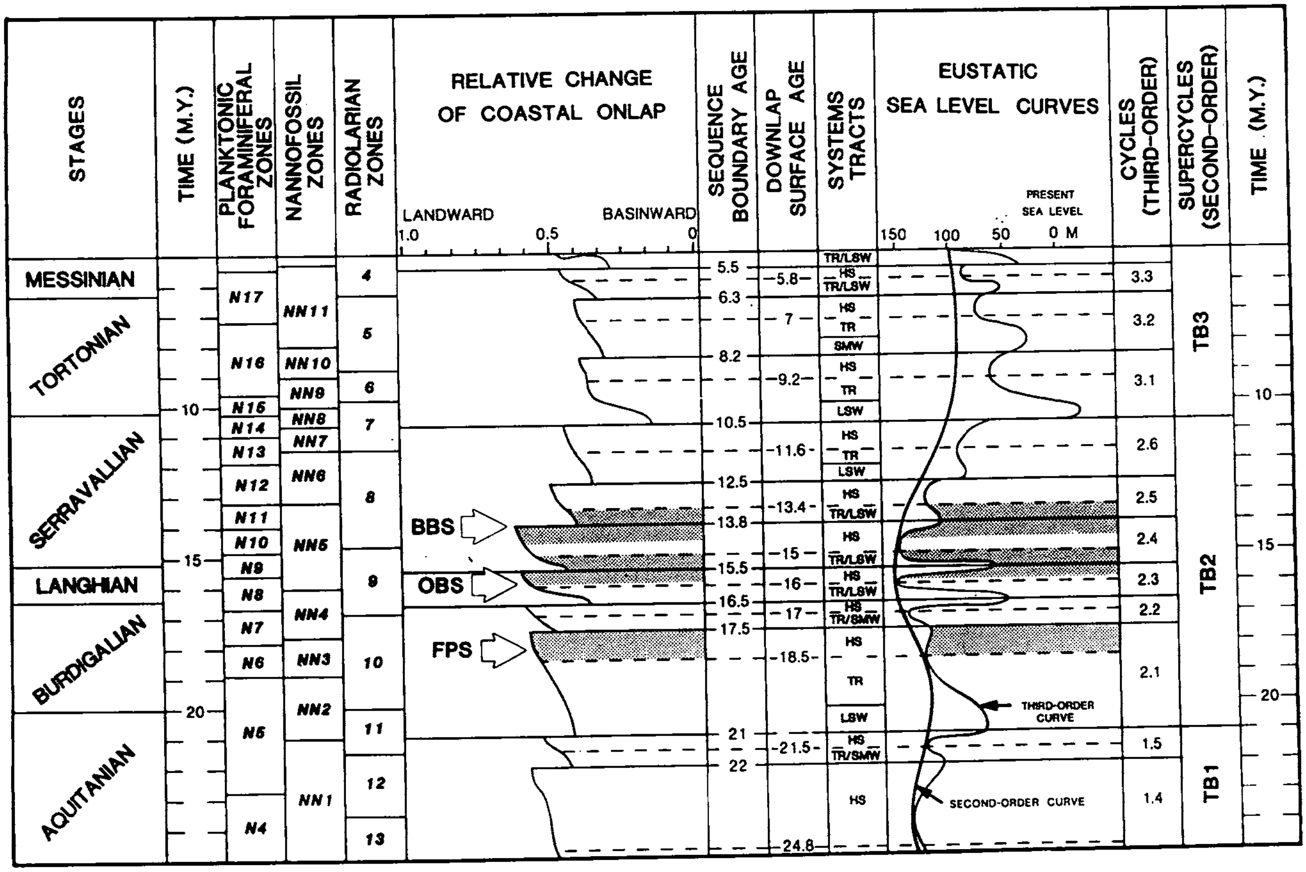

FIGURE 7. Miocene third-order depositional sections of North Carolina superimposed upon the global eustatic cycles proposed by Haq et al. (1987) and based upon seismic data of Stephen W. Snyder (1982) and biostratigraphic data of Scott W. Snyder (1988). The coastal onlap curve, eustatic sea-level estimates, juxtaposition of global biostratigraphic zonal schemes, and the calibration of these biochrons with absolute time are from Haq et al. (1987). Planktonic biostratigraphic zones are as follows: planktonic foraminiferal zones from Blow (1969 and 1979); nannofossil zones from Martini (1971); and radiolarian zones from Riedel and Sanfillipo (1978). Modified from Scott W. Snyder (1988).

in North Carolina, specific production statistics for the region are proprietary; however, in 1980, about 10% of domestic production came from the Aurora Phosphate District (Cathcart et al., 1984). In spite of the extremely large phosphate reserve situation for southeastern United States, mounting land use and environmental pressures cause much speculation about the future availability of land-based phosphate reserves. This expanding pressure on the world's most important phosphate deposits is generating increased interest in the extensive deposits that occur within deeper portions of the sediment basins or on the continental shelf (Riggs, 1986a; 1986b).

Heavy minerals constitute a third mineral resource that occurs locally in potentially economic concentrations, but is not presently being produced from the Coastal Plain. Recent land-based exploration activity by numerous companies has stimulated considerable discussion and anticipation of future heavy mineral mining.

At present, the hard mineral extraction industries in coastal North Carolina are located on the Coastal Plain. Consequently, these resources are fairly well known. Consideration of offshore resources must deal with the potential. Since continental shelves are geologically only submerged portions of the continent, it is logical to assume that the mineral potential should be comparable to that found on land, if not greater. However, detailed geologic investigation, exploration, and research in the marine environment is extremely expensive, technologically difficult, and generally a relatively "new" science.

Present limiting economic and technological restraints for recovery of marine minerals are rapidly being overcome by major technological advances in other fields such as channel dredging and offshore petroleum exploration and development. Also, the U.S. Department of Interior has become actively involved in developing regulations for the actual leasing and mining of undersea minerals within the U.S. Exclusive Economic Zone (EEZ) and Outer Continental Shelf (OCS) regions, underscoring the increased interest and anticipation of future development of important marine mineral resources. Major questions that must be addressed before any resources are actually recovered from the continental shelf include the following.

1. What is the quantity, quality and distribution of specific potential mineral resources (beach replenishment sands, heavy minerals, phosphate, and associated sediment components)?
2. What are the potential impacts of resource recovery upon water quality, associated benthic habitats, and other user groups such as various commercial and sport fisheries?
3. What is the habitat resiliency in response to specific mineral and energy resource exploitation?
4. What are the potential impacts of hard-mineral resource development upon the adjacent shorelines and land-based coastal activities?
5. What is the extent and variation in types of hardbottom habitats throughout the coastal system and what determines the great differences in their productivity? Is it possibile to increase hardbottom productivity through habitat modification and mineral resource exploitation?

Phosphates

The total amount of phosphorus that was precipitated from the ocean and occurs in Upper Cenozoic sediments of the southeast U.S. continental margin is staggering. Much of this phosphorus occurs in minor concentrations throughout many sediment facies and will never be of economic interest. However, within the Upper Cenozoic section, phosphate-rich sediments occur within three straigraphic units (Figure 4).

1. The early to middle Miocene Pungo River Formation is very extensive and occurs throughout the Aurora and Onslow Embayments.
2. The Pliocene lower Yorktown Formation occurs throughout the Aurora Phosphate District.
3. The Pleistocene-Holocene surface sediments occur in the Frying Pan Phosphate District of Onslow Bay.

Multiple depositional units within the Pungo River Formation contain extensive phosphorites with successively decreasing amounts of phosphate occurring in the lower Yorktown and Pleistocene-Holocene sediments, respectively. Vast deposits of the Miocene phosphate are currently being mined from the Pungo River Formation at Aurora, North Carolina.

Many workers have studied the Pungo River Formation since Brown (1958) first described subsurface phosphorites from Beaufort County. Phosphorites of the North Carolina continental shelf were first noted by Luternauer and Pilkey (1967) and Pilkey and Luternauer (1967). More recent seismic, paleontologic, sedimentologic, and stratigraphic studies have increased our understanding of phosphatic sediments throughout the continental margin. The results of this subsequent research are summarized in this volume with a compilation of all published abstracts.

Cathcart et al. (1984), DPRA (1987), Powers et al. (1990), Riggs (1989), Riggs and Manheim (1988), and Riggs et al. (1985) have summarized the size and extent of the potential phosphate resources within the North Carolina continental margin. The resource estimates vary widely depending upon the area included and the resouce category considered; regardless of what is included, the resulting estimates are all extremely large. Within the Aurora Embayment, estimates range from 10 billion upward to 21 billion tons of phosphate concentrate with grades between 29% and 32% P_2O_5. Within Onslow Embayment, estimates range up to 21 billion tons of phosphate concentrate with grades ranging from 23% to 31% P_2O_5 for phosphates that are lithologically and chemically similar to those currently being mined in the Aurora Phosphate District. Consequently, the future potential for development of these extensive phosphate resources is very great.

Sand and Gravel Aggregate

Major sand bodies, some containing extensive amounts of shell aggregate and heavy minerals, are present in many different forms in both the modern sediment environments and throughout the Upper Cenozoic sediments of the continental margin. These sand bodies are classically associated with coastal sequences deposited during former sea-level events that occur repeatedly within the Coastal Plain and continental shelf. Sand bodies formed in many different depositional regimes; the depositional processes within each regime determine the composition and geometry and include the following:

1. fluvial channel fill complexes;
2. beach face sand wedges;
3. inlet channel fill plugs;
4. surficial shelf sand blankets;
5. oblique shoreface shoals; and
6. cross-shelf shoals.

Preliminary stratigraphic and seismic studies have begun to define sand bodies within the Onslow and Aurora Embayments (Duane and Stubblefield, 1988; Hine and Stephen W. Snyder, 1985; Meisburger, 1979; Mixon and Pilkey, 1976; Riggs et al., 1985, in press; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1990; Swift, 1976; Swift et al., 1972).

Most active sand mining occurs within surficial deposits. Extensive high-resolution seismic surveys carried out during the past decade suggest that sand deposits are also abundant in the shallow subsurface throughout the continental margin. These deposits will become increasingly available as slurry mining and deep dredging technology are improved and as the demand increases for new sources of beach nourishment sands for long-term barrier island shoreline management schemes.

Heavy Minerals

Minerals such as ilmenite and rutile (titanium), monazite and xenotime (rare earths), zircon (zirconium), and gold are concentrated in placer deposits in ancient alluvial-fluvial sediments draining the Piedmont and Appalachian Provinces (Feiss et al., 1991). In addition, these deposits have been continuously reworked into both ancient and modern coastal systems in response to repeated fluctuations of sea level through geologic time. Consequently, many Upper Cenozoic fluvial and coastal sediments contain potentially economic deposits of heavy minerals.

Seismic surveys and associated drilling (Hine and Stephen W. Snyder, 1985; Riggs and Mallette, 1990; Riggs et al., 1985, 1990, in press; Scarborough et al., 1982; Stephen W. Snyder, 1982; Stephen W. Snyder et al., 1982, 1990) continue to demonstrate that ancient fluvial channel and barrier beach deposits are extremely important components in Upper Cenozoic sediment sequences throughout the North Carolina continental margin sediments. Many of these channel and beach facies are known to contain a poorly understood and yet unevaluated suite of heavy minerals.

Continental Shelf Hardbottoms

Onslow Bay is generally a sediment-starved shelf system dominated by hardbottoms. These hardbottoms represent the outcrop patterns of various Tertiary and Quaternary sediment sequences as they wrap around the Carolina Platform. Hardbottoms are important because they provide critical habitat for prolific benthic communities, which in turn attract economically significant reef fishes. However, there are many different types of hardbottoms and they are not equally productive; a large proportion of hardbottoms are seafloor deserts, whereas others are virtual oases. The compositon, morphology, and distribution patterns of the different Tertiary and Quaternary sediment sequences, along with the presence and mobility of a thin and scattered veneer of modern sand, are important factors that help determine community structure and total productivity of specific portions of the continental shelf system. Thus, hardbottoms represent a crucial nonliving resource that directly effects the economic value of associated living resources.

The North Carolina continental margin contains many potential energy and mineral resources. Recognition of this potential has focused increasing attention on hardbottoms during the past decade. An understanding of the dynamics of associated biologically important hardbottoms is critical for understanding the trade-offs and consequences associated with the management and exploitation of any of these potential resources. What are the consequences of mining beach replenishment sands or phosphate upon the associated hardbottoms and their fish resources? Are these conflicting uses of the margin diametrically opposed or are there trade-offs that could actually benefit both uses? Can the recovery of one resource (dredging of surficial sands for beach nourishment) actually create or improve the associated living resources (increase the availability, surface area, and morphology of hardbottoms for increased biomass production)?

REFERENCES CITED

Baker, P., and Allen, M., 1990, Occurrence of dolomite in Neogene phosphatic sediments, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 6, p. 75-86.

Blackwelder, B.W., 1980, Late Cenozoic marine deposition in the United States Atlantic coastal plain related to tectonism and global climate: Paleogeography, Paleoclimatology, Paleoecology, v. 34, p. 87-114.

Blow, W.H., 1969, Late middle Eocene to Recent planktonic foraminiferal biostratigraphy, in Bronniman, P., and Renz, H.H., editors, Proceedings of the First International Conference on Planktonic Microfossils volume 1: E.J. Brill, Leiden, The Netherlands, p. 199-421.

Blow, W.H., 1979, The Cainozoic Globigerinida: E.J. Brill, Leiden, The Netherlands, 1413 p.

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

Cathcart, J.B., Sheldon, R.P., and Gulbrandsen, R.A., 1984, Phosphate-rock resources of the United States: U.S. Geological Survey, Circular 888, 48 p.

Dillon W.P., Paull, C.K., Buffler, R.T., and Fail, J.P., 1979, Structure and development of the Southeast Georgia Embayment and northern Blake Plateau; preliminary analysis, in Watkins, J.S., Montadert, L., Dickerson, P.W., editors, Geologic and geophysical investigations of continental margins: American Association of Petroleum Geologists Memoir 29, p. 27-46.

Development Planning and Research Associates, Inc. (DPRA), 1987, The economic feasibility of mining phosphorite deposits of the continental shelf adjacent to North Carolina: Manhattan, Kansas, unpublished company report No. 3707.000 for the U.S. Department of Interior, Minerals Management Service, 166 p.

Duane, D.B., and Stubblefield, W.L., 1988, Sand and gravel resources: U.S. Atlantic continental shelf, in Sheridan, R.E., and Grow, J.A., editors, The Atlantic Continental Margin, U.S.: Geological Society of America, The Geology of North America, volume I-2, chapter 24, p. 481-500.

Feiss, P.G., Maybin, A.H., Riggs, S.R., and Grosz, A.E., 1991, Mineral resources of the Carolinas, in Horton, J.W., and Zullo, V.A., editors, The Geology of the Carolinas: Carolina Geological Society 50th Anniversary Volume, University of Tennessee Press, Knoxville, chapter 19, p. 319-346.

Gibson, 1982, Depositional framework and paleoenvironments of Miocene strata from North Carolina to Maryland, in Upchurch, S.B., and Scott, T.M., editors, Miocene of the Southeastern United States: Florida Bureau of Geology Special Publication No. 25, p. 1-22.

Gibson, T.C., 1983, Stratigraphy of Miocene through Lower Pleistocene strata of the U.S. Central Atlantic Coastal Plain, in Ray C.E. editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, No. 53, p. 35-80.

Grow, J.A., Mattick, R.E., and Schlee, J.S., 1979, Multichannel seismic depth sections and interval velocities over outer continental shelf and uppper continental slope between Cape Hatteras and Cape Cod, in Watkins, J.S., Montadert, L., and Dickerson, P.W., editors, Geological and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 65-83.

Haq, B.U., Hardenbol, J., and Vail P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1167.

Hine, A.C., and Riggs, S.R., 1986, Geologic framework, Cenozoic history, and modern processes of sedimentation on the North Carolina continental margin, in Textoris, D.A., editor, SEPM Field Guidebooks, Southeastern United States Third Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, p. 129-194.

Hine, A.C., and Snyder, Stephen W., 1985, Coastal lithosome preservation: evidence from the shoreface and inner continental shelf off Bogue Banks, North Carolina: Marine Geology, v. 63, p. 307-330.

Idris, F.M., 1983, Cenozoic stratigraphy and structure of the South Carolina lower Coastal Plain and Continental Shelf: Ph.D. Thesis, University of Georgia, Athens, 125 p.

Klitgord, K.D., and Behrendt, J.C., 1979, Basin structure of the United States Atlantic continental margin, in Watkins, J.S., Montadert, L., Dickerson, P.W., editors, Geologic and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists, Memoir 29, p. 85-112.

Mallette, P.M., 1986, Lithostratigraphic analysis of cyclical phosphorite sedimentation within the Miocene Pungo River Formation, North Carolina continental shelf: M.S. Thesis, East Carolina University, Greenville, N.C., 186 p.

Martini, E., 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation, in Proceedings of the Second Planktonic Conference, Edizioni Tecnoscienza, Rome, v. 2, p. 739-785.

Meisburger, E.P., 1979, Reconnaissance geology of the inner continental shelf, Cape Fear region, North Carolina: U.S. Army Corps of Engineers, Coastal Engineering Research Center, Ft. Belvoir, Virginia, Technical Report TP79-3, 135 p.

Miller, J.A., 1982, Stratigraphy, structure, and phosphate deposits of the Pungo River Formation of North Carolina: North Carolina Department of Natural Resources and Community Development, Geological Survey Bulletin 87, 32 p.

Mixon, R.B., and Pilkey, O.H., 1976, Reconnaissance geology of the submerged and emerged coastal plain province, Cape Lookout Area, North Carolina: U.S. Geological Survey Professional Paper 859, 45 p.

Luternauer, J.L., and Pilkey, O.H., 1967, Phosphorite grains: their application to the interpretation of North Carolina shelf sedimentation: Marine Geology, v. 5, p. 315-320.

Parsons, B., and Sclater, J.G., 1977, An analysis of ocean floor bathymetry and heat flow with age: Journal of Geophysical Research, v. 82, p. 803-827.

Pilkey, O.H., and Luternauer, J.L., 1967, A North Carolina shelf phosphate deposit of possible commercial interest: Southeastern Geology, v. 8, p. 33-51.

Popenoe, P., 1985, Cenozoic depositional and structural history of the North Carolina margin from seismic-stratigraphic analyses, in Poag, C.W., editor, Geologic Evolution of the United States Atlantic Margin: Van Nostrand Reinhold Co., New York, p. 125-188.

Powers, E.R., 1987, Diatom biostratigraphy and paleoecology of the Miocene Pungo River Formation, North Carolina continental margin: M.S. Thesis, East Carolina University, Greenville, N.C., 225 p.

Powers, E.R., Crowson, R.A., Riggs, S.R., Snyder, Stephen W., Snyder, Scott W., and Hine, A.C., 1990, Chemical characteristics and re-evaluation of the phosphate resource potential in Onslow Bay, North Carolina continental shelf: Marine Mining, v. 9, p. 1-41.

Riedel, W.R., and Sanfillipo, A., 1978, Stratigraphy and evolution of tropical Cenozoic radiolarians: Micropaleontology, v. 24, p. 61-96.

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

Riggs, S.R., 1984, Paleoceanographic model of Neogene phosphorite deposition, U.S. Atlantic continental margin: Science, v. 223, no. 4632, p. 123-131.

Riggs, S.R., 1986a, Future frontier for phosphate in the Exclusive Economic Zone--continental shelf of southeastern United States, in Lockwood, M., and Hill, G., editors, The Exclusive Economic Zone Symposium Exploring the New Ocean Frontier: National Oceanographic and Atmospheric Administration Special Publication, Rockville, Maryland, p. 97-107.

Riggs, S.R., 1986b, Future U.S. phosphate resources: a new perspective, in Bush, W.R., and McCarl, H.C., editors, Economics of Internationally Traded Minerals: Society of Mining Engineers, Inc., Littleton, Colorado, p. 153-159.

Riggs, S.R., 1989, Phosphate deposits of the North Carolina coastal plain, continental shelf, and adjacent Blake Plateau, USA, in Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F., editors, Phosphate Rock Resources: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume II, chapter 7, p. 42-52.

Riggs, S.R., and Belknap, D.F., 1988, Upper Cenozoic processes and environments of continental margin sedimentation: eastern United States, in Sheridan, R.E., and Grow, J.A., editors, The Atlantic Continental Margin, U.S.: Geological Society of America, The Geology of North America, volume I-2, chapter 8, p. 131-176.

Riggs, S.R., and Mallette, P.M., 1990, Patterns of phosphate deposition and lithofacies relationships within the Miocene Pungo River Formation, North Carolina continental margin, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 31, p. 424-443.

Riggs, S.R., and Manheim, F.T., 1988, Mineral resources of the U.S. Atlantic continental margin, in Sheridan, R.E., and Grow, J.A., editors, The Atlantic Continental Margin, U.S.: Geological Society of America, The Geology of North America, volume I-2, chapter 25, p. 501-520.

Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Snyder, Scott 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, p. 189-204.

Riggs, S.R., Snyder, Stephen W., Hine, A.C., Snyder, Scott W., Ellington, M.D., and Mallette, P.M., 1985, Geologic framework of phosphate resources in Onslow Bay, North Carolina continental shelf: Economic Geology, v. 80, p. 716-738.

Riggs, S.R., Snyder, Stephen W., Snyder, Scott W., and Hine, A.C., 1990, Stratigraphic framework for cyclical deposition of Miocene sediments in the Carolina Phosphogenic Province, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 29, p. 381-395.

Riggs, S.R., York, L.L., Wehmiller, J.F., and Snyder, Stephen W., in press, High frequency depositional patterns resulting from Quaternary sea-level fluctuations in northeastern North Carolina, in Fletcher, C., and Wehmiller, J.F., editors, Quaternary coasts of the United States: Society of Economic Paleontologists and Mineralogists, Special Publication.

Scarborough, A. K., Riggs, S.R., and Snyder, Scott W., 1982, Stratigraphy and petrology of the Pungo River Formation, central coastal plain of North Carolina: Southeastern Geology, v. 23, no. 4, p. 205-216.

Schlee, J.S., 1982, Summary report of the sediments, structural framework, petroleum potential, and environmental conditions of the United States middle and northern continental margin in area of proposed oil and gas lease sale no. 82: U.S. Geological Survey, Open-File Report No. 81-1353, 133 p.

Snyder, Scott, W., editor, 1988, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina continental shelf: Cushman Foundation Special Publication Number 25, 189 p.

Snyder, Stephen W., 1982, Seismic stratigraphy within the Miocene Carolina Phosphogenic Province: chronostratigraphy, paleotopographic controls, sea-level cyclicity, Gulf Stream dynamics, and the resulting depositional framework: M.S. Thesis, University of North Carolina, Chapel Hill, 183 p.

Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1982, Miocene seismic stratigraphy, structural framework and sea-level cyclicity, North Carolina continental shelf: Southeastern Geology, v. 23, p. 247-266.

Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1990, The seismic stratigraphic record of shifting Gulf Stream flow paths in response to Miocene glacioeustacy: implications for phosphogenesis along the North Carolina continental margin, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 30, p. 396-423.

Swift, D.J.P., 1976, Coastal sedimentation, in Stanley, D.J., and Swift, D.J.P., editors, Marine Sediment Transport and Environmental Management: New York, John Wiley and Sons, p. 255-310.

Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P., and Sears, P., 1972, Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America, in Swift, D.J.P., Duane, D.P., and Pilkey, O.H., editors, Shelf Sediment Transport Process and Pattern: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross Inc., p. 499-514.

Vail, P.R., and Mitchum, R.M., 1979, Global cycles of relative changes of sea level from seismic stratigraphy, in Watkins, J.S., Montadert, L., and Dickerson, P.W., editors, Geological and Geophuysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 469-472.

Ward, L.W., and Strickland, G.L., 1985, Outline of Tertiary stratigraphy and depositional history of the U.S. Atlantic Coastal Plain, in Poag, C.W., editor, Geologic Evolution of the United States Atlantic Margin: Van Nostrand Reinhold Co., New York, p. 87-124.

BIBLIOGRAPHY OF ABSTRACTS

M. Monographs, Book Chapters, and Journal Articles (53)

M1 Occurrence of dolomite in Neogene phosphatic sediments: Baker, P., and Allen, M., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 6, p. 75-86.

ABSTRACT

Dolomite is a common mineral in the phosphatic sediments of the Miocene-age Pungo River Formation of North Carolina, Hawthorn Group of Florida, Monterey Formation of California, as well as many other phosphatic sediments around the world. This dolomite forms as a product of early diagenesis in these organic-rich sediments. The dolomite is originally a poorly ordered, Mg-depleted protodolomite, but eventually undergoes a solution-reprecipitation reaction which increases its ordering and alters its chemical and stable isotopic composition. The high organic carbon contents of these sediments are necessary to promote microbial sulfate reduction. Sulfate reduction is the dominant process of organic carbon mineralization in these sediments, liberating the organically-bound phosphorus to solution to allow apatite precipitation. Sulfate reduction also elevates pore-water alkalinity and removes dissolved sulfate from the pore waters enabling dolomite formation.

The overall detrital sedimentation rate is one of the most important controls on the eventual fraction of dolomite (or apatite) forming in the sediments. If the rate of terrigenous sedimentation is too high, dolomite (or apatite) will be masked by detritus. Abundant dolomite formation requires low detrital sedimentation rates. Similarly, phosphorite (sensu stricto) formation does not necessarily require reworking or winnowing (suggested by many other workers), but it does require low detrital sedimentation rates.

Dolomite precipitation in phosphatic sediments may take place within the zone of sulfate reduction or in the deeper zone of methanogenesis. High abundances of dolomite in a sediment require that most of this dolomite formed at shallow burial depths. Phosphate precipitation occurs shallower and faster than dolomite precipitation. Most of the apatite in a phosphorite deposit precipitates within a few centimeters of the sediment-water interface in the uppermost zone of sulfate reduction. Small amounts of apatite may precipitate at greater depths. In most cases, dolomite precipitation must post-date apatite precipitation.

The stable isotopic compositions of apatites and dolomites originally reflect the environment of authigenesis. When buried, however, both minerals undergo diagenetic isotopic exchange reactions with the pore waters. This exchange obscures the interpretation of the environment of authigenesis based solely on stable isotopic analysis.

M2 Preface for Neogene to Modern Phosphorites: Burnett, W.C., and Riggs, S.R., editors, 1990, Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, 464 p.

PREFACE

History of IGCP project 156 - Phosphorites

Phosphate Deposits of the World is a series of multi-author volumes summarizing the results of an international research program on phosphate deposits (IGCP Project 156). The International Geological Correlation Program (IGCP) was jointly established by UNESCO and the International Union of Geological Sciences (IUGS) in 1972 in order to facilitate the acquisition and distribution of knowledge of mankind's resources and environment. A project to study sedimentary phosphate deposits (phosphorites) was formally accepted as IGCP Project 156 in early 1977.

The original Project Directors, Peter J. Cook and John Shergold (both currently affiliated with the Australian Bureau of Mineral Resources), organized the inaugural meeting in the form of a 'Field Workshop and Symposium'. This workshop, held in Australia in 1978, became the model for over a dozen similar meetings over the next 10 years. Scientists from a variety of relevant disciplines assembled, both in a seminar and field setting, for discussions concerning the origin of marine phosphorite. The success of the first meeting encouraged many others to become involved and eventually the Project had many hundred participants. Project 156 went on to become one of the largest, best known, and successful of all IGCP projects.

It was recognized early in the development of the Project that in order to be successful in addressing the wide range of questions relevant to an understanding of phosphorites, it would be necessary to set up thematic working groups. A total of four such working groups were ultimately established.

Working Group I - 'Proterozoic and Cambrian Phosphorites'
(Co-Chairmen: P.J. Cook and J.H. Shergold);
Working Group II - 'International Phosphate Resource Data Base'
(Co-Chairmen: A.J.G. Notholt and R.P. Sheldon);
Working Group III- 'Young Phosphogenic Systems'
(Co-Chairmen: W.C. Burnett and S.R. Riggs); and
Working Group IV - 'Cretaceous and Tertiary Phosphorites'
(Co-Chairmen: K. Al-Bassam, J. Lucas, and S. Sassi).

Each of the volumes in this series Phosphate Deposits of the World summarizes the results of one working group, with the working group chairman as editors.

Accomplishments of Project 156

Over the life of the project, there have been significant advances in the dual aims of facilitating an exchange of ideas and in formation, and encouraging research into all aspects of phosphate deposits. Some of the more significant achievements are as follows.

1. Holding of meetings. The Project has convened several very successful international field workshops and seminars, most of them at the site of a major phosphate deposit: Australia (1978), western USA (1979), Mongolian

People's Republic (1980), Mexico (1981), India (1981), People's Republic of China (1982), Morocco and Senegal (1983), USSR (1984), southeastern USA (1985), Venezuela (1986), Tunisia (1987), Jordan (1988), Peru (1988), and England (1988). These meetings have provided ample opportunity to visit the deposits at the outcrop and have allowed maximum interaction among the participants in an informal setting.

2. Encouragement of research. Although the Project never had the financial resources to directly sponsor research, it had an impressive catalytic role in the research funding of many of its participants. One outstanding example was 'PHOSREP', the Phosphate Research Project, held in Australia in 1987. Funding was provided by the Australian and US governments for a multidisciplinary, international team of scientists to carry out a comprehensive study of pre-Cambrian, Neogene, and modern phosphorites in Australia, both on land and offshore. This and other Project-related research has had a major impact on our understanding of the nature and origin of phosphate deposits.
3. Exchange of information. A considerable amount of information has been disseminated by participants in the Project through their publications in scientific journals and in special publications prepared by the Project for International Conferences. Phosphate Deposits of the World represents the major contribution in this area. In addition, the Project has published 19 issues of the IGCP 156 newsletter, distributed to over 700 scientists in 60 countries.
4. Training. The Project has provided training to many scientists from less-developed countries by ensuring that a significant number attend each of our international workshops, and by holding training courses on phosphate geology. This component of our Project has been very successful and has ensured that many geologists from developing countries have obtained firsthand knowledge of phosphate deposits.

Purpose and Content of this Volume

This volume, Neogene and Modern Phosphorites, the third in the series of four volumes on phosphate deposits of the world, is a collection of papers put together to present new information pertaining to the origin of Neogene and Modern marine phosphorites. However, a glance at the table of contents will show that we have not restricted the volume to only those papers dealing specifically with phosphorites, but have included several papers that deal with associated authigenic sediments (dolomite, clay minerals, etc.) and the prevailing oceanic environment during the Miocene, one of the most important phosphogenic episodes in the geologic record.

A major portion of the papers contained in this volume were presented at a 2-day symposium on the 'Genesis of Neogene and Modern Phosphorites' organized by Project 156. The symposium, held in Tallahassee, Florida in 1985, brought together some of the foremost experts in the world in many diverse areas geochemistry, paleoceanography, sedimentary petrology, and many other fields. The purpose of both the symposium and this volume is to summarize the most current thinking with respect to the origin of marine phosphorites.

This volume has evolved beyond a standard proceedings volume. We have added several components that have either developed since the conference was held or were not possible to present at that time. For example, several of the papers in Part II describe Neogene deposits (Cuba, Sea of Japan, etc.) that have never before appeared in the western literature.

We have organized this volume into four parts: (1) The Modern Setting - a description of upwelling processes in the modern ocean and examples of phosphorite formation in both upwelling and non-upwelling environments; (2) Modern and Neogene Phosphorites and Associated Sediments - contains new descriptions of Neogene deposits from several areas of the world, on land, offshore, and oceanic islands; (3) The Neogene Environment - contains insights into the environmental setting present in the world's oceans at the time of one of the most important phosphogenic episodes; and (4) Neogene Phosphorites of California and the Southeastern US - contains a detailed investigation of two of the best known Miocene age deposits including a special 4-part section on the latest research accomplished on the North Carolina continental margin. Together, these papers on phosphorites, associated sediments, and prevailing environments should offer the most up-to-date insights available on the origin of marine sedimentary phosphorite.

M3 Neogene phosphorites of southeastern U.S.A.: Burnett, W.C., Riggs, S.R., and Sheldon, R.P., 1985, Episodes, v. 8, p. 269-270.

TEXT

Although there is no global shortage of phosphate, the billions of tons of ore that have been identified are rather inequitably distributed. Morocco and the U.S.A. now dominate the phosphate export trade. Many countries, especially in Asia, Africa and Latin America, have no domestic production and lack hard currency to pay for phosphate imports. Accordingly, there is much under utilization of phosphate-based fertilizers by Third and Fourth World countries, those most in need of increasing food production. Clearly, the uneven supply of phosphate rock is one of the key factors preventing maximization of agriculture in many parts or the globe.

An IGCP project to address the question of world phosphate resources as well as scientific questions concerning the age, distribution, and origin of marine sedimentary phosphate deposits was initiated in 1978 by two Australian scientists, Peter Cook and John Shergold. Project 156 -- Phosphorites has since become one of the most active within IGCP, and field workshops, training courses and seminars have been held in Australia, U.S.A., India, Mongolia, China, Morocco, Thailand, and the U.S.S.R. The Project is currently in the process of producing a series of four volumes, entitled Phosphate Deposits of the World, which is to be published by the Cambridge University Press.

The 8th International Field Workshop and Seminar on Phosphorites, held recently in North Carolina and Florida, was attended by over 150 scientists from 40 countries. It was preceded by a short course for geologists from developing countries at East Carolina University on phosphate geology.

The phosphate resource potential of the southeastern U.S.A. is extremely large. However, mounting land use and environmental pressures cause considerable uncertainty regarding the availability of future land-based phosphate reserves, particularly in Florida. The result has been an increased interest in the deeper and lower-grade deposits of other portions of the southeast U.S., including the extensive offshore resources of the Atlantic continental shelf.

The first phase of the field trip was an examination of the deep and totally unweathered stratigraphic section in the recently developed Aurora, North Carolina phosphate district. Future potential of the newly discovered deposits on the continental shelf were considered during a cruise on board the National Science Foundation vessel R/V Cape Hatteras. Exploration techniques including geologic sampling, high-precision seismic profiling, and side-scan sonar were emphasized during this cruise. Also included was an aerial excursion, which permitted excellent views of the phosphate deposits together with the large-scale structures that have controlled their deposition. The geology of the modern and Pleistocene barrier island and estuarine coastal systems was also clearly visible.

In Florida the phosphatic sequences, which are regarded as originally similar to those in North Carolina, are altered by a major weathering profile. The group examined the least-weathered portion in drill cores from south Florida, and then traced the increasing degree of weathering in shallow mines of the updip area of central Florida. The extremely weathered portions were visited in the hardrock phosphate district on the Ocala Upland. Unraveling the stratigraphic and mineralogical complexities produced by the diagenetic processes of weathering is critical to an understanding of the depositional history of the central Florida deposits.

Following the field trip a symposium was held in Tallahassee, Florida, on "Genesis of Neogene to Modern Phosphorites". This was designed to synthesize knowledge concerning the southeastern U.S. phosphate system, compare it to other deposits, and discuss its origin in light of recent studies on modern ocean-floor phosphorites. Papers on modern phosphorite environments were followed by a review of the Neogene environment including its global paleogeography, the effect of changing conditions on the geochemical cycles of S, C, O and phosphate, and the relationships between changing climates, cyclic sedimentation, and the development of the extensive U.S. phosphatic sediments. The proceedings of the symposium will be published by Cambridge University Press.

Plans are currently being finalized for the next Project 156 Field Workshop and Seminar to be held in Venezuela, March 16-26, 1986. A special Project 156 symposium on "Cyclicity And Phosphogenesis" has also been planned for the 1986 International Sedimentological Congress to be held in Canberra, Australia, August 24-30. Further details of this and other Project activities are available from W. Burnett (Dept. Oceanography, Florida State Univ., Tallahassee, FL 32306, U.S.A.) or S. Riggs (Dept. Geology, East Carolina Univ., Greenville, NC 27834, U.S.A.), the current Project Leaders.

M4 A method for preparation of phosphate samples for oxygen isotope analysis: <u>Crowson, R.A., Showers, W.J., Wright, E.K., and Hoering, T.C., 1991</u>, **Analytical Chemistry, v. 63, no. 20, p. 2397-2400.**

ABSTRACT

A refined method for the preparation of phosphate samples for oxygen isotope analysis has been developed. Phosphate samples are digested in HF, purified using a strongly anion exchange resin, and then precipitated as silver phosphate using the Firsching method. Oxygen isotopes are then extracted from silver phosphate by reaction with bromine pentafluoride and converted to CO_2 in preparation for isotopic analysis using a ratio mass spectrometer. The procedure

has been optimized and analysis performed on standards ranging in size from 30 mg to less than 2 mg with a standard error of ± 0.05 per mil. Advantages of the refined silver phosphate technique over the established bismuth phosphate technique are 1) the relative simplicity of the method, 2) silver phosphate is not hygroscopic, and 3) ability to analyze very small samples (2 mg to 10 mg).

M5 Geology of the Aurora Phosphate District: Crowson, R.A., Snyder, Scott W., Riggs, S.R., and Mallette, P.M., 1985, in Snyder, Scott W., Riggs, S.R., Partin, B., Mallette, P., and Walker, R., editors, Eighth International Field Workshop and Symposium on Neogene Phosphorites of Southeastern United States, International Geological Correlation Program 156--Phosphorites, East Carolina University, Greenville, N.C., p. 17-32.

INTRODUCTION

The Aurora Phosphate District is an active mining district located in the coastal plain province and within ten miles of Aurora, North Carolina. The phosphate deposits occur in the Miocene Pungo River Formation and are situated within the Aurora Embayment, a Miocene depositional basin bounded to the north and south by paleotopographic highs. This mining district has been an important producer of phosphate fertilizer products since the opening of the Lee Creek Mine by Texasgulf, Inc. (TgI) in 1965. A second phosphate operation is currently being developed by North Carolina Phosphate Company (NCPC) adjacent to the TgI operation. Collectively, NCPC and TgI control all known economic phosphate deposits in North Carolina.

M6 Seismic reflection and side scan sonar profiling: Hine, A.C., 1985, in Snyder, Scott W., Riggs, S.R., Partin, B., Mallette, P., and Walker, R., editors, Eighth International Field Workshop and Symposium on Neogene Phosphorites of Southeastern United States, International Geological Correlation Program 156--Phosphorites, East Carolina University, Greenville, N.C., p. 84-94.

INTRODUCTION

By generating short duration acoustic pulses at set intervals from a device towed behind a vessel and by receiving these same pulses reflected from the seafloor and subsurface horizons, we can produce seismic reflection profiles which are the basis for making structural and stratigraphic interpretations. This is a very powerful and useful technique for it provides us with a continuous data set across a depositional basin, continental shelf, etc. However, since seismic reflection profiling is a remote sensing technique, it is limited in that we cannot directly determine lithologies. Through the imprecise art of seismic facies analysis, we can make inferences concerning lithology from seismic data. A drill hole, of course, provides a highly detailed lithologic data base. However, this understanding exists only at one point. Ideally, to understand the subsurface geology of an area, we must utilize the techniques of direct sampling (drilling, vibracoring) and indirect sampling/remote sensing (seismic reflection/refraction profiling, gravity, magnetics).

Side scan sonar profiling is fundamentally different from seismic reflection profiling in that acoustical pulses generated by the side scan sonar are used to map the surface of the seafloor, not to penetrate it. Hence, it is not a seismic device in that we are not using acoustic signals to vibrate the earth; we are not generating elastic waves to propagate through rocks and sediment. Side scan sonar is an excellent tool for generating seafloor maps for numerous types of geological purposes, finding wrecks, and locating pipelines. Depending upon the frequency, it can be used for detailed work (can reveal 1 cm diameter steel cable lying on the seafloor or for small-scale mapping (covering large areas: 60 km on either side of the ship).

M7 Geologic framework, Cenozoic history, and modern processes of sedimentation on the North Carolina Continental Margin: Hine, A.C., and Riggs, S.R., 1986, in Textoris, D.A., editor, SEPM Field Guidebooks, Southeastern United States Third Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, p. 129-194.

INTRODUCTION

This field trip provides the unique opportunity to take a large number of participants to sea on one of the newest research vessels owned by the National Science Foundation in order to (1) see how geologic oceanographic research is conducted along the continental margin; and (2) discuss the results of a six year, NSF funded research project that has involved a number of scientists from six universities. The overall objective of this research is to determine the Cenozoic geologic history of the lower coastal plain, continental shelf, and upper continental slope of the North Carolina continental margin. As you will see, this is an enormous undertaking integrating the talents of geological, physical, chemical and biological oceanographers all examining data collected from seven major cruises (many of them on the R/V Cape Hatteras) totalling over 116 days at sea. Table I below outlines the total data base from which the contributions in this field guide, the supplement to the field guide, and presentations on the ship out at sea are based. Figures 1 and 2 illustrate the distribution of seismic lines and vibracores in Onslow Bay.

Like many large projects, we started with specific objectives that have multiplied and evolved as time went on. Our original interest and still central research objective is to determine how, when, where, and under what conditions phosphate-rich sediments were deposited along the Carolina continental margin.

A major phosphate mining operation is located on the lower coastal plain at Aurora, North Carolina (Texasgulf, Inc) which extracts phosphate ore from the Miocene Pungo River Formation. In addition, synthesis of many boreholes located throughout the North Carolina coastal plain and studies of surface grab samples on the adjacent continental shelf by Pilkey and Luternauer (1967), lead to the conclusion that the Pungo River Formation extended seaward across the continental shelf of Onslow Bay.

Deposition of phosphate-rich sediments and other unusual authigenic minerals on the North Carolina sea-floor, as well as post-depositional diagenetic events, also occurred throughout the southeastern United States and many other places in the world. In Florida, the correlative lithostratigraphic unit is the

Hawthorn Group; together these Miocene sediments supply approximately 30% of the world's phosphate needs. The extent and size of the Miocene phosphate-rich units, the unusual suite of associated minerals, and the seemingly global nature of phosphate deposition during Pungo River/Hawthorn time provided the basis for our initial research.

In addition, we were perplexed by the well-accepted idea that phosphate deposits resulted from extensive and vigorous upwelling events. However, it was not clear how upwelling events could have been so prevalent along this particular continental margin in the past; established oceanographic and climatological models did not predict this. So,it became obvious that our research would have to explain major changes within the paleoceanographic phenomena along the margin through time. In addition, we would have to explain why the phenomena which led to phosphogenesis, occurred primarily during the Neogene but not earlier in the Tertiary nor later in the Quaternary to any comparable degree.

From this initial conceptual framework, the research in Onslow Bay has expanded geographically into the North Carolina estuarine/lower coastal plain and seaward to the shelf-edge and upper slope. It has also expanded stratigraphically to include much of the Tertiary and Quaternary section and modern marine processes to find appropriate analogs comparable to the ancient record. We have integrated the fields of seismic stratigraphy, lithostratigraphy, biostratigraphy, and geochemistry to generate numerous, closely time-spaced, paleogeographic, paleoceanographic, and paleoenvironmental reconstructions. Based upon all these products, we are beginning to develop solutions to the problems outlined above.

The field trip will consider the complex Geologic history of an extremely dynamic depositional and erosional system of the mid-Atlantic continental shelf and slope. Utilizing high-resolution seismic profiling, side-scan sonar, box cores and various surface samplers, we will make a geologic transect upsection through outcropping Paleogene carbonates, Neogene phosphates, Plio-Pleistocene carbonate hardgrounds, and siliciclastics of the Frying Pan Shoals. Weather permitting, we will then proceed across small shelf-edge reefs, examine erosional terraces and glauconite sediments on the upper slope, and continue onto the northern Blake Plateau. We will visit two different areas and deploy many of the remote sensing and direct sampling devices that we have found to be critical to our data collecting.

Unfortunately, we cannot take along nor deploy the vibracore which was the basis of nearly all direct sampling within the subsurface. This device takes up too much space, requires a significant amount of time to deploy, and is quite hazardous. For your information, we have included some photos of the vibracore operation in the field guide (see Ship Operations and Specifications).

During day #1, we will visit the outcrop site of the Miocene phosphate-rich sequences. The Frying Pan area (phosphate district) lies within south-central Onslow Bay as outlined on Figure 2 and on the field trip/cruise track map (Fig. 3). We will steam around Frying Pan Shoals, a large cape-retreat massif, to reach this area. Once there, we will traverse the gently southeast dipping and outcropping Tertiary stratigraphic section using high-resolution seismic profilers 1) a 3.5 kHz hull-mounted and 2) a towed system with electro-mechanical transducer with hydrophone. We will then back-track and deploy bottom grab sampler at sites chosen from examination of the seismic data. In addition, we will deploy the side scan sonar to examine the erosional topography of sporadically outcropping Quaternary limestones that unconformably overlie the

Tertiary sequences. Finally, we will retrieve blocks of these biologically productive carbonate hardbottoms using a rock dredge.

During day #2, we will steam to the continental shelf-edge and upper portion of the continental slope as outlined on the field trip/cruise track map (Fig. 3). Using a deeper penetrating seismic reflection profiling device (air gun) we will illustrate complex shelf progradation and erosion patterns that occurred during the Quaternary. Bottom samplers will illustrate the presence of a totally different sediment suite as compared to that seen during day #1.

During both days, a substantial amount of time will be used in getting to/from the area of interest. We plan to present a number of short lectures and demonstrations that will familiarize you with various oceanographic techniques and the geology of the Carolina continental margin.

Discussions on the field trip will include the shallow structural framework; shelf/slope processes of deposition and erosion produced by rapidly fluctuating sea level and Gulf Stream dynamics; alternating conditions of siliciclastic, phosphate, and carbonate sedimentation; Cenozoic depositional history; and the inter-relationship of Pleistocene and Holocene processes to Cenozoic sedimentation.

TABLE 1. DATA BASE FOR NORTH CAROLINA CONTINENTAL MARGIN RESEARCH PROJECT

CRUISE	SHIP	DATA**	DATES	DAYS
I.	R/V EASTWARD	VC, SS, HRS	May 1980	19
II.	R/V ENDEAVOR	VC, SS, HRS	Oct 1980	10
III.	R/V COLUMBUS ISELIN	VC, SS, HRS	May 1981	18
IV.	R/V CAPE HATTERAS	VC, SS, HRS	May 1982	19
V.	R/V CAPE HATTERAS	VC, SS, HRS, SSS	May 1983	17
VI.	R/V NITRO	Estuarine HRS	June 1983	20
VII.	R/V CAPE HATTERAS	BC, SS, HRS, SSS	Oct 1983	5
VIII.	R/V CAPE HATTERAS	BC, SS, HRS, SSS,TV	Dec 1984	4
IX.	R/V PEIRCE	BC, SS, HRS, SSS	Dec 1985	4

**VC = Vibracoring, BC = Boxcoring, SS = Surface Sampling, HRS = High-Resolution Seismic Profiles (Uniboom, Sparker, Airgun); SSS = Side-Scan Sonar Profiles; TV = Bottom TV Profiles

TABLE 2. SHIPBOARD DATA ACQUIRED ON 9 RESEARCH CRUISES		
TYPE OF DATA	UNITS	NUMBER
1. 9 Meter vibracores		144
2. Stratigraphic section cored (ave. 6.4 meters/core)	m	923
3. Pore-water samples		127
4. Shipek samples		340
5. Rock dredge hauls		26
6. Boxcores		18
7. High-resolution seismic subbottom profiles		
Uniboom	km	4,251
Sparker	km	917
3.5 kHz	km	7,643
1³inch air gun	km	208
8. Side-scan sonar profiles	km	340
9. Bottom TV profiles	hrs	6

M8 **Coastal lithosome preservation: evidence from the shoreface and inner continental shelf off Bogue Banks, North Carolina: Hine, A.C., and Snyder, Stephen W., 1985, Marine Geology, v. 63, p. 307-330.**

ABSTRACT

Seismic and vibracore data from the continental shelf as well as borehole data from an adjacent barrier island indicate that the migrating shoreface, responding to rising sea level, has nearly completely removed the entire coastal sedimentary record in northern Onslow Bay, North Carolina. This process was active throughout the Quaternary and even the late Tertiary as middle Tertiary sediments and rocks directly crop out on the sea floor in vast areas of this shelf sector.

Seaward of Bogue Banks (a Holocene barrier island located along northern Onslow Bay) seismic sequences have been truncated by the modern shoreface which extends to about 12 m depth. Correlations with borehole data on the island indicate that these sequences are Pleistocene and Holocene in age. The Holocene sequences contain numerous channels which are interpreted to be relict tidal inlets. However, none extends vertically lower than the shoreface indicating that landward translation of the shoreface would remove most of even the deepest Holocene coastal lithosomes, parts of the Pleistocene and even a portion of the Tertiary.

The middle and inner portions of the continental shelf have been incised by numerous channels. Channel facies are an important component of shelf sedimentary and stratigraphic sequences and comprise about one-third of northern Onslow Bay. Similar seismic infilling facies and vibracore data as well as the poor preservation potential of the tidal inlet throats indicate that the channels were lower coastal plain streams. The infilling sediments are mostly muds with

some sands and shells. Dates from shells via the amino acid racemization technique are Pleistocene in age.

These channels, with some having multiple infilling events, assume greater importance when one recognizes that essentially they alone hold the vast majority of the Quaternary record of numerous sea-level fluctuations.

M9 Diagnostic foraminifera and paleoecology of the Pungo River Formation, central Coastal Plain of North Carolina: Katrosh, M.R., and Snyder, Scott W., 1982, Southeastern Geology, v. 23, p. 217-232.

ABSTRACT

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

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

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

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

M10 Resistance to hurricane disturbance of an epifaunal community on the Continental Shelf off North Carolina: Kirby-Smith, W.W., and Ustach, J., 1986, Estuarine, Coastal and Shelf Science, v. 23, p. 433-442.

ABSTRACT

Hurricane Diana was stalled over the continental shelf of central North Carolina 11-13 September 1984 in the vicinity of a previously studied epifaunal community (30 m depth). Two research cruises following the hurricane used still camera and TV transects to obtain data which allowed an evaluation of storm-related effects on taxa of algae, sponges, corals, echinoderms and fish. Analysis of 35-mm slides suggested no effects attributable to the hurricane except observations of damaged coral heads and dead mussels. Analysis of television transects indicated no storm related changes from the previous study in frequency of occurrence of large epibenthic taxa. Hurricane damage was much less than anticipated and it is hypothesized that these coral reef-type communities are adapted to or structured by strong bottom currents generated by the frequent passage of gales and that the passage of hurricanes causes little additional stress.

M11 Preliminary stratigraphic report on the Pungo River Formation in Onslow Bay, Continental Shelf, North Carolina: Lewis, D.W., Riggs, S.R., Hine, A.C., Snyder, Stephen W., Snyder, Scott W., and Waters, V.J., 1982, in Scott, T.M., and Upchurch, S.B., editors, Miocene of the Southeastern United States: Southeastern Geological Society and Florida Bureau of Geology, Special Publication Number 25, p. 122-137.

ABSTRACT

The distribution of an extensive sequence of Tertiary phosphorites has been delineated in the shallow subsurface across the continental shelf of Onslow Bay, North Carolina. Extensive vibracoring and high resolution subbottom profiling (3.5 kHz, Uniboom, and sparker) have revealed a broad belt of phosphatic sediments that extend southwestward for 100 km from western Bogue Banks, across the shelf, to the outer portion of Frying Pan Shoals off Cape Fear. Locally along this zone, the Tertiary phosphorites have been and continue to be eroded, supplying reworked phosphate grains to the Pleistocene and Holocene sediments in concentrations averaging a few percent, with local areas containing 20% and occasionally reaching 90%. The reworked phosphate is dominantly fine grained, well rounded, very dark brown to black and is commonly found mixed with fine grained, well rounded, caramel colored phosphate grains.

The Tertiary section in Onslow Bay consists primarily of Oligocene or lower Miocene units unconformably overlain by sediments of middle Miocene age which are, in turn, unconformably overlain by either Pliocene or Pleistocene sediments. The Oligocene or lower Miocene sediments are predominantly moldic, sandy limestones and fine quartz sands. The middle Miocene consists of four major sediment sequences with facies variations within each. Three of these sediment sequences are found in northern Onslow Bay. These include (1) a barnacle hash,

muddy dolomitic barnacle hash, and barnacle-rich dolosilt; (2) interbedded clay, quartz sand, and chert-bearing dolosilt; and (3) fossiliferous muddy phosphorite sands, phosphatic quartz sands, and calcareous quartz sands. The fourth sediment group is found in southern Onslow Bay. This group consists of phosphorite sands, phosphorite quartz sands, muddy phosphatic quartz sands, and foram-rich phosphate and quartz-bearing mud. The Onslow Bay sediment sequence resembles that found in the Pungo River section of the mining district near Aurora, North Carolina. Preliminary analysis suggests that the foraminiferal faunas are similar.

Phosphorite units in northern Onslow Bay contain mostly medium brown intraclastic and skeletal phosphate grains in concentrations which average 10 to 15% but occasionally reach 20 to 25% of the total sediment. Phosphorite units of the Pungo River Formation in southern Onslow Bay contain dominantly dark brown pelletal phosphate grains which average 20 to 40% and occasionally constitute 50 to 65% of the total sediment.

M12 The U.S. phosphate industry: pressures for evolutionary change: Marvasti, A., and Riggs, S.R., 1989, Marine Technology Society Journal, v. 23, no. 1, p. 27-36.

ABSTRACT

The position of the U.S. phosphate industry as the dominant world producer is likely to change in the near future. The mining capacity of the industry from high-grade, shallow deposits on land has been rapidly diminishing in recent years. This paper examines the reasons for this decline and presents a comprehensive analysis of the problems faced by the U.S. phosphate industry. The economic aspect of these problems is particularly emphasized. The paper argues that survival of the industry and its ability to compete internationally depends upon its successful exploitation of either the deeper land-based phosphate resources or those of the southeastern U.S. continental shelf. However, development of new mining technologies such as hydraulic slurry methods is essential for the utilization of the new sources of supply.

M13 Potential for marine mining of phosphate within the U.S. Exclusive Economic Zone (EEZ): Marvasti, A., and Riggs, S.R., 1987, Marine Mining, v. 6, p. 291-300.

ABSTRACT

The U.S. phosphate industry has, historically, been the dominant world producer. However, the industry has recently been facing growing pressures by the exhaustion of low-cost land-based resources, foreign competition, unfavorable public policies resulting from environmental concerns, and attractiveness of alternative land uses. Even though phosphorus is not recognized as a strategic mineral, its important role in the production of inorganic fertilizer demands that special attention be given to the future of the industry.

Survival of the industry in the future, in part, depends upon its successful application of a suitable mining technology, such as hydraulic slurry mining, to either the deep, high-grade, land-based resources, or the offshore deposits within the Exclusive Economic Zone (EEZ). Potentials of the offshore phosphate deposits of southern California, Georgia and North Carolina are compared. Based on the available geological knowledge, this paper identifies the deposits on the North Carolina continental shelf, especially the Frying Pan Area, as the most promising for exploitation in the near future.

M14 Evolution of the Cape Fear Terrace: A complex interaction between the Gulf Stream and a paleo-shelf edge delta: Matteucci, T.D., and Hine, A.C., 1987, Marine Geology, v. 77, p.185-205.

ABSTRACT

A high-resolution seismic stratigraphic study of the Cape Fear Terrace (outer continental shelf off Cape Fear, North Carolina) combined with bio-lithographic data have yielded a complex chronostratigraphic framework of the Quaternary sequences that comprise this portion of the North American continental margin. The Cape Fear Terrace is one of six terraces or protuberances that form significant topographic irregularities along the South Carolina and North Carolina shelf-slope break.

The Cape Fear Terrace is situated upon an anomalous, point-source, prograding, shelf margin feature which has protruded out onto the upper slope throughout much of the Quaternary. This upbuilding/outbuilding followed a period of active submarine erosion in which the ancestral Gulf Stream and/or associated meanders cut an erosional path beneath the present shelf margin during the early Pliocene. The protuberance was originally constructed during a relative lowstand of sea level as a shelf-edge delta. Severe modification of this deltaic lobe occurred during a relative highstand of sea level as Gulf Stream activities began to more effectively modify the margin. The anomalous thick accumulation of shelf-edge sediments acted as a barrier to flow inducing complex flow patterns of the Gulf Stream causing preferential erosion on its down stream side.

Subsequent deposition may have resulted during more elevated highstands of sea level, as evidenced by the presence of active sand waves in the terrace protuberance region today. Once this shelf-edge bathymetric irregularity had been established, the Gulf Stream acted as a dynamic force inducing cellular flow structures within the shelf environment and enabling sediments to be transported seaward along the paleo-shoals complex.

M15 Comparison of sonographs taken before and after Hurricane Diana, Onslow Bay, North Carolina: Mearns, D.L., Hine, A.C., and Riggs, S.R., 1988, Geology, v. 16, p. 267-270.

ABSTRACT

High-resolution, side-scan sonar data collected from the middle continental shelf of Onslow Bay, North Carolina, before and after an intense storm (Hurricane Diana, September 11-13, 1984) were used to investigate the impact on this shelf surface. Wave hindcasting predicts that significant wave heights and periods

were 6 m and 10 s during the storm's passage, and horizontal water velocity at the sea-floor was 125 cm/s. Comparison of prestorm and poststorm sonographs revealed no measurable sea-floor changes. Distinct spatial patterns representing textural variations between Miocene muddy sand and coarse Holocene clean sand, as well as extensive areas of loose rock debris, appeared similar. The storm-dominated nature of this shelf surface results primarily from its sediment-starved existence and the equilibrium that has been reached with the region's ambient, high-energy setting.

M16 Radiolarians from the Miocene Pungo River Formation of Onslow Bay, North Carolina Continental Shelf: Palmer, A.A., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 163-178.

ABSTRACT

Samples from Onslow Bay vibracores containing siliceous microfossils were obtained for biostratigraphic and paleoenvironmental studies of radiolarians. Three early to middle Miocene radiolarian zones were recognized: Stichocorys wolffii Zone (Frying Pan Section), Calocycletta costata Zone (Onslow Bay Section) and Dorcadospyris alata Zone (Bogue Banks Section) on the basis of 22 age-diagnostic species.

An average of 16 taxa (of approximately generic level) per sample were observed in the Frying Pan and Onslow Bay sections, with subequal representation by spumellarians and nassellarians. Seven taxa were predominant (consistently > 5% of the assemblage) in the Frying Pan Section, six in the Onslow Bay Section. Radiolarians were too sparse in samples of the Bogue Banks Section for quantitative studies.

The assemblages generally consist of shallow-dwelling groups, although a few specimens of deep-dwelling taxa occur in one core from the Bogue Banks Section, perhaps suggesting strong upwelling or intrusions from deep levels of the Gulf Stream. Abundance and diversity of radiolarians are lower in the Onslow Bay sections than in correlative units of the mid-Atlantic Miocene, suggesting that different paleoenvironmental factors prevailed in each region.

M17 Diatom biostratigraphy and paleoecology of the Miocene Pungo River Formation, Onslow Bay, North Carolina Continental Shelf: Powers, E.R., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 97-161.

ABSTRACT

Diatom floras in Pungo River Formation sediments of the North Carolina continental margin indicate an age of late early to middle Miocene. Biostratigraphic age assignments of stratigraphic sections approximating third-order coastal onlap events (Frying Pan, Onslow Bay and Bogue Banks

Sections, from oldest to youngest) are based on zonal indicator species of Abbott's (1978) Atlantic Miocene Diatom Zones (AMDZ). The Frying Pan Section is assigned to Zone I (Burdigalian), the Onslow Bay Section to Zones II and III (Langhian) and the Bogue Banks Section to Zone VI (Serravallian).

Diatom assemblages indicate shallow marine deposition. Influx of oceanic waters varied through time, probably as a response to changes in sea level and intensity of upwelling currents. Predominantly benthic assemblages in the Frying Pan Section give way to greater proportions of planktonic species in overlying sections. Shelf waters cooled and upwelling intensified during deposition of the Bogue Banks Section. Preservation of the diatom assemblages varied as a function of the permeability of enclosing sediments and the composition of associated sediment particles.

M18 Chemical characteristics and re-evaluation of the phosphate resource potential in Onslow Bay, North Carolina Continental Shelf: Powers, E.R., Crowson, R.A., Riggs, S.R., Snyder, Stephen W., Snyder, Scott W., and Hine, A.C., 1990, Marine Mining, v. 9, p. 1-41.

ABSTRACT

In 1985, a preliminary evaluation of the phosphate resource potential for known deposits on the continental shelf in Onslow Bay, North Carolina, was published (Riggs et al., 1985). In 1987, an economic feasibility study by Development Planning and Research Associates, Inc. considered the economic potential for mining these phosphate deposits that occur in water depths between 10 and 35 m. The DPRA study utilized computer models to re-evaluate the previous analytical and seismic data of 1985. The present article formally publishes the chemical data base, structural contour and isopach maps, and a re-evaluation of potential phosphate resources for each of five phosphate bearing beds.

Approximately 20.7 billion tons of in-place phosphate concentrate are predicted to occur within two distinct phosphate districts in Onslow Bay. The Frying Pan phosphate district in southwestern Onslow Bay contains two phosphate-bearing beds (FPS-1 and FPS-2) predicted to contain approximately 10.5 billion tons of in-place phosphate concentrate with total sediment grades ranging up to 22.90% P_2O_5 and an adjusted average concentrate grade of 29.86% P_2O_5. The Northeast Onslow Bay phosphate district contains three phosphate bearing beds (BBS-1, BBS-2 and BBS-8) predicted to contain approximately 10.2 billion tons of in-place phosphate concentrate with total sediment grades ranging up to 9.77% P_2O_5 and an adjusted average concentrate grade of 30.69% P_2O_5. The Onslow Bay phosphates are lithologically and chemically similar to phosphates currently being mined in the nearby Aurora phosphate district, North Carolina.

M19 Phosphate deposits of the North Carolina Coastal Plain, Continental Shelf, and adjacent Blake Plateau, USA: Riggs, S.R., 1989, in Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F. editors, Phosphate Rock Resources: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume II, chapter 7, p. 42-52.

ABSTRACT

Phosphorite sediments occur within two geographic provinces of the North Carolina portion of the southeastern United States Atlantic continental margin (Fig. 7.1). The Aurora Embayment, which contains the Aurora Phosphate District, is situated within the coastal plain between latitude 35° and 36° N and longitude 76° and 77° W. The Onslow Embayment, which contains the Northeast Onslow Bay and Frying Pan Phosphate districts, is situated on the continental shelf between latitude 33° 40′ and 34° 40′ N and longitude 76° 40′ and 77° 40′ W. A third geographic province containing phosphorite sediments is a 22,000 km^2 area on the northern portion of the Blake Plateau (Manheim et al., 1980). These deposits are located almost due south of Onslow Bay, off the continental shelf and slope in 250 to 1000 m of water, and generally occur between 31° and 33° N and 77° and 80° W.

Three sequences of phosphate-rich sediments occur within the North Carolina continental margin and include the following (Fig. 7.2). (1) The lower to middle Miocene Pungo River Formation is very extensive and occurs throughout the Aurora and Onslow Embayments. (2) The Pliocene lower Yorktown Formation occurs throughout the Aurora Embayment. (3) The Holocene surface sediments occur in the Frying Pan district of Onslow Bay. The Blake Plateau phosphorites are interpreted by Manheim et al. (1980) to be lag deposits primarily derived from the Miocene phosphorites on the continental margin which were eroded by Gulf Stream processes.

M20 Model of Tertiary phosphorites on the world's continental margins: Riggs, S.R., 1987, in Teleki, P.G., Dobson, M.R., Moore, J.R., and von Stackelberg, U., editors, Marine Minerals: NATO Advanced Research Workshop, D. Reidel Publication Company, Dordricht, Holland, p. 99-118.

ABSTRACT

Shallow subsurface Tertiary sediments of mid-latitude, modern continental margins of the world contain a tremendously extensive and poorly known Neogene sediment sequence that has a high theoretical potential for containing major deposits of unconsolidated phosphate sediments. Reworked phosphates occurring in thin, Holocene surface sediments are important tracers for these shelf deposits which may crop out or more commonly occur in the shallow subsurface. This hypothesis should be tested by combining techniques of high-resolution seismics with detailed networks of vibracores on continental shelf areas with anomalous phosphate concentrations in the surface sediments. Ultimately, deeper core drilling is required to adequately understand the third dimension. Future mining and production will undoubtedly combine existing technology from the

offshore petroleum industry with new technology being developed within the mineral industry such as hydraulic slurry mining.

M21 Future frontier for phosphate in the Exclusive Economic Zone--Continental Shelf of southeastern United States: Riggs, S.R., 1986, in Lockwood, M., and Hill, G., editors, The Exclusive Economic Zone Symposium Exploring the New Ocean Frontier: National Oceanographic and Atmospheric Administration Special Publication, Rockville, Maryland, p. 97-107.

ABSTRACT

Research on the southeastern U.S. continental margin has lead to a series of important scientific developments which demonstrate the potential for extensive, high-grade phosphate deposits within the EEZ. 1. The Miocene was the major episode of phosphate formation. 2. Very thick sequences of Miocene sediments accumulated on the continental margin as part of this last major depositional episode. 3. Phosphate deposits occurring on the present coastal plain represent only the updip portion of the total volume of phosphate-rich sediments deposited during the Miocene; the greatest volume of sediments occurs in the subsurface of the continental shelf. 4. Known deep basinal and offshore phosphate deposits are very rich, fine-grained, unconsolidated phosphorites with only minor amounts of diluent siliciclastics. 5. Within the phosphogenic provinces, the formation of phosphate occurred through a broad range of depositional environments on the shelf and slope. 6. The Miocene was characterized by major sea-level cyclicity; each cyclic event caused the depositional environments and associated formation of phosphorites to migrate across the continental margin. 7. Recent research in Onslow Bay, North Carolina, delineated extensive submarine phosphate deposits in the shallow subsurface of the continental shelf. 8. The extensive, subsurface Miocene sediments on the continental shelves are very poorly known in most areas.

The phosphate resources of the continental shelves have not been considered seriously in the past because: 1. only small, very low-grade deposits occurring within surficial shelf sediments were adequately known; 2. extensive land-based resources have been available to large-scale open-pit mining; and 3. mining technology for large-scale production of deep, offshore resources, has been non-existent. Continued research and delineation of vast potential subsurface resources will lead to the development of new mining technologies (i.e., hydraulic slurry mining integrated with the advanced technology already being utilized in the offshore petroleum industry). Changing land-use patterns, environmental pressures on conventional mining, exhaustion of shallow high-grade resources, and increased pressure from expanding production in other countries throughout the world will force the serious consideration of the extensive marine resources and open the development of phosphates within the EEZ in the near future.

M22 Future U.S. phosphate resources: a new perspective: Riggs, S.R., 1986, in Bush, W.R., and McCarl, H.C., editors, Economics of Internationally Traded Minerals: Society of Mining Engineers, Inc., Littleton, Colorado, p. 153-159.

ABSTRACT

Extensive phosphate resources occur within the Miocene Hawthorn and Pungo River Formation which have not been considered in the past since they were poorly known and were not available to conventional mining. These resources include 1) deep phosphates that occur below 75 meters of overburden within major sediment basins throughout the southeastern coastal plain, and 2) offshore phosphates that occur on the continental shelf and within the U.S. Exclusive Economic Zone (EEZ). The future potential of these two vast resources will be realized with development of new mining technologies such as hydraulic slurry mining and integrated with advanced technology already being utilized in the offshore petroleum industry.

M23 Phosphogenesis and its relationship to exploration for Proterozoic and Cambrian phosphorites: Riggs, S.R., 1986, in Cook P.J., and Shergold, J.H., editors, Proterozoic and Cambrian Phosphorites: Cambridge University Press, Cambridge, England, Phosphorites of the World, volume I, chapter 25, p. 352-368.

INTRODUCTION

Most sedimentary rocks in the geological column and sediments on the seafloor contain very minor concentrations of phosphatic components (less then 0.3% P_2O_5). However, periodically through geological time, phosphorites (taken here as sedimentary rocks with 5% P_2O_5, or greater) have formed on the seafloor in response to specialized oceanic conditions and accumulated in sufficient concentrations to form major stratigraphic units of regional extent. The poorly understood prerequisites and processes that led to the origin of these anomalous phosphorite units include a multitude of complex variables which interact through time.

The formation and subsequent accumulation of phosphorites sufficient to form a major stratigraphic unit with the potential of becoming an economic deposit requires a specialized set of conditions in specific geological settings. The prerequisites for such phosphorite sedimentation define the phosphogenic system which is largely controlled by the tectonic setting. Since sediments are direct products of the regional tectonic framework and geological history, stratigraphic patterns represent the recorded response of the type, magnitude, duration, and spatial location of regional tectonic events or lack of such events. The tectonic framework largely determines the geographical latitude; the physical geometry of the deep-ocean plateau, continental margins, and epicontinental seas; global sea level position and pattern of fluctuations; and the associated oceanographic current regimes which determine the physical, chemical and biological conditions of the seafloor environments. The regional structural framework then determines the detailed sedimentary environments, their geometries, and the physical, chemical, and biological processes producing the phosphorites and associated sediment assemblages.

Phosphorites, a product of anomalous marine conditions, occur simultaneously with and adjacent to a group of additional anomalous sediments. These associated sediments become mixed and interbedded with the phosphates as the chemical systems pulse and oscillate with changing depositional conditions and fluctuating sea levels. This complex of sediments constitutes the phosphogenic assemblage and is outlined in Table 25.1. No single phosphatic sequence contains all of these associated minerals; each deposit is associated with some of them either as precursor or postcursor events, interbedded facies, or as contemporaneous and laterally equivalent depositional sequences. Different combinations of the associated sediments constitute the various phosphate assemblages, some of which are listed in Table 25.2. Each assemblage is a product of specific environmental conditions of deposition and reflects a specific genesis. If the complexities of phosphate genesis are to be unravelled, these associated sediments must be considered since they are integral pieces of the phosphate puzzle.

Although phosphogenic sediment systems represent abnormal conditions of sedimentation, these conditions have occurred often enough in the geological past to produce deposits which are not uncommon on a worldwide basis. The future economics of developing and recovering adequate supplies of phosphorus for the fertilizers necessary to feed the world are not going to be a function of whether phosphorus exists or not, but rather of its availability with respect to international political situations and of its minability. The world has abundant major phosphate deposits; it will be a long time before this critical commodity runs out. However, many individual countries do not have an adequate internal supply of fertilizer raw materials to meet their rapidly expanding needs. This is particularly true of many developing third world nations who, in addition, cannot afford to buy the raw materials on the open international market. Thus, it becomes increasingly imperative to refine and improve our understanding of the basic models for the origin and occurrence of phosphorite. This sophistication can only increase the probability of discovering 'new' phosphate deposits in those developing areas.

M24 Paleoceanographic model of Neogene phosphorite deposition, U.S. Atlantic Continental Margin: Riggs, S.R., 1984, **Science, v. 223, no. 4632, p. 123-131.**

SUMMARY

The Neogene stratigraphic section of the southeastern U.S. continental shelf-coastal plain system is characterized by (i) a series of major regional phosphogenic episodes; (ii) a strong spatial relationship between the structural or topographic framework and phosphate deposition; and (iii) distinct cyclical and regional patterns of deposition of the terrigenous carbonate and phosphate lithofacies. The complex depositional patterns are explained by a paleoceanographic model based upon the interaction of glacial eustatic sea-level fluctuations, associated changes in climate, and the dynamics of the Gulf Stream

in response to the bathymetric configurations of the continental margin during the past 20 million years.

M25 Patterns of Miocene phosphate sedimentation on the southeastern United States Continental Margin, in Non-Metallic Mineral Ores: Riggs, S.R., 1984, VNU Science Press, Proceedings of the 27th International Geologic Congress, v. 15, p. 201-222.

ABSTRACT

Neogene phosphate sedimentation on the southeastern United States continental margin is characterized by the following depositional patterns. 1. Major phosphogenic episodes occurred during early to middle Miocene, Pliocene, and possibly Pleistocene times. 2. Most depositional cycles consist of terrigenous, phosphate, and carbonate lithofacies which are repeated through time with distinct regional controls along the continental margin. 3. A strong spatial relationship exists between structural or topographic highs and adjacent depositional embayments. 4. Distribution of specific phosphate grain types is related to paleoenvironmental conditions through the depositional system.

M26 Upper Cenozoic processes and environments of continental margin sedimentation: eastern United States: Riggs, S.R., and Belknap, D.F., 1988, in Sheridan, R.E., and Grow, J.A., editors, The Geology of North America, volume I-2, The Atlantic Continental Margin, U.S.: Geological Society of America, chapter 8, p. 131-176.

INTRODUCTION

Most early studies of the U.S. Atlantic continental margin were dominated by the concept of 'layer-cake' stratigraphy with disruptions in continuity often explained by 'yo-yo' processes of basin faulting. Recent studies now demonstrate that these two concepts are not totally satisfactory in explaining the stratigraphic patterns of the past 24 million-year history of the Atlantic margin.

During the past two decades, increasing sophistication of such tools as high-resolution seismic stratigraphy, biostratigraphic time zonations, and absolute dating techniques have provided a detailed basis for interregional correlations and environmental interpretations of upper Cenozoic lithostratigraphic units. The coastal plain and continental shelf are now recognized as parts of a coherent geologic province on a passive plate margin that have responded as an integral unit to complex sets of rapidly changing environmental conditions. The resulting upper Cenozoic sediment record is characterized by extremely variable lithologies with complex geometries and which are extensively dissected by unconformities.

The large-scale structural framework produced by the early tectonic history of the Atlantic continental margin controlled subsequent regional patterns of upper Cenozoic sedimentation. However, detailed depositional histories have been more complexly interwoven with climatic change and climatically controlled processes of glaciation, deglaciation, and rapid glacio-eustatic sea-level fluctuations than with regional tectonism and structural processes. This realization necessitates the increased recognition of erosional processes as equal counterparts to depositional processes and as a major controlling factor in determining the final distribution and character of the partially preserved regional and local stratigraphic records.

Extreme climatic fluctuations and associated continental glaciation and deglaciation resulted in rapid changes in paleoceanographic processes throughout the upper Cenozoic (Vail and others, 1977; Matthews, 1984). These changes include: 1) fluctuation in global sea level, which causes oceanic waters to move on and off the continental margin; 2) interaction of changing sea level with continental margin bathymetry, which causes modification of the path, intensity, and processes of the Gulf Stream and associated currents; 3) different oceanographic water masses, which have varying physical and chemical characteristics, alternately dominate the margin; and 4) conditions of sediment deposition and accumulation that alternate with erosion and truncation by both submarine currents and subaerial processes. Changing climatic conditions also produce extensive latitudinal migration of climatic zones; modification of vegetative cover, weathering, and fluvial processes; and alternating episodes dominated by siliciclastic sedimentation with episodes of authigenic sedimentation and minor siliciclastic dilution.

Thus, continental margin basin development and sediment accumulation during the upper Cenozoic is largely the result of cyclical paleoclimatic and paleoceanographic conditions and processes that interact with the geometry of the margin and regional patterns of differential thermal subsidence through time. The shelf-slope geometry determines whether sediment erosion or deposition takes place and, if sediment is deposited, whether it accumulates as vertical accretion on the shelf or lateral progradation off the shelf-edge. Also, the modern sedimentary environments and sedimentary processes presently active within the province are similar to portions of the ancestral upper Cenozoic systems; however, they only represent momentary time slices within a continuously changing sequence of paleonvironments.

M27 Phosphate exploration and resource potential on the North Carolina Continental Shelf: <u>Riggs, S.R., Hine, A.C., Snyder, Stephen W., Lewis, D.W., Ellington, M.D., and Stewart, T.L., 1982</u>, **Offshore Technology Conference Proceedings, Dallas, Texas, v. 2, p. 737-748.**

ABSTRACT

An extensive network of high resolution Uniboom/sparker/3.5 kHz subbottom seismic profiles in combination with 9 m vibracores were obtained across the North Carolina continental shelf in Onslow Bay. The resulting data has delineated a depositional pattern of Neogene sediments around the east flank of the Cape Fear Arch. This broad southeast trending structural high, located on top of the older Carolina Platform, has controlled the deposition and distribution of Cenozoic units across the mid-Atlantic shelf. The Neogene section is dominated by the Miocene Pungo River Formation, a downdip thickening sediment wedge which dips east and southeast off the Cape Fear Arch. The Pungo River consists of numerous depositional sequences, each abruptly truncated by

an erosional surface and associated channels. The depositional sequences, which may reflect third- and fourth-order cyclical events within the mid-Miocene second-order transgressive cycle, are characterized by interbedded lithologies consisting of phosphorite sands, phosphatic foraminiferal muds, dolosilts, and calcareous quartz sands. Some phosphorite sands also occur in the Holocene sand sheet which forms a thin discontinuous cover on the Pungo River sediments in the Frying Pan Area.

The preliminary evaluation of phosphate resources in Onslow Bay has delineated several excellent prospects with a vast resource potential. The Pungo River Formation crops out in a northeast-southwest trending belt which is over 150 km long by 40 km wide and extends into the subsurface to the east and south. Shallow vibracores have penetrated 8 beds which contain significantly anomalous concentrations of phosphate, 5 of which can be considered potential phosphate resources. Based upon the preliminary stratigraphic, seismic, and chemical analyses, these 5 beds are estimated to contain 1.5 billion short tons of phosphate concentrate with grades between 28% and 30% P_2O_5 and a moderate to high resource potential. The other 3 beds are extensive units which contain minor concentrations of phosphate and have a low resource potential. This new continental shelf phosphate province will become technically available at a time in the near future when the rapidly expanding demand for fertilizers and agricultural products combined with the ever-increasing land-use and environmental pressure produces an unacceptable escalation in the cost of mining the land-based reserves.

M28 Cyclic deposition of Neogene phosphorites in the Aurora area, North Carolina, and their possible relationship to global sea-level fluctuations: Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Snyder, Scott W., 1982, Southeastern Geology, v. 23, no. 4, p. 189-204.

ABSTRACT

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

This sequence of upper Tertiary sediment units suggests a cyclical pattern controlled by global eustatic sea-level fluctuations. Each depositional unit, its carbonate cap, and the associated unconformable surfaces may correlate with

established third-order sea-level cycles of Vail and others (1977 and 1979). Units A, B, and C appear to represent the maximum transgressive portion of the second-order Miocene supercycle. Phosphate sedimentation was coincident with each of the third order transgressions, which culminated in carbonate sedimentation at the apex of each transgressive cycle. The magnitude of phosphate deposition in the Aurora Area increased with each third-order cycle to a maximum during the transgression forming the apex of the second-order supercycle. Unit D was deposited only over the eastern portion of the area as a regressive facies of the Miocene supercycle. The Pliocene Yorktown sediments were deposited during the next supercycle. The lower Yorktown phosphorites coincided with the transgression while the nonphosphatic upper Yorktown was deposited during the subsequent regressive phase.

M29 Patterns of phosphate deposition and lithofacies relationships within the Miocene Pungo River Formation, North Carolina Continental Margin: Riggs, S.R., and Mallette, P.M., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 31, p. 424-443.

ABSTRACT

From southern Florida through North Carolina, the Miocene section contains 1) abnormally high concentrations of phosphate; 2) an associated suite of authigenic minerals (dolomite, silica polymorphs, clinoptilolite) and organic matter; 3) regional patterns of phosphate, carbonate, and siliciclastic sedimentation; and 4) cyclical lithologic patterns produced by alternating deposition and erosion (Riggs, 1984). Data from the Miocene Pungo River Formation in North Carolina suggest that paleoenvironmental conditions producing these phosphorite sediment sequences changed dramatically and periodically in response to complex interactions of both global and regional paleoceanographic events during the Miocene.

M30 Mineral resources of the U.S. Atlantic continental margin: Riggs, S.R., and Manheim, F.T., 1988, in Sheridan, R.E., and Grow, J.A., editors, The Atlantic Continental Margin, U.S.: The Geology of North America, volume I-2, Geological Society of America, chapter 25, p. 501-520.

INTRODUCTION

Most geologic materials may be usable resources in some form and at some time, whether it be for general land fill and aggregate, beach replenishment, construction material, or as a source of metals and fuels. Thus, most natural materials occurring within the Atlantic continental margin are resources, defined as "materials, including those only surmised to exist, that have present or anticipated future value" (U.S.G.S., 1980). Whether a resource becomes a reserve or not (an economically recoverable commodity) depends upon the properties and economic values of that material, which are determined by the following factors:

(a) availability, concentration, and occurrence of the material; (b) methods of recovering and processing the commodity; (c) transportation costs of ore and beneficiated products; and (d) environmental setting and costs of permitting and mitigation. Also, the economics of a given mineral resource change dramatically in response to new technological advances, discoveries of new deposits, or as industrial and social demands change through time. An increasingly critical component associated with the economics for development of any mineral commodity, is a good geologic knowledge of the resource base.

At present, most hard mineral extraction industries of the Atlantic continental margin are located on the coastal plain (Fig. 1). Consequently, these resources are fairly well known and they will encompass a large portion of this section. Consideration of offshore resources must deal with the potential; since the continental shelves are geologically only submerged portions of the continent, it is logical to assume that the mineral potential should be comparable to that found on land. However, detailed geologic investigation, exploration, and research in the marine environment is extremely expensive, technologically difficult, and generally a relatively "new" science. Present limiting economic and technological restraints for recovery of marine minerals are rapidly being overcome by major technological advances resulting from offshore petroleum exploration and development. Also, the United States Department of the Interior has become actively involved in developing regulations for the actual leasing and mining of undersea minerals within the U.S. Exclusive Economic Zone (EEZ) and Outer Continental Shelf (OCS) regions, underscoring the increased interest and anticipation of future development of important marine mineral resources.

Those resources considered in this chapter (Fig. 1) include minerals that either have been recovered, are presently being recovered, or are known to occur in significant concentrations to be considered potential future resources. This chapter excludes petroleum, water, and sand and gravel resources (these resources are discussed by Mattick and Libby-French, Kohout and others, and Duane and Stubblefield, this volume).

M31 Paleoceanographic and paleoclimatic controls of the temporal and geographic distribution of Upper Cenozoic continental margin phosphorites: Riggs, S.R., and Sheldon, R.P., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 18, p. 207-222.

ABSTRACT

Phosphorite was formed during all major sea-level transgressions during the 67 million years of Cenozoic history. However, some periods were more important than others with respect to producing large volumes of phosphorites and preserving them in the geologic column. During the Upper Cretaceous, Paleocene and Eocene major episodes of phosphogenesis occurred within Tethys, a major east-west ocean, which produced extensive phosphorites throughout the Middle East, Mediterranean, and northern South American regions. By Middle Eocene, this circumglobal ocean had been destroyed by plate tectonic processes. During the rest of the Cenozoic, the north-south Pacific and Atlantic Oceans dominated global circulation patterns and phosphogenesis shifted to the bounding

continental margins. Phosphogenesis took place on small and local scales throughout the Upper Cenozoic; however, specific episodes of phosphogenesis have occurred on much larger scales that reflect global paleoclimatic and paleoceanographic events. These Upper Cenozoic episodes of phosphogenesis have the following general relationships: 1) they were closely linked with development of polar glaciation that began during the Upper Oligocene; 2) they occurred during early to mid-stages of transgression associated with second-order eustatic sea-level fluctuations; 3) they reached maximum development during the TB2 second-order sea-level cycle (upper lower to middle Miocene); 4) they were controlled on a regional basis by inter-relationships between the geologic setting, paleoceanographic processes such as boundary current dynamics, and the third- and fourth-order sea-level fluctuations; and 5) they occur extensively in the subsurface of modern continental shelf and slope environments with local to regional occurrences of the updip portions on adjacent coastal plains.

M32 Patterns of cyclic sedimentation of the Upper Cenozoic section, North Carolina Coastal Plain: Riggs, S.R., and Snyder, Scott W., 1986, in Textoris, D.A., editor, SEPM Field Guidebooks, Southeastern United States, Third Annual Midyear Meeting: Society of Economic Paleontologists and Mineralogists, p. 333-372.

PREFACE

The intent of this guidebook is to 1) provide a geological overview of cyclical Neogene and Quaternary deposits of the North Carolina Coastal Plain, including phosphatic sequences that most strikingly document lithologic responses to recurring changes in sea level; and 2) outline mining practices and environmental considerations related to the extraction of phosphate. The open-pit mine of Texasgulf, Inc exposes splendid stratigraphic section that will be supplemented by materials from drill cores located in the surrounding area. We hope that the following collection of papers will provide insight into the general geology, stratigraphy, paleontology and economic geology of this intriguing and complex succession of Upper Cenozoic sediments.

The first three papers describe the regional geologic setting (Hoffman), the basic mineralogy of phosphates (McClellan et al.) and the detailed geology of the phosphate mining district (Snyder, Scott W., et al.) Next is a series of papers describing the historical development of mining activities (Chamness), control of groundwater (Hird), mining procedures (Hird), utilization of spoils (Edwards) and environmental programs (Gilmore). The final paper, by Gilmore, describes specific points of interest at the Lee Creek Mine, briefly relating all of these topics to one another in order to present a unified picture of a complex, multifaceted industry.

M33 **Hardbottoms: their character and distribution in Onslow Bay, North Carolina Continental Shelf: Riggs, S.R., Snyder, Scott W., Mearns, D., and Hine, A.C., 1986, University of North Carolina Sea Grant College Publication Number UNC-SG-86-25, poster.**

INTRODUCTION

Hardbottoms are firm surfaces that form underwater mesas on the continental shelf. Most people picture the continental shelf as flat, shifting sands with sporadic rock outcroppings that attract fish. These outcroppings are actually edges of large mesas. Ancient rivers carved channels through these mesas to form edges called scarps when the continental shelf lay exposed during periods of lower sea level. Fishermen seek out the hardbottom scarp because fish are abundant there. The highest scarps are geologically young (tens of thousands of years old), attract the most fish and consist of pure limestone. Lower scarps are older (tens of millions of years old), and consist of impure limestone, sandstone or hardened clay.

Low-relief hardbottoms (scarps up to 0.5 m) rise just above a layer of moving sands. Marine life is more abundant on the scarps than in the surrounding sand bottoms. High-relief hardbottoms (scarps more than 2 m) are the most productive. Where hardbottoms stand above moving sands, many plants and animals attach to or bore into the scarps. Rock rubble eroded from the scarps provides additional habitats in front of the mesas for reef fish to congregate and feed. Sand ramps form a transition between the hardbottom mesas and the lower-lying sea floor. They form when sands are swept across a mesa, accumulate and bury the scarp. Interscarp highs are underlain by hardbottoms with a layer of shifting sand that scours the bottom and prevents attachment of many types of bottom organisms. Interscarp lows often consist of clay and clay-rich sands partially covered by shifting sands. A few burrowing animals live here, but mobile sands generally prevent most attached organisms.

M34 **Stratigraphic framework for cyclical deposition of Miocene sediments in the Carolina Phosphogenic Province: Riggs, S.R., Snyder, Stephen W., Snyder, Scott W., and Hine, A.C., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 29, p. 381-395.**

ABSTRACT

This paper, PART I of a four-part series, presents the general geologic setting for the Miocene phosphorites and associated sediments of the Pungo River Formation on the Carolina continental margin. It is a chronostrati-graphic overview of at least 18 fourth-order seismic sequences interpreted to be the product of high-frequency (<200 Ky), high-amplitude (>50 m), sea-level fluctuations during the Miocene. Subsequent papers of the series (Chapters 30 through 32) describe in detail the sedimentological responses, patterns of

environmental change, and complex history of deposition and erosion along the Carolina margin through these 18 or more sea-level events.

M35 Geologic framework of phosphate resources in Onslow Bay, North Carolina Continental Shelf: Riggs, S.R., Snyder, Stephen W., Hine, A.C., Snyder, Scott W., Ellington, M.D., and Mallette, P.M., 1985, Economic Geology, v. 80, p. 716-738.

ABSTRACT

High-resolution Uniboom, sparker, and 3.5 kHz subbottom seismic profiles, in combination with 9 meter vibracores from Onslow Bay, delineate a belt of Neogene sediments which crop out on the North Carolina continental shelf around the east flank of the mid-Carolina platform high. This broad, southeast-trending basement high has controlled the general distribution of Cenozoic sediment sequences within the mid-Atlantic continental margin. The Neogene section includes the Miocene Pungo River Formation, which thickens downdip to the east and southeast off the mid-Carolina platform high. The Pungo River Formation consists of three third-order and at least 21 fourth-order seismic depositional sequences, many of which are abruptly truncated by erosional surfaces and associated channels. These seismic sequences reflect third- and fourth-order eustatic sea-level cycles within the Miocene second-order transgressive sea-level cycle. The fourth-order seismic sequences appear to be equivalent to cyclic lithostratigraphic units characterized by interbedded phosphorite sands, phosphatic foraminiferal muds, calcareous quartz sands, calcarenites, and dolosilts. Some phosphorite sands also occur in the Holocene sand sheet which forms a thin and discontinuous cover on the Pungo River sediments in the Frying Pan phosphate district.

Preliminary evaluation of phosphate resources in Onslow Bay has delineated several potential economic prospects. The Pungo River Formation crops out in a northeast-southwest-trending belt which is 150 km long by 25 to 50 km wide and extends into the subsurface to the east and southeast. In two different areas within Onslow Bay, vibracores have penetrated five beds which contain anomalous concentrations of phosphate. Two beds within the Frying Pan phosphate district are estimated to contain 3.75 billion metric tons of phosphate concentrate with an average content of 29.2 percent P_2O_5. The other three beds in the northeast Onslow Bay phosphate district are extensive units with low to intermediate phosphate content within the total sediment (up to 9.8% P_2O_5). These three 'lean' deposits contain at least 780 million metric tons of phosphate concentrate with average P_2O_5 contents which range from 29.7 to 31 percent. Phosphate resources in the Frying Pan phosphate district have a moderate to high potential for economic development, whereas those in the northeast Onslow Bay phosphate district have a low potential for economic development. This newly discovered continental shelf phosphate province could become economically feasible to mine in the near future when rapidly expanding demand for fertilizers and agricultural products, combined with ever-increasing land-use pressures, produces an unacceptable escalation in the cost of mining land-based reserves.

M36 Stratigraphy and petrology of the Pungo River Formation, central Coastal Plain of North Carolina: Scarborough, A. K., Riggs, S.R., and Snyder, Scott W., 1982, Southeastern Geology, v. 23, no. 4, p. 205-216.

ABSTRACT

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

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

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

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

M37 Paleoenvironments: offshore Atlantic U.S. margin: Schlee, J.S., Manspeiser, W., and Riggs, S.R., 1988, in Sheridan, R.E., and Grow, J.A., editors, The Atlantic Continental Margin, U.S.: The Geology of North America, volume I-2, Geological Society of America, chapter 16, p. 365-385.

INTRODUCTlON

The U.S. Atlantic continental margin, which stretches 1,850 km from Georges Bank in the north to the Blake Plateau in the south, encompasses an area of 655,000 km^2. The margin comprises several sedimentary basins of different shapes with platforms in between (see Schlee and Klitgord, this volume). The basins appear to have begun their subsidence at about the same time and to have undergone similar rift and postrift phases of development that resulted in a similar sedimentary section (Schlee and Jansa, 1981). Our objectives in this paper are (1) to portray, at selected intervals, the paleogeography of the margin during the Mesozoic and Cenozoic, (2) to discuss the temporal development of the paleoshelf edge, and (3) to outline the major elements of the several different sedimentary regimes that have prevailed (rift, postrift, carbonate-clastic, and authigenic sediment accumulations).

The main sources of data are interpretations of multichannel seismic-reflection profiles (Dillon 1982; Dillon and others, 1983a; Grow and others, 1979; Schlee, 1981; Schlee and Fritsch, 1982; Schlee and others, 1985), released drill hole data (Scholle, 1977,1979,1980; Scholle and Wenkam, 1982; Poag, 1982a, 1982b; Libby-French, 1981, 1984), and Deep Sea Drilling Project (DSDP) data (Hollister and Ewing, 1972; Tucholke and Vogt, 1979; Benson and Sheridan, 1978; Sheridan, and Gradstein, 1983; Van Hinte and Wise, 1987; Poag and Watts, 1987). With few exceptions (Schlee, 1981; Schlee and Fritsch, 1982), published interpretations of offshore basins have been based on a detailed analysis of one or at best a few key profiles (Grow and others, 1979,1983; Poag, 1982a, b, 1985). Our approach in this chapter is to present interpretations in the form of eight time-slice maps with a brief discussion about data sources, paleogeography, and ties to adjacent areas.

During the construction of the Atlantic continental margin, several major phases of sedimentation have occurred. Simply stated, the Atlantic margin passed through an early rifting stage, an intermediate carbonate-platform stage, and a later clastic infill stage. These stages have resulted in distinctive patterns of sedimentation; thus we discuss each stage separately as a model of sedimentation: its geometry or shape, distinguishing seismic facies, paleogeography, rock types, distinctive unconformities, and rates of subsidence. These models show different parts of the entire margin, both along eastern North America, and along the conjugate Northwest African margin, based on the work of von Rad and others (1982).

M38 BSEM evaluation of carbonate diagenesis: benthic foraminifera from the Miocene Pungo River Formation, North Carolina: Showers, W.J., Lent, R.M., and Margolis, S.V., 1987, Geology, v. 15, p.731-734.

ABSTRACT

Backscatter scanning electron microscopy (BSEM) was used to evaluate microdiagenesis in biogenic carbonates of the Pungo River Formation, a phosphate-bearing, Miocene, continental shelf deposit in North Carolina. Results of this new high-resolution technique correlate well to the downsection $\delta^{18}O$ variation of three species of benthic foraminifera. This technique is useful in the evaluation of diagenesis prior to isotopic analysis for paleoclimatic and paleoceanographic purposes.

M39 Relationships between benthic foraminiferal assemblages and Neogene phosphatic sediments, North Carolina Coastal Plain and Continental Shelf: Snyder, Scott W., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 32, p. 444-464.

ABSTRACT

The Miocene Pungo River Formation and Pliocene Yorktown Formation record numerous episodes of cyclic sedimentation along the North Carolina continental margin. Pungo River sediments occur in the subsurface of the modern coastal plain and in outcrop-shallow subcrop across the modern continental shelf of Onslow Bay. Yorktown sediments crop out across the coastal plain but are best exposed in the quarry of Texasgulf, Inc.

Sediment cycles are largely siliciclastic, but some include phosphorites and/or carbonate caprocks. Presumably, phosphate-rich sediments were deposited in nutrient-rich, oxygen-depleted environments, whereas 'cleaner' quartzitic sands accumulated in well-oxygenated conditions. Benthic foraminiferal assemblages are consistent with this interpretation. Phosphatic horizons contain assemblages that are numerically dominated by species of *Bolivina*, *Bulimina*, and *Buliminella*. Muddy sediments with moderate phosphate content contain an abundance of species of *Florilus* and *Nonionella*. Such assemblages occur in modern seas where there are oxygen-minimum zones and sewage outfalls. Quartz and carbonate sands are predominated by species of *Cibicides*, *Valvulineria*, and *Hanzawaia*. Extant representatives exist in similar sediment types where bottom waters are well oxygenated.

The relationship between foraminiferal assemblages and phosphate content is not entirely predictable because other environmental variables affect foraminifera. However, assemblages are generally sensitive indicators of bottom-water mass conditions (i.e. nutrient and oxygen levels).

M40 Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Snyder, Scott, W., editor, 1988, Cushman Foundation Special Publication Number 25, 189 p.

PREFACE

With the development of detailed magneto-, chrono-, and biostratigraphic organizational schemes (Berggren and others, 1985; Bolli and others, 1985; Haq and others, 1987), geologists working on more limited regional and stratigraphic scales have a powerful framework within which to interpret their findings. Conversely, results from smaller-scale studies are now relevant to a broad spectrum of workers around the globe.

The meticulous attention to detail so essential to small-scale studies can, in turn, provide information that may be useful in refining global schemes. For example, the chronology and patterns of fluctuating sea levels (Haq and others, 1987) can be tested in order to distinguish eustatic from local effects. Although individual small-scale studies cannot justify modifying larger-scale models, their cumulative contribution eventually may be significant.

Miocene sediments beneath the North Carolina continental shelf record a complex history related to changes in the world ocean and to their local geographic setting with respect to changing circulation patterns along the ocean margin. Paleontological analyses, an essential element in reconstructing that history, are the focus of this volume. Samples are from vibracores (maximum length of 9 meters), but data from the shallow subsurface can be extrapolated into down-dip sections on the basis of high-resolution seismic analyses.

M41 Synthesis of biostratigraphic and paleoenvironmental interpretations of Miocene sediments from the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Snyder, Scott W., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 179-189.

ABSTRACT

The Miocene Pungo River Formation in Onslow Bay represents three episodes of deposition, each with an estimated duration of approximately 1 million years. The Frying Pan Section is middle Burdigalian in age (18.4 to 17.4 Ma), the Onslow Bay Section spans the Langhian (15.9 to 14.9 Ma), and the Bogue Banks Section is middle Serravallian in age (13.0 to 12.0 Ma). Each section approximates a third-order seismic sequence within second-order supercycle TB2 of Haq and others (1987).

Pungo River Formation sediments were deposited in a middle sublittoral to upper bathyal bathymetric setting. The Frying Pan Section in southern Onslow Bay contains phosphorites which accumulated in nutrient-enriched, oxygen-poor waters introduced by marine upwelling. To the north, clastic sediments accumulated in more oxygen-enriched bottom waters. The Onslow Bay Section comprises prograding clinoforms of siliciclastic sediments that accumulated in

high-energy, well oxygenated bottom conditions. Phosphorites in the Bogue Banks Section of central Onslow Bay coincide with a minor upwelling event, whereas mixed phosphorite-siliciclastic sediments in northern Onslow Bay correspond with the introduction of colder, well oxygenated waters, possibly from a northerly source.

M42 Overview of Neogene and Quaternary geologic history, North Carolina Continental Margin (Onslow Bay): Snyder, Scott W., and Riggs, S.R., 1989, in George, R.Y., and Hurlbert, A.W., editors, North Carolina Coastal Oceanography Symposium: NOAA, National Undersea Research Program, Research Report 89-2, University of North Carolina--Wilmington, p. 131-149.

ABSTRACT

Neogene and Quaternary sediment patterns on the Onslow Bay continental shelf are, in large part, the product of eustatic sea-level fluctuations. The lower to middle Miocene Pungo River Formation was deposited during second- order supercycle TB2 (Haq et al., 1987). At least eighteen fourth-order seismic sequences within the formation can be grouped into three third-order seismic sequences (Frying Pan, Onslow Bay and Bogue Banks), each of which corresponds to the maximum landward extent of a third-order coastal onlap event. Despite the influence of eustatic sea-level fluctuations on the depositional history of the continental shelf, not all known third-order coastal onlap events are represented by the Miocene sediments of Onslow Bay. In addition to relative position of sea level, factors such as topographic configuration of the shelf and flow path and intensity of the Gulf Stream influenced depositional-erosional patterns and the distribution of phosphatic and siliciclastic sediments. Explaining why specific onlap events are represented by deposits whereas others are not will require additional research. General lack of Pliocene deposits across the Onslow Bay shelf and in portions of the adjacent coastal plain region cannot be adequately explained solely by sea-level fluctuations. Gentle upward movement along the Mid-Carolina Platform High seems a more likely explanation for the present distribution of marine Pliocene deposits.

Quaternary deposits were also strongly influenced by high frequency fluctuations of sea level. Widespread carbonates deposited during interglacial marine transgressions were later altered and partially eroded by subaerial and fluvial processes during glacial regressive phases. Where dissected, the resulting carbonate hardbottoms are bounded by exposed rock scarps which support a prolific marine biota. Unconsolidated sediments in low areas between the hardbottoms are the site of secondary mineralization, including minor reprecipitation of phosphate dissolved from underlying Pungo River phosphorites.

M43 Geology of the Aurora Phosphate District: Snyder, Scott W., Crowson, R.A., Riggs, S.R., and Mallette, P.M., 1986, in Textoris, D.A., editor, SEPM Field Guidebooks, Southeastern United States, Third Annual Midyear Meeting: Society of Economic Paleontologists and Mineralogists, p. 345-357.

INTRODUCTION

The Aurora Phosphate District is located in the general vicinity of Aurora, North Carolina (Fig. 1). It encompasses the area of active mining, and it lies within the Aurora Embayment, a Miocene depocenter bounded to the north and south by paleotopographic highs (Riggs et. al, 1982). The District has been an important producer of phosphate fertilizer products since the opening of the Lee Creek Mine by Texasgulf, Inc. in 1965. With its 1985 purchase of North Carolina Phosphate Corporation, which had planned development of a tract adjacent to the existing Lee Creek Mine, Texasgulf gained control of all known economic phosphate deposits in the Aurora District. In general, economic deposits of phosphate in the North Carolina Coastal Plain occur within 10 miles of Aurora.

M44 Overview of seismic stratigraphy and lithofacies relationships in Pungo River Formation sediments of Onslow Bay, North Carolina Continental Shelf: Snyder, Scott W., Mallette, P.M., Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 1-14.

ABSTRACT

The Miocene Pungo River Formation of the North Carolina continental shelf (Onslow Bay) comprises at least 18 fourth-order seismic sequences that can be grouped into three larger-scale sections which correlate approximately with third-order coastal onlap events. Fourth-order seismic sequences generally correspond to discrete depositional sequences. Seven regional lithofacies occur within these sequences. Microfossil distributional patterns can best be understood within the context of this seismic and lithologic framework.

M45 Guidebook, Eighth International Field Workshop and Symposium on Neogene Phosphorites of Southeastern United States: Snyder, Scott W., Riggs, S.R., Partin, B., Mallette, P.M., and Walker, R., 1985, editors, International Geological Correlation Program 156--Phosphorites, East Carolina University, Greenville, North Carolina, 144 p.

PREFACE

The intent of this guidebook is to 1) provide a geological overview of Neogene phosphate deposits in the southeastern United States, and 2) outline mining practices and discuss associated geological and environmental considerations.

The first section of the guidebook discusses the basic mineralogy of phosphorites and estimates phosphate resources of the southeastern United States. Section two focuses on North Carolina. Topics relating to phosphate deposits on the coastal plain include the basic geological framework, the history of phosphate mining and basic mining procedures (with particular emphasis on specific geological/engineering problems and their solutions). Descriptions of the stops at Texasgulf's Lee Creek Mine relate all these topics to one another in order to present a unified picture of a complex, multifaceted industry. Discussion of North Carolina phosphates concludes with a section describing the offshore deposits in Onslow Bay. Section three deals with the phosphate deposits of Florida, beginning with the general geological and stratigraphic framework followed by more detailed descriptions of specific geographic areas or particular geological aspects of these deposits.

We hope that this format provides participants in the IGCP-156 Eighth International Field Workshop and Symposium with a clear and concise summary of Neogene phosphorites of the southeastern United States. Although much of the material presented herein is excerpted from previously published literature, some information is firsthand. Its presentation here is not intended to supersede publication in other, more formal scientific journals.

M46 Synthesis of phosphatic sediment-faunal relationships within the Pungo River Formation: paleoenvironmental implications: Snyder, Scott W., Riggs, S.R., Katrosh, M.R., Lewis, D.W., and Scarborough, A.K., 1982, Southeastern Geology, v. 23, no. 4, p. 233-246.

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.

M47 Sequence stratigraphy of Miocene deposits, North Carolina Continental Margin: Snyder, Scott W., Snyder, Stephen W., Riggs, S.R., and Hine, A.C., 1991, in Horton, J.W., and Zullo, V.A., editors., Geology of the Carolinas: Carolina Geological Society, 50th Anniversary Volume, University of Tennessee Press, Knoxville, chapter 15, p. 263-273.

INTRODUCTION

The primary objective of this paper is to summarize a chronostratigraphic interpretation of the Miocene section of North Carolina by integrating physical stratigraphic relationships with biostratigraphic information. The relative chronostratigraphic framework was generated through seismic sequence analyses (Stephen W. Snyder, 1982; Stephen W. Snyder and others, 1990), whereas biostratigraphic studies utilized planktonic foraminifers and calcareous nannofossils (Scott W. Snyder and others, 1988), diatoms (Powers, 1988), and radiolarians (Palmer, 1988). Biostratigraphic constraints utilized herein represent the maximum precision attainable by synthesizing information from all of these microfossil groups (Scott W. Snyder, 1988).

M48 Occurrence and biostratigraphy of planktonic foraminifera and calcareous nannofossils in Pungo River Formation sediments from Onslow Bay, North Carolina Continental Shelf: Snyder, Scott W., Steinmetz, J.C., Waters, V.J., and Moore, T.L., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 15-42.

ABSTRACT

Planktonic foraminifera and calcareous nannofossils recovered from Pungo River Formation sediments in Onslow Bay permit correlation of three stratigraphic sections, each of which approximates a third-order coastal onlap event, with standard ages: Frying Pan Section = middle Burdigalian, Onslow Bay Section = Langhian, and Bogue Banks Section = upper Serravallian. Integrated foraminiferal and nannofossil data also provide biostratigraphic constraints for some fourth-order seismic sequences: FPS-1 and FPS-2 = lower Zone N6, FPS-6 = upper N6 to lower N7, OBS-2 and OBS-3 = mid N8 to upper N9, and BBS-1 to BBS-5 = N12 through N14. The durations of hiatuses between successive third-order sections are approximately 1.0 to 1.5 Ma, whereas those between fourth-order sequences cannot be resolved biostratigraphically.

M49 Benthic foraminifera and paleoecology of Miocene Pungo River Formation sediments in Onslow Bay, North Carolina Continental Shelf: Snyder, Scott W., Waters, V.J., and Moore, T.L., 1988, in Snyder, Scott W., editor, Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina Continental Shelf: Cushman Foundation Special Publication Number 25, p. 43-96.

ABSTRACT

Of 104 benthic foraminiferal species identified from Miocene strata in Onslow Bay, 27 occur commonly enough to be useful in paleoenvironmental interpretations. Variations in the abundance and distribution of six species (Bolivina paula, Buliminella elegantissima, Valvulineria floridana, Lenticulina americana, Hanzawaia concentrica and Cibicides floridanus) account for about 84% of the total variance in benthic foraminiferal assemblages. B. paula and B. elegantissima thrive under conditions of nutrient enrichment and oxygen depletion. The other species thrive in well-oxygenated bottom waters. Biofacies, which are largely defined by the relative abundance of these six species, indicate that changing water mass properties, particularly with reference to nutrient and dissolved oxygen content, exerted control over Miocene benthic foraminiferal distributions.

Individual biofacies, each defined by cluster analysis, generally coincide with specific lithofacies, indicating that substrate type also influenced benthic faunal distributions. Lithofacies were related to some extent to water mass chemistry, as phosphate accumulated in nutrient-enriched, oxygen-depleted waters associated with coastal upwelling: siliciclastics predominated under well-oxygenated conditions. Hence, water mass properties and substrate type combined to partially control the species content and distribution of Miocene benthic foraminiferal biofacies. Other environmental factors and diagenetic processes obscured details of faunal-sediment relationships such that only generalized, larger-scale patterns remain.

M50 The seismic stratigraphic record of shifting Gulf Stream flow paths in response to Miocene glacio-eustacy: implications for phosphogenesis along the North Carolina Continental Margin: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, volume III, chapter 30, p. 396-423.

ABSTRACT

Miocene deposition along the North Carolina continental margin occurred in response to a global, second-order, high stand of sea level (TB2). However, the depositional evolution of this continental margin was completely regulated by multiple, high-frequency (100 to 300ky), high-amplitude (50 to 200m) sea-level fluctuations. Physical stratal relationships indicate the ancestral western boundary current (Gulf Stream precursor) traversed a lateral path tens of kilometers wide in response to each of these high-frequency cycles of sea-level

change. Moreover, the geometrics portrayed in regional Miocene outcrop-subcrop maps suggest the shifting flow-track positions also dictated the evolution and decay of local paleotopographic controls, the development of shelf embayments and basins, and also significantly influenced the sedimentary infill histories of these local depocenters.

Along the North Carolina continental margin, secular variations in location and flow configuration of the Miocene western boundary current appear to have been determined by an interplay between the position of sea level relative to the elevation of major bathymetric highs (obstructions). Important Miocene bathymetric barriers included the Charleston Bump Complex (CBC) and the Cape Lookout High (CLH). During relatively low sea levels, major boundary current frontal events initiated by the CBC resulted in steering the Gulf Stream seaward of the North Carolina margin. This stimulated shelf-margin growth and sediment drift-building episodes. Conversely, when sea levels were relatively high, the Gulf Stream bypassed barriers within the CBC and scoured the North Carolina shelf margin before being deflected eastward by the CLH farther downstream. Repeated scour associated with these higher stands of sea level eventually excavated a large shelf-margin basin (outer Onslow Bay Basin).

Persistent upwelling episodes resulted when the Gulf Stream had to steer seaward of topographic obstructions. Topographic steering originates from instabilities set-up via horizontal shear between streamlines in a boundary current as it swiftly flows past stationary bathymetric features. Common by-products of this type of frictional interaction are the initiation of topographic waves and the subsequent shedding of cyclonic eddies. The latter are characterized as shallow, warm-cored, frontal filaments separated from the main axis of the Gulf Stream by upwelled slope waters. Miocene flow-track maps show that the ancestral western boundary current had to steer around the Cape Lookout High several times. The sites of predicted upwelling episodes resulting from these deflection events appear to coincide with the organic- rich depositional regimes which ultimately led to phosphate mineralization within the Aurora Embayment. Although the link between the Cape Lookout High and the Aurora Phosphate District is now established, more work is needed to better define the relative timing between topographic steering, upwelling, and phosphogenesis within this system.

Repetitive lateral shifts by the Gulf Stream in response to multiple sea-level changes provided the foundation for the cyclicity observed in Miocene depositional and erosional patterns of North Carolina. More importantly, however, it was the relative position of sea level with respect to major bathymetric obstructions which controlled the position, flow dynamics, and therefore the influence of the Miocene boundary current on sedimentary patterns found in the Pungo River Formation.

M51 Miocene seismic stratigraphy, structural framework and sea-level cyclicity, North Carolina Continental Shelf: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1982, Southeastern Geology, v. 23, no. 4, p. 247-266.

ABSTRACT

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

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

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

M52 The impact of Hurricane Diana on the North Carolina Shelf: <u>Vaughan, N.D., Johnson, T.C., Mearns, D.L., Hine, A.C., Kirby-Smith, W.W., Ustach, J.F., and Riggs, S.R., 1987</u>, **Marine Geology, v. 76, p. 169-176.**

ABSTRACT

Intense storms, including hurricanes, are believed to have an important impact upon the biota and sediment cover on the continental shelf. Hurricane Diana crossed Onslow Bay, North Carolina, during September 1984 and provided an opportunity to examine its effect on the sea floor. An area in the bay transited by the hurricane had been surveyed previously by side-scan sonar, 3.5 kHz echosounding, and underwater television. We re-surveyed the area in November 1984 with the same techniques and collected box cores for sedimentary structure analysis. The post-hurricane survey yielded no unequivocal evidence of hurricane impact on the sea floor and, surprisingly, showed an abundance of seemingly delicate benthic organisms thriving on the impacted area. Sedimentary structures in the box cores included rip-up clasts and cross-laminations that are indicative of a dynamic sedimentary environment, but they could have formed during non-hurricane storm conditions. The lack of a dramatic signature on the sea floor from Hurricane Diana is attributed to the low sediment influx and frequent

occurrence of intense storms on the North Carolina shelf. These factors result in an "armored" depositional environment that shows little response to the passage of each successive storm.

M53 Planktonic foraminiferal biostratigraphy of the Pungo River Formation, southern Onslow Bay, North Carolina Continental Shelf: Waters, V.J., and Snyder, Scott W., 1986, Journal of Foraminiferal Research, v. 16, p. 9-23.

ABSTRACT

The Pungo River Formation in the Frying Pan region of southern Onslow Bay consists of six seismic sequences, designated FPS-1 to FPS-6. Each sequence represents genetically related strata bounded by unconformities which were traced and mapped throughout the North Carolina continental margin. Vibracores penetrating these sequences, reveal distinct diastemic contacts between successive sequences, indicating a discontinuous pattern of deposition. Sediment samples from FPS-1, FPS-2, and FPS-6 were available for this study. Biostratigraphic analyses denote a Burdigalian (late early Miocene) age for Pungo River sediments in this area. Sequences FPS-1, FPS-2, and the lower portion of FPS-6 (characterized by the co-occurrence of Globigerinatella insueta, Globigerinoides quadrilobatus altiapertura, and Catapsydrax unicavus) are assigned to planktonic foraminiferal Zone N6. The remainder of sequence FPS-6 (marked by the first appearance of Globigerinoides sicanus praesicanus, Globorotalia scitula praescitula, and G. acrostoma) lies within the early portion of Zone N7. When compared to global coastal onlap curves, Frying Pan Pungo River Formation deposits fall within the third order Miocene TM 1.4 transgression. The duration of hiatuses separating sequences FPS-1 to FPS-6 is less than can be resolved by biostratigraphy. If related to Vail's curve, these hiatuses must correspond to fourth- or higher-order sea level fluctuations within the larger scale TM 1.4 transgression.

BIBLIOGRAPHY OF ABSTRACTS

T. Theses and Dissertations (27)

T1 **The origin of dolomites in the phosphatic sediments of the Miocene Pungo River Formation, North Carolina: Allen, M.R., 1984, M.S. Thesis, Duke University, Durham, N.C., 50 p.**

ABSTRACT

The Miocene Pungo River Formation has been divided into four cyclic units in the Aurora Phosphate District of North Carolina. Eighteen similar units have been identified on the continental shelf off North Carolina (Riggs, 1984). Each unit begins with a terrigenous facies which grades upwards into a phosphatic facies and is capped by a marine carbonate facies. The carbonate consists of barnacle, foraminifera, and other shell fragments, calcite mud, and, in some units, dolosilt and dolomite mud. The dolomite occurs as dispersed euhedral rhombs which often have opaque or highly birefringent centers. X-ray diffraction and elemental analyses identify the dolomite as non-stoichiometric (42-48 mole % Mg) and poorly ordered.

Oxygen isotope ratios of the Pungo River dolomites range from $\delta^{18}O$ = +3.14 to +5.60 o/oo PDB. These values indicate dolomite formation in wholly marine porewaters. Carbon isotope values range from $\delta^{13}C$ = -4.35 to +1.01 o/oo PDB. These slightly negative values are interpreted to be a mixture of isotopically light carbon from organic matter and isotopically heavier carbon from precursor calcium carbonate.

The strontium, iron, manganese, and zinc contents of the Pungo River dolomites are low, averaging 226, 271, 32, and 14 ppm respectively. These low concentrations are believed to be indicative of dolomite precipitation in very shallow marine porewaters, within the zone of sulfate reduction. Sodium concentrations for these dolomites average 916 ppm.

T2 **Mineralogy and sedimentology of the clay-sized fraction, Miocene Pungo River Formation, North Carolina Continental Margin: Allison, M.A., 1988, M.S. Thesis, East Carolina University, Greenville, N.C., 130 p.**

ABSTRACT

The Miocene Pungo River Formation is a sequence of phosphatic sediments which ranges in age from middle Burdigalian to Serrivallian. This sequence occurs in outcrop and shallow subcrop on the continental shelf of Onslow Bay, North Carolina but occurs only in the subsurface on the adjacent coastal plain. XRD, SEM, EDX and chemical analysis of clay minerals in the Pungo River Formation indicate that smectite, illite, kaolinite and chlorite are of detrital origin, whereas palygorskite and sepiolite exhibit authigenic textures. Smectite and illite, the dominant clay minerals, always occur together in approximately equal proportions that remain constant across regional lithofacies and depositional sequence boundaries. Kaolinite and minor chlorite occur together in variable

concentrations. They are generally confined to muddy quartz sand lithofacies that were deposited on the shallow shelf, proximal to major clastic-sediment point sources. Palygorskite and sepiolite typically co-occur and are associated with dolomite-rich lithofacies. These Mg-clays appear to have formed penecontemporaneously with dolomite in oxygen-deficient, deep-shelf to upper-slope environments. The phosphorite lithofacies contains a non-distinctive, smectite-illite assemblage with minor amounts of other clays.

Clay mineral data support the following conclusions. 1) Upsection depositional patterns between shallow-shelf kaolinitic assemblages and deep-shelf Mg-clay assemblages reflect regressive portions of sea-level cycles. 2) Clay minerals occurring in lowstand intervals characterized by diagenesis during multiple Miocene sea-level events show no structural alteration. 3) Illite occurring in phosphatic and dolomitic lithofacies exhibits relatively better crystallinity, probably because the depositional environment supported fewer benthic organisms whose activities may structurally disorder this clay. 4) Scarcity of detrital 4-layer clays and lack of large-scale variations in clay mineralogy suggest that warm climatic conditions existed at least periodically on the adjacent continent from the late-early through middle Miocene.

T3 Isotopic composition of the Miocene phosphorite sediment sequence on the Carolina Continental Margin: a detailed record of glacio-eustatic sea-level cyclicity: Crowson, R.A., in progress, Ph.D. Dissertation, North Carolina State University, Raleigh, N.C.

T4 Nearshore rock exposures and their relationship to modern shelf sedimentation, Onslow Bay, North Carolina: Crowson, R.A., 1980, M.S. Thesis, East Carolina University, Greenville, N.C., 66 p.

ABSTRACT

The nearshore ocean floor (water depths of fifteen meters or less) in West Onslow Bay, North Carolina reflects a complex relationship between the carbonate rock exposures and the surrounding modern sediments. A limestone containing pelecypod molds and casts, probably the Pollocksville Member of the Belgrade Formation, with extensive interbeds of fossil oyster bioherms (Crassostrea gigantissima) is exposed on approximately 50% of the sea floor around New River Inlet.

Two major kinds of processes are presently acting upon this ancient rock surface to produce the modern topography, sediments and carbonate rock exposures. The dominant constructive processes are controlled by biologic agents which include vermitid gastropod reefs, encrusting algae, corals and sediment trapping bryazoans. The dominant destructive processes are controlled by the mechanical agents of waves and currents and by the biologic agents of boring pelecypods and polychates and burrowing crustaceans.

The results of the processes are: 1) highly irregular rock surfaces with steep landward facing scarps (up to 5 meters in relief) subparallel to the beach with large boulders at their base; 2) a series of vermitid gastropod reefs growing along, the crest of the scarps in the vicinity of New River Inlet; and

3) the production of a thin blanket of loose sediment that varies in texture from boulders to mud and is composed dominantly of limestone rock fragments, quartz sand, carbonate mud and a mixed assemblage of modern and fossil shell material. Thus, the modern processes operating on the rock surface result in distinct morphologic features and the production of sediments which have a strong internal heritage.

T5 Geochemical facies analysis and stratigraphic correlation of Miocene phosphorite beds in the Aurora district of North Carolina: Dolfi, R.M., 1983, M.S. Thesis, North Carolina State University, Raleigh, N.C., 87 p.

ABSTRACT

Seventy-seven samples of pelletal phosphorite from the Miocene Pungo River Formation have been analyzed for trace elements. Samples were collected from drill cores within and adjacent to the Aurora mining district in North Carolina. Trace-element concentrations have been determined by instrumental neutron-activation analysis.

Trace elements in individual drill cores display distinct vertical profiles which are correlative to lithology, particularly phosphatic laminae. Lateral correlation of elemental trends in adjacent drill cores is possible within part of the area studied. Absolute concentrations and shale-normalized patterns of the rare-earth elements help elucidate paleoenvironments of phosphogenesis. Correlation of rare-earth elements with uranium and thorium is interpreted to indicate the paleogeographic distribution of relatively oxidizing versus reducing regions during early diagenesis of the most phosphate-rich beds in the Pungo River Formation.

T6 Major and trace element composition of phosphorites of the North Carolina Continental Margin: Ellington, M.D., 1984, M.S. Thesis, East Carolina University, Greenville, N.C., 96 p.

ABSTRACT

The concentration of twenty-one major and trace elements (mainly transition metals) has been determined by inductively coupled argon plasma emission spectroscopy (ICAPES) on 114 samples of phosphate pellets, intraclasts, skeletal material, and microsphorite. Samples are from two major phosphate districts in North Carolina: 1) Aurora Phosphate District (APD) located in the coastal plain and 2) Frying Pan Phosphate District (FPPD) located in Onslow Bay on the continental shelf. Samples from the APD include representatives of the early (?) to early middle Miocene Pungo River Formation units A and B, the middle Miocene Pungo River Formation unit C, and the Pliocene Yorktown Formation unit LY. The early Miocene Pungo River Formation unit FPS-1 and Pleistocene/Holocene unit FP-H were sampled from the FPPD.

Descriptive statistics and common factor analysis (SAS) suggest that the different phosphate grain types are chemically distinctive. 1) Microsphorite grains contain the highest amount of included material (reflected by high Al,

Fe, Si, K, and Ti contents) and the smallest amount of carbonate fluorapatite (reflected by the lower P and Ca contents). 2) Skeletal grains contain small amounts of included material and the greatest amount of carbonate fluorapatite. 3) Intraclastic and pelletal grains are intermediate in composition with intraclastic grains more similar to microsphorite and pelletal grains more similar to skeletal grains. 4) Although carbonate fluorapatite is by far the dominant mineral phase, the abundance of many of the major and trace elements including Fe, Al, Si, K, Ti, As, Cr, Mo, Ni, and V are influenced by the clay mineral abundance. 5) Other phases directly affect major and trace element compositions as follows: iron sulfides (Fe), iron oxides (Fe, As, Mn, and Mo), organic matter (Cd, Zn, and Mo), and carbonate fluorapatite (P, Ca, Cd, and Zn).

Cluster analysis and descriptive statistics performed on pelletal grains suggest that specific phosphorite units exhibit unique major and trace element signatures. 1) Unit FPS-1 pellets are characterized by moderate concentrations of both major and trace elements. This, in combination with smooth surface textures and associated well preserved foraminifera, suggests that minimal post-depositional alteration has affected these grains. 2) Unit A and lower unit B in the APD exhibit relatively high concentrations of Al, Fe, Cr, and As. Abundances of these elements suggest an increased clay mineral content within the pellets; high major elemental abundances also correspond to higher clay contents within the total sediment. 3) Pellets from upper unit B and unit C in the APD are very similar in composition to those found in unit FPS-1 except that Cd and Zn concentrations are higher in the APD. Elevated Cd and Zn values may reflect enriched paleonutrient conditions at the time of phosphogenesis. 4) Pellets from unit LY in the APD exhibit high values for Mo, relatively high values for P, Ca, Fe, As, Cd, and Zn, and low values for Al and Si. Low Al and Si values indicate lower amounts of included material while elevated Fe and As values indicate the presence of iron oxides/hydroxides. Minor oxidation of these grains may be related to past or present subaerial diagenetic events. Elevated Mo, Cd, and Zn values may reflect unique paleoenvironmental conditions, secondary enrichments (iron oxides), or abundant organic inclusions. 5) Pellets from unit FP-H are characterized by elevated Fe and As and low Cd, Zn, and Mo values. It is suggested that these grains have undergone at least one episode of oxidation leading to gains in Fe and As with corresponding losses of organic matter.

T7 Carbonate petrology, diagenesis, sedimentology and geochemistry of the Miocene Pungo River Formation, Aurora Phosphate District, Beaufort County, North Carolina: <u>Foregang, J., 1987</u>, M.S. Thesis (not defended), East Carolina University, Greenville, N.C., 230 p.

ABSTRACT

The Pungo River Formation in the Aurora Phosphate District (APD) consists of four cyclically deposited depositional sequences, each characterized by an upper omission surface. These units are informally designated A, B, C and D in ascending stratigraphic order. Units A and B are late Burdigalian (late early Miocene) in age, units C and D are Langhian (middle Miocene) in age.

Differences occur in carbonate composition and diagenesis between depositional units; however, the lateral character within each unit is consistent throughout the APD. Carbonate sediments are composed of 1) calcitic lime mud,

2) biogenic skeletal material, 3) dolomite, and 4) local carbonate cements. All carbonate components are either low magnesium calcite (<2.5 mole % $MgCO_3$) or poorly-ordered, calcian dolomite with a mean trace composition of Sr = 260 ppm, Fe = 394 ppm, Mn = 20 ppm. Dolomite is the primary carbonate component in units A, B and D and is considered to be an early diagenetic product precipitated at or near the sediment-water interface in the marine phreatic zone within sediments undergoing organic matter diagenesis. Minor dolomite occurs in unit C and is texturally replacive of precursor fine-grained carbonate. This dolomite possibly formed via the mixed-water model of dolomitization. Diagenetic calcite cement and neomorphic textures are considered products of meteoric diagenesis.

Carbonate sediments range from unconsolidated to indurated units and occur as 1) laterally continuous beds capping depositional units; 2) thin interbeds within phosphorite and siliciclastic sands; 3) local, isolated nodules and lenses; and 4) subordinate components disseminated within phosphorite and siliciclastic sands.

Petrographic analysis reveals the following textures associated with calcite components: 1) pervasive development of molluscan-moldic porosity and later occlusion of porosity by sparite cementation, 2) intra- and intergranular sparite and skeletal bladed to blocky sparite cementation, 3) echinodermal syntaxial rim cementation, and 4) equant to subequant poikilotopic calcite cementation. The dolomite components show the following textures: 5) local dolomitization of precursor skeletal and non-biogenic carbonate, 6) intracrystalline dissolution of multi-zoned calcian dolomite which is compositionally controlled, 7) relict intracrystal porosity commonly filled with calcite cement, and 8) calcitization of dolomite grains occurring in burrow in-fill structures. Local silicification of carbonate components produces a later-stage textural fabric.

Carbonate sediment in the APD was deposited during high-frequency, forth-order glacioeustatic sea level fluctuations with durations ranging from 0.1 to 1.0 Ma. The mode of deposition and type of carbonate formed in the section may be related to the magnitude and duration of each sea level event, and to the position of that event relative to global eustacy.

T8 Uranium-phosphorus determinations for selected phosphate grains from the Miocene Pungo River Formation, North Carolina: Indorf, M.S., 1982, M.S. Thesis, East Carolina University, Greenville, N.C., 80 p.

ABSTRACT

The Aurora Phosphate District is located in the Central Coastal Plain of North Carolina. Phosphate production is from phosphorite sediments of the Pungo River Formation. This thesis evaluates the relationship between uranium content and phosphorus content within the phosphorite facies of the Pungo River Formation in terms of regional location, stratigraphic position, grain size, and grain type.

A total of 154 subsamples representing five core hole locations were examined for this study. They were obtained from 19 sediment samples representing units A, B, C, and D/DD of the Pungo River Formation and 3 sediment samples representing the Yorktown Formation. Subsamples consisted of phosphate grains selected from the 0ϕ, 2ϕ, and 4ϕ size ranges. Grains in the 0ϕ and 2ϕ

size ranges were further separated into intraclast, skeletal fragment, pellet, and discoid grain type groups.

Uranium and phosphorus contents have been determined by fluorometric and spectrophotometric methods, respectively. Uranium contents ranged from 5.1 to 285.9 ppm U. Phosphorus contents ranged from 23.25 to 38.22% P_2O_5. The combined mean uranium content was calculated to be 92.5 ± 27.4 ppm U. The combined mean phosphorus content was calculated to be 30.64 ± 0.84% P_2O_5.

There are no significant trends in the regional distribution of uranium and phosphorus in the study area. Phosphate grains from unit D/DD may be slightly depleted in uranium and phosphorus relative to underlying and overlying units. There is an apparent inverse relationship between grain size and mean uranium content. The mean uranium content was 71.6 ppm U for 0ϕ size phosphate grains; 82.3 ppm U for 2ϕ size phosphate grains; and 123.5 ppm U for 4ϕ size phosphate grains. The mean phosphorus and uranium contents of skeletal grains were slightly higher than those of the intraclast, pellet, and discoid grains.

The apparent differences which have been identified among the data as grouped by core hole, unit, grain size, and grain type are very slight. The differences exist within an overall context of extreme variance. Statistical comparisons show that the mean values for the particular subgroups are essentially the same.

T9 Trace element and stable isotopic trends associated with diagenesis of selected benthic foraminifers from Miocene sediments: Jones, W.E., 1988, M.S. Thesis, East Carolina University, Greenville, N.C., 150 p.

ABSTRACT

Analyses of the benthic foraminifers Hanzawaia concentrica (a probable epifaunal morphotype), Bolivina paula and Florilus pizarrensis (probable infaunal morphotypes) from a fourth-order seismic sequence (FPS-1) in the lower Miocene section of the Pungo River Formation, Onslow Bay, North Carolina, provide a record of the type and pattern of diagenesis. Scarcity of calcareous microfossils results in a less detailed sampling of the same foraminifers from Pungo River Formation Units A, B and C in the Aurora Phosphate District, Beaufort County, North Carolina. Trends in Sr/Ca ratios provide the most useful geochemical record of diagenesis. From south to north within FPS-1, Sr/Ca ratios decrease as both the intensity of recrystallization and the mean grain size of sediments increase, all of which reflects increased diagenesis toward an early Miocene point-source for siliciclastics. Ratios also decrease upward within the sequence along its entire extent, revealing a diagenetic profile in which the intensity of alteration diminishes downward from the overlying unconformity. Sr/Ca ratios from units in the Aurora Phosphate District are similar to those of Southern and Central Onslow Bay. Ratio values are lower for the infaunal morphotypes than for the epifaunal morphotype, suggesting Miocene pore-waters were lower in Sr/Ca than were bottom waters.

All three species show very little stratigraphic isotopic variation, so that trends upward within FPS-1 in Onslow Bay and within Aurora Phosphate District Units A, B and C are difficult to relate in any meaningful way to other

indicators of diagenetic intensity. Isotopic data are generally consistent with diagenesis in a marine pore-water environment.

T10 Foraminiferal paleoecology and biostratigraphy of the Yorktown and Pungo River Formations: Beaufort, Pamlico, Craven and Carteret Counties, North Carolina: Katrosh, M.R., 1981, M.S. Thesis, East Carolina University, Greenville, N.C., 161 p.

ABSTRACT

Benthic foraminiferal assemblages of the Pungo River Formation from the central North Carolina Coastal Plain indicate deposition in near-shore inner continental shelf to middle shelf environments.

In Beaufort and Pamlico Counties, part of the Aurora Embayment, faunas from the lower part of the formation (Units A and B) are dominated by Buliminella elegantissima, Caucasina gracilis, and Elphidium excavatum. Florilus pizzarensis, Cibicides lobatulus, Elphidium limatulum, Nonionella miocenica, Hanzawaia concentrica, and H. nipponica occur sporadically and are of secondary importance when present. High faunal dominance (averaging greater than 50%), low diversity values (Shannon-Wiener Information Function averaging 1.4), and the rarity of planktic foraminifera suggest that these units were deposited in nearshore, shallow water environments. With the exception of E. limatulum, dominant species from the upper part of the formation (Units C, D, and DD) are those of secondary importance in the lower units. Faunal dominance averages 33%, diversity values are moderate (averaging 2.3), and planktic specimens are more abundant. These units were deposited in more open water marine environments.

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

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

Based on planktic foraminifera, an age range from the latter part of Zone N. 7 to the latter part of Zone N. 8 (late Early Miocene) is tentatively proposed for the entire Pungo River section in the study area.

Benthic foraminiferal assemblages from the Yorktown Formation indicate deposition during an initial marine transgression (the lower Yorktown) followed by a general marine regression (the upper Yorktown). The lower Yorktown is a fining upward sequence of terrigenous sediments dominated by Buliminella elegantissima, Caucasina gracilis, and Florilus pizzarensis. Species of secondary importance include Cibicides lobatulus, Nonionella miocenica, Fursenkoina fusiformis, and Elphidium excavatum. Species diversity values are generally high (averaging 2.7) and faunal dominance is low (averaging 34%). The upper Yorktown

is a coarsening upward sequence of terrigenous sediments in which planktic specimens become progressively scarcer. It is dominated by Cibicides lobatulus, Elphidium excavatum, Hanzawaia concentrica, Florilus pizzarensis, and Bolivina lowmani. Species of secondary importance include Cancris sagra, Globocassidulina crassa, Bolivina paula, and Uvigerina subperigrina. Species diversity values are generally lower than those for the lower Yorktown (averaging 2.4). Faunal dominance averages 35%, ranging as high as 47% in one sample. There is a general shift upward through the unit from characteristic midshelf assemblages to faunas indicative of more nearshore environments. Water depths were probably no greater than 50 to 60 meters during maximum transgression, and were ≤ 30 or 40 meters during that portion of the regressive cycle that has been preserved.

Planktic foraminifera indicate an age of late Early to early Late Pliocene (middle of Zone N. 18 to the lower-middle of Zone N. 20) for Yorktown and equivalent strata (Duplin Formation).

T11 The stable isotopic stratigraphy of the Pungo River Formation, North Carolina: Lent, R.M., 1985, M.S. Thesis, North Carolina State University. Raleigh, N.C., 68 p.

ABSTRACT

The stable isotopic composition of three benthic foraminifera (Siphogenerina lamellata, Hanzawaia concentrica and Bolivina paula), and sedimentary organic carbon have been used to interpret the environment of deposition and the post-depositional history of the mid-Miocene Pungo River Formation. The Pungo River Formation, located in the subsurface of North Carolina and outcropping on the continental shelf, contains unusually high concentrations (up to 60%) of phosphate (Riggs et al., 1985). Ten vibracores from Onslow Bay were analyzed to determine the isotopic composition of the benthic foraminifera and the sedimentary organic carbon. In addition to the vibracores, one drill core from the coastal plain was analyzed for organic carbon. Strontium geochemistry and SEM back scattering electron analyses indicate that the two large epifaunal benthic foraminifera (Siphogenerina lamellata and Hanzawaia concentrica) have undergone diagenesis (50 to 80% bulk recrystallization). The stable isotopic composition of these foraminifera suggest that the diagenesis occurred in a marine environment associated with a fresh water dispersal system. The SEM backscattering electron technique indicates that Bolivina paula, an infaunal foraminifera, has undergone less bulk recrystallization, and has secondary carbonate encrustation on interior wall of the test chambers. By constructing a productivity indicator using the $\delta^{13}C$ composition of Bolivina paula, a relationship between productivity and phosphate deposition can be demonstrated.

The $\delta^{13}C$ composition of the total organic carbon (TOC) from Onslow Bay varies from -24.976 to -21.017 per mil. High sample heterogeniety of some samples suggests post-collection alteration of the TOC may have occurred. The $\delta^{13}C$ of the TOC from coastal plain drill core varies from -20.363 at the top of the formation to -22.564 near the bottom of the formation. Based on the isotopic composition approximately 45% of the TOC near the bottom of the formation has a terrestrial origin. The percentage of terrestrial carbon decreases to

approximately 17% at the top of the formation. The decrease in terrestrial carbon is consistent with the major transgression during the Miocene.

T12 Preliminary stratigraphy of the Pungo River Formation of the Atlantic Continental Shelf, Onslow Bay, North Carolina: Lewis, D.W., 1981, M.S. Thesis, East Carolina University, Greenville, N.C., 75 p.

ABSTRACT

The distribution of an extensive sequence of Tertiary sediments has been delineated in the shallow subsurface across the continental shelf of Onslow Bay, North Carolina. Vibracoring and high resolution subbottom profiling (3.5 kHz, Uniboom, and sparker) have revealed a broad belt of phosphatic sediments that extend southwestward for 125 km from the western Bogue Banks, across the shelf, to the outer portion of Frying Pan Shoals off Cape Fear.

The Tertiary section in Onslow Bay consists of Oligocene and/or Lower Miocene moldic, sandy limestones and fine quartz sands unconformably overlain by sediments of the Middle Miocene Pungo River Formation which are, in turn, unconformably overlain by either Pliocene and/or Pleistocene sediments. The Pungo River Formation consists of three sediment members with facies variations within each in northern Onslow Bay. These include 1) a quartz sand member; 2) a biorudite member; and 3) a phosphatic sand member. The other Pungo River facies are found in southern Onslow Bay near Frying Pan Shoals and consists of phosphorite sands, phosphorite quartz sands, phosphatic quartz sands, foram-rich muds, and clayey dolosilts. Preliminary analysis of the Onslow Bay sedimentary sequence and the associated foraminiferal faunas suggest that they are similar to that found in the Pungo River section of the mining district near Aurora.

Phosphorite units in northern Onslow Bay contain mostly medium brown intraclastic and skeletal phosphate grains in concentrations which average 10 to 15% but occasionally reach 20 to 25% of the total sediment. Phosphorite units in the Frying Pan area contain dominantly dark brown pelletal phosphate grains which average 20 to 40% and occasionally constitute 50 to 65% of the total sediment.

T13 Clay mineralogy of the Pungo River Formation, Onslow Bay, North Carolina Continental Shelf: Lyle, M.E., 1984, M.S. Thesis, East Carolina University, Greenville, N.C., 129 p.

ABSTRACT

The Pungo River Formation in Onslow Bay, North Carolina consists of the Burdigalian (late early Miocene), Langhian (early middle Miocene), and the Serravallian (middle Miocene) depositional sequences as defined by seismic stratigraphy and biostratigraphy. X-ray diffraction analyses have defined the clay mineral composition of these sequences as follows:

Serravallian (BBS Depositional Sequence)	Montmorillonite	50 to 70%
	Illite	25 to 40%
	Chamosite	1 to 10%
	Sepiolite	not detectable
Langhian (OBS Depositional Sequence)	Montmorillonite	6 to 45%
	Illite	41 to 89%
	Sepiolite	3 to 18%
	Chamosite	not detectable
Burdigalian (FPS Depositional Sequence)	Montmorillonite	25 to 70%
	Illite	27 to 70%
	Chamosite	0 to 24%
	Sepiolite	3 to 18%

Clinoptilolite, a zeolite mineral, is present infrequently in the Burdigalian, not detectable in the Langhian, and present throughout the Serravallian. Well crystallized, mica-derived montmorillonite and a poorly crystallized illite are interpreted to be of terrigenous origin. Sepiolite, chamosite, and a glauconitic illite, are interpreted to be of authigenic origin. Clinoptilolite is interpreted to be authigenic in the Burdigalian sediments and detrital in the Serravallian. The diagenetic alteration of clays and formation of zeolite is thought to be related to variations in availability of Fe, Mg, and Si in response to changing climatic conditions, weathering processes, and sea-level fluctuations.

T14 Lithostratigraphic analysis of cyclical phosphorite sedimentation within the Miocene Pungo River Formation, North Carolina Continental Shelf: Mallette, P.M., 1986, M.S. Thesis, East Carolina University, Greenville, N.C., 186 p.

ABSTRACT

The Miocene Pungo River Formation occurs in outcrop and shallow subcrop across 5000 km^2 of the North Carolina continental shelf in Onslow Bay. The formation contains three N-S trending, unconformity bound, depositional sequences which dip gently seaward. These sequences, referred to as the Frying Pan Sequence (FPS = late Burdigalian), Onslow Bay Sequence (OBS = Langhian) and Bogue Banks Sequence (BBS = Serravallian) are products of third-order sea-level cycles and were originally recognized on the basis of seismic and biostratigraphic techniques. Lithologic descriptions from 95 nine-meter vibracores demonstrate that the depositional sequences can also be distinguished on the basis of their characteristic lithofacies, which reflect deposition in shelf, shelf margin and shelf environments, respectively.

The Frying Pan Sequence comprises four major lithofacies: 1) phosphorite (10 to 65% phosphate), 2) siliciclastic (sand and mud), 3) mixed carbonate and siliciclastic, and 4) foraminiferal quartz sand. The Onslow Bay Sequence comprises three major lithofacies: 1) biogenic carbonate, 2) interbedded quartz sand and dolosilty mud, and 3) organic-rich mud. The Bogue Banks Sequence is subdivided into five major lithofacies: 1) quartz sand, 2) phosphatic quartz sand

(3 to 9% phosphate), 3) phosphorite quartz sand (10 to 25% phosphate), 4) dolosilty mud, and 5) carbonate. Lithofacies distribution within the Frying Pan and Onslow Bay Sequences is controlled by antecedent topography and location of sediment source areas. In northern Onslow Bay, biogenic carbonate sediments are associated with the Cape Lookout High, a shallow region with low siliciclastic influx. Siliciclastic sediments of central Onslow Bay fine southward away from a source area on the adjacent landmass. Minimum dilution by siliciclastic sediments in southern Onslow Bay, coupled with upwelling and reducing bottom conditions, resulted in accumulation of organic matter and authigenesis of phosphorite and dolomite. Lithofacies distribution within the Bogue Banks Sequence could not be directly related to prominent paleotopographic features or sediment source areas.

Cyclical patterns of sedimentation within third-order depositional sequences represent the lithologic response to high-frequency glacioeustatic sea-level fluctuations. The ideal lithic cycle consists of basal muddy siliciclastic sands, overlain by muddy foraminiferal phosphorite sands, overlain by foraminiferal or diatomaceous muds. This vertical succession of lithologies represents deposition during the transgressive phase of a fourth-order sea-level cycle. Ideal lithic cycles are not laterally persistent but grade into either uniform or interbedded sediment sequences. Diagenesis during subaerial and submarine exposure results in dissolution of primary sedimentological components including phosphate, dolomite, calcareous macrofossils, and calcareous and siliceous microfossils, as well as reprecipitation and neogenesis of secondary sedimentological components including phosphate, dolomite, zeolite and calcite cements.

T15 Distribution and petrology of glauconitic sediments in the Miocene Pungo River Formation, Onslow Bay North Carolina Continental Shelf: Mallinson, D.J., 1988, M.S. Thesis, East Carolina University, Greenville, N.C., 131 p.

ABSTRACT

The petrology and distribution of the glaucony facies are determined for the Miocene Pungo River Formation in Onslow Bay, North Carolina. The glauconitic grains comprising the glaucony facies consist of five types which are defined petrographically and chemically. These types represent different stages of evolution from a mixed-layer glauconitic smectite-illite (Type 2) to a glauconitic illite (Type 4). Type 1 grains may also contain mixed-layer glauconitic smectite-illite, however, data was not sufficient to prove this definitively. Type 5 grains are aggregate glauconitic illite grains that have been reworked. Evolution occurs as ferric and ferrous iron and magnesium substitute for aluminum in the octahedral layer and potassium replaces H_2O in the interlayer position. There is a shift of the (001) peak from 10.8-12 angstroms to 10.1 angstroms due to the collapse of the interlayer region. The progressive formation and evolution of the glauconitic minerals, accompanied by the dissolution of the original carbonate substrate grain results in the evolution of grains from Type 1 to Type 4.

Regional and stratigraphic distribution indicate that the major sedimentologic controls are sediment grain-size and mineralogy. These, in turn,

are controlled by paleogeography and water-depths within the depositional basin, the location of sediment point sources and maximum upwelling, and third- and fourth-order sea-level fluctuations.

Sedimentary trends indicative of fourth-order sea-level fluctuations were noted in fourth-order depositional sequences. This trend consists of basal carbonate fluorapatite ooids and phosphatized skeletal grains, overlain by glauconitic sediments increasing upwards in abundance and mineralogic maturity, and capped by ferric-hydroxide-stained sediments. This trend is interpreted to represent a portion of a condensed section formed during a fourth-order transgression and highstand and partially eroded and oxidized during a subsequent regression.

Analyses of the clay-size fraction revealed the presence of ferric smectites and illites probably of a detrital nature. Also apparent was an upward increase in the iron concentration within the clay-size fraction of several fourth-order seismic sequences. This trend may result from the seaward migration of the nearshore zone of chemical precipitation of iron-hydroxides and oxidation of detrital iron minerals.

T16 Organic carbon and nitrogen concentrations and stable isotopic ratios of organic carbon in the Miocene Pungo River Formation, North Carolina Continental Shelf: Maxwell, M.E., 1990, M.S. Thesis, University of North Carolina, Chapel Hill, N.C., 84 p.

ABSTRACT

Over 200 sediment samples from vibracores collected in Onslow Bay on the North Carolina continental shelf were analyzed for organic carbon and nitrogen concentrations. A select group was also analyzed for organic carbon $\delta^{13}C$. In general, organic carbon concentrations increased with decreasing grain size, with the exception of primary phosphorites, which contained higher average organic carbon concentrations in comparison with sediments of similar grain size. Organic carbon $\delta^{13}C$ variations indicated that terrestrial input of organic matter in Onslow Bay during the Miocene varied with fourth-order sea level changes. Highly phosphatic sections, located mid-transgression in the sequence of sea level rise and fall (Riggs, 1984), preserved distinctively marine isotopic signals.

T17 High resolution seismic stratigraphy of the North Carolina Continental Margin--the Cape Fear region: sea-level cyclicity, paleobathymetry, and Gulf Stream dynamics: Matteucci, T.D., 1984, M.S. Thesis, University of South Florida, St. Petersburg, Florida, 100 p.

ABSTRACT

A high-resolution seismic stratigraphic study of the Cape Fear region (mid to outer continental shelf between Cape Fear and the Cape Fear Terrace off North Carolina) combined with bio-lithostratigraphic data has yielded a chronostratigraphic framework of the Tertiary and Quaternary sequences that comprise this portion of the North American continental margin.

Glacioeustatic and/or geoeustatic sea-level changes throughout the Cenozoic and concomitant fluctuations in the axis of the Gulf Stream (North Atlantic Gyre) have largely determined the nature of the associated depositional and erosional features. In general, relative high stands of sea level have correlated with more landward incursions of the Gulf Stream onto the shelf margin. Major submarine erosional flow paths have been imprinted on the Cape Fear region during relative highstands of the late Paleocene-early Eocene, late Eocene, late Oligocene, early Miocene, and early Pliocene.

Relative lowstands of sea level have resulted in a seaward displacement of the Gulf Stream axis allowing the shelf margin to prograde outward. During rapid regressions, however, in which sea level dropped below the shelfbreak (such as during high frequency glacioeustatic sea level fluctuations) subaerial exposure and truncation of the shelf occurred.

The Cape Fear Terrace is an anomalous, point-source, prograding, shelf-margin feature which has experienced positive relief throughout much of the Quaternary. It was originally built up during a lowstand of sea level with the construction of a shelf-edge deltaic feature. Severe modification of this delta front occurred during a relative highstand of sea level as the Gulf Stream began to impinge upon the margin. The anomalous thick accumulation of shelf-edge sediments acted as a barrier to flow inducing complex flow patterns of the Gulf Stream. Excavation of these sediments yielded a terrace feature with preferential erosion on the upstream side.

Subsequent deposition in the terrace region may have occurred during fairly high stands of sea level, as evidenced by the presence of active seaward prograding sand waves in the terrace region today. Once this shelf-edge bathymetric irregularity (the terrace) had been established, the Gulf Stream acted as a dynamic force inducing cellular flow structures within the shelf environment, enabling sediments to be transported seaward along the paleo-shoals complex.

T18 Continental shelf hardbottoms in Onslow Bay, North Carolina: their distribution, geology, biological erosion and response to Hurricane Diana, September 11-13, 1984: Mearns, D.L., 1986, M.S. Thesis, University of South Florida, St. Petersburg, Florida, 150 p.

ABSTRACT

High-resolution seismic and side-scan sonar profiling, in addition to vibracoring and rock dredging, demonstrate that morphologically- and lithologically-complex hardbottoms (exposed rock surfaces) crop out extensively on the inner and middle continental shelf of Onslow Bay, North Carolina. Composed of mixed calcareous quartz sandstones and fossiliferous limestones, the hardbottoms vary in their surface relief (0 to 8 m), geomorphology (ramp and scarp margins) and subbottom associations (outcrop- and channel-controlled). Low-relief Tertiary hardbottoms are primarily scattered in northeastern Onslow Bay while moderate- to high-relief Quaternary hardbottoms dominate in southwestern Onslow Bay.

Hardbottoms were formed during mid- to late-stage transgressions as carbonate sedimentation increased at the expense of terrigenous siliciclastics. Petrography of hardbottom rocks indicates that early cementation occurred in the

submarine environment. Thus, these rocks may represent true hardgrounds.

Tertiary hardbottoms represent the upper portions of lithologic units formed in response to third- and fourth-order sea-level cycles. Of many units sampled by vibracore, or correlative sequences delineated by seismic analysis, relatively few are capped by hardbottom lithofacies. Quaternary hardbottoms, which unconformably overlie these Tertiary sequences, are often formed in association with the infilling of relict fluvial channels. Preferential cementation of the upper portions of the channel-infill facies develops the hardbottom. Subsequent erosion of adjacent, uncemented strata provide the initial surface relief. Thus, the distribution of Quaternary hardbottoms is partially controlled by an antecedent drainage system whereby individual channel-hardbottom complexes reflect the meandering form of original stream beds.

Presently, hardbottoms are being extensively bioeroded by endolithic bivalves. These surfaces are being reduced to residual sediments and rock debris. Excavation occurs primarily along the hardbottom base. Through this process of rock undercutting, structural failure yields distinctive escarpments laden with massive (7 m X 15 m) boulders. A similar style of bioerosion has been occurring since at least the late Oligocene.

Direct comparison of sonograph images, collected prior to and following Hurricane Diana, failed to reveal any measurable seafloor changes, indicating that the shelf surface in Onslow Bay is in equilibrium with its ambient, high-energy setting.

T19 Foraminiferal biostratigraphy and paleoecology of the Miocene Pungo River Formation, central Onslow Embayment, North Carolina Continental Margin: Moore, T.L., 1986, M.S. Thesis, East Carolina University, Greenville, N.C., 160 p.

ABSTRACT

The Pungo River Formation in Central Onslow Embayment consists of three third-order seismic sequences (FPS, OBS, and BBS), which comprise smaller, fourth-order seismic sequences bounded by unconformities. Biostratigraphic analyses indicate a Burdigalian (late early Miocene) age for the FPS sequences. FPS-1 through FPS-3 and the lower portion of FPS-6 are assigned to planktonic foraminiferal Zone N6 (Blow, 1969, 1979) based on the concurrent ranges of secondary indicator species such as Globigerinoides quadrilobatus altiapertura, Catapsydrax unicavus, Globorotalia birnageae, Globigerinoides quadrilobatus praeimmaturus and Globigerinoides subquadratus. The middle and upper portion of the FPS-6 sequence lies within the early portion of Zone N7 (based on the first appearance of Globigerinoides sicanus praesicanus). The OBS sequence is Langhian (early middle Miocene) in age and is assigned to planktonic foraminiferal Zone N9 (characterized by the appearance of Orbulina universa and the disappearance of early Miocene taxa). The age of the BBS sequence in Central Onslow Bay cannot be as accurately estimated due to the long stratigraphic ranges of species present. However, in Northern Onslow Bay the disappearance of the Globigerinoides sicanus complex, along with the co-occurrence of Globigerinoides bollii and Globorotalia siakensis (Snyder, pers. comm., 1985), suggests a Serravallian (middle Miocene) age corresponding to Zones N11-N14. When compared

to coastal offlap/onlap curves, the FPS, OBS, and BBS sequences fall within the third-order Miocene TM 1.4, 2.1 and 2.2 transgressions, respectively (Vail et al., 1977; Vail and Mitchum, 1979).

Moderate species diversity and faunal predominance in benthic assemblages indicate deposition on the middle to outer continental shelf. Three distinct benthic foraminiferal associations in Central Onslow Bay are each associated with a particular sediment type throughout the sequences. Change in species composition of benthic assemblages reflects variations in water mass properties and sediment type, rather than paleobathymetry. The FPS-1, FPS-2 and FPS-3 sequences are slightly predominated by Bolivina paula and other species associated with high-nutrient, low-oxygen conditions characteristic of upwelling zones. Increased abundance of Valvulineria floridana and Cibicides americanus in the FPS-6 sequence suggests transition from conditions of modest nutrient supply to more highly oxygenated, normal marine conditions. The strong predominance of Cibicides americanus in the OBS-3 sequence suggests a well oxygenated, open marine environment. Bolivina paula predominates in the BBS-1 and BBS-2 sequences. In BBS-1, the abundance of this species, in association with diatoms and high phosphate content suggests strong upwelling conditions. The predominance of Bolivina paula in BBS-2 is probably related to its preferential preservation involving mechanical destruction of other species that may have been present.

T20 Diagenesis of benthic foraminifera in the Miocene Pungo River Formation of Onslow Bay, North Carolina Continental Shelf: Moretz, L.C., 1987, M.S. Thesis, East Carolina University, Greenville, N.C., 110 p.

ABSTRACT

Benthic foraminifera in Pungo River sediments of Onslow Bay have undergone several types of diagenesis, each with varying degrees of intensity that relate to cyclic sedimentation within the formation. The upper surfaces of seismic sequences are commonly diastemic, and diagenetic alteration decreases with increasing distance downward from such surfaces. A recrystallization index based on five species of benthic foraminifera and trends in Sr/Ca ratios of Hanzawaia concentrica and Bolivina paula as measured by x-ray fluorescence proved useful for delineation of unconformable contacts, even those difficult to recognize lithologically.

Both lithofacies and seismic sequences may be differentiated by differences in recrystallization and Sr/Ca ratios among benthic foraminifera. Lithofacies which may be distinguished from one another include the phosphorite of southern Onslow Bay, the biogenic carbonate and siliciclastic sand of northern and central Onslow Bay, the siliciclastic and organic-rich mud of southern Onslow Bay. Sediment grain size seems to be the most important factor controlling recrystallization. Sediments fine southward in Onslow Bay away from a Miocene siliciclastic point-source to the northwest. Recrystallization is more pronounced in northern and central Onslow Bay, decreasing in intensity as sediments fine to the south. Isopachous cement, low in Fe and Mg, was probably precipitated in an early marine diagenetic environment.

Post-depositional mineralization occurs primarily in the organic-rich sediments of southern Onslow Bay where clinoptilolite and phosphate infills test

chambers. Framboidal pyrite, often found in association with clinoptilolite, is the most widespread type of authigenic mineral, whereas clinoptilolite is the most abundant.

T21 Diatom biostratigraphy and paleoecology of the Miocene Pungo River Formation, North Carolina Continental Margin: Powers, E.R., 1987, M.S. Thesis, East Carolina University, Greenville, N.C., 225 p.

ABSTRACT

Diatom assemblages in the Pungo River Formation from the continental shelf of Onslow Bay and from the Aurora Phosphate District on the emerged coastal plain refine biostratigraphic ages and identify upwelling events in the early to middle Miocene sequences along the North Carolina continental margin. Three third-order depositional sequences (the Frying Pan FPS, Onslow Bay OBS, and Bogue Banks Sequences BBS, from oldest to youngest) within the Pungo River Formation of Onslow Bay were age dated based on indicator species of Abbott's 1978 Atlantic Miocene Diatom Zones (AMDZ). The Frying Pan Sequence is assigned to Zone I (Burdigalian), the Onslow Bay Sequence to Zones II and III (Langhian) and the Bogue Banks Sequence to Zone VI (Serravallian). Four lithostratigraphic units in the Aurora Phosphate District (A,B,C and D from oldest to youngest) were also dated. Diatom assemblages in unit A are assignable to Zone I, but floral elements not used in Abbott's zonation indicate deposition earlier than the Frying Pan Sequence of Onslow Bay. Unit B in Aurora is assigned to Zone I and is correlative with the Frying Pan Sequence. Units C and D are assigned to Zones II and III, indicating equivalence to the Onslow Bay Sequence. Sediments equivalent to the Bogue Banks Sequence were not observed in the Aurora study area.

Diatom assemblages in both study areas indicate shallow marine deposition. In Onslow Bay the influx of oceanic waters varied through time, probably in response to changes in sea level and intensity of upwelling currents. Predominantly benthic assemblages in the Frying Pan Sequence give way to greater proportions of planktonic species in overlying sequences. Shelf waters cooled and upwelling intensified during deposition of the Bogue Banks Sequence. In the Aurora study area, little up-section change in benthic predominated assemblages occurred. Though upwelling species are rare, the presence of phosphorite in diatomaceous intervals at Aurora suggests deposition in an area adjacent to upwelling centers.

Preservation of the diatom assemblages varied as a function of the permeability of enclosing sediments and the composition of associated sediment particles. The inverse relationship between diatom preservation and zeolite occurrence in Pungo River sediments suggests dissolution of diatoms provided a source of silica for zeolite formation.

T22 **Stratigraphy and petrology of the Pungo River Formation, central Coastal Plain of North Carolina:** Scarborough, A.K., 1981, **M.S. Thesis, East Carolina University, Greenville, N.C., 78 p.**

ABSTRACT

The Middle Miocene Pungo River Formation 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 Formation 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 Formation 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 Formation 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 Formation 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 Formation 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 Formation 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.

T23 Trace-element analysis of the clay-silt fraction of the Pungo River Formation, North Carolina: Siedlecki, M., 1983, M.S. Thesis, North Carolina State University, Raleigh, N.C., 128 p.

ABSTRACT

Fifty samples of clay-silt sediment separated from the Miocene Pungo River Formation have been analyzed for trace-element concentrations. Samples were collected from drill cores within the Aurora mining district in North Carolina. Trace-element concentrations have been determined by neutron-activation analysis.

The clay-silt samples are composed of 1-5% organic material, 13-60% carbonate minerals, 13-20% cristobalite, 1-13% phosphorite grains and 31-35% terrigenous material. The terrigenous material is the dominant influence on the REE signal in the samples. Rare-earth-element distribution patterns in the lower portion of the Pungo River Formation exhibit positive Ce and Eu anomalies which suggest that deposition occurred under conditions which differed from present-day. These conditions may have included high nutrient supply and a shallow oxygen minimum.

T24 Miocene sea-level cyclicity: resolution of frequency and estimates of amplitudes from the stratigraphic record of the Carolina Platform: Snyder, Stephen W., in progress, PhD Dissertation, University of South Florida, St. Petersburg, Florida.

ABSTRACT

Miocene stratigraphic sections from the sedimentary prism overlying the Carolina Platform were studied in an effort to resolve sea-level changes characteristic of orbitally-forced glacioeustasy.

Interpretations from a dense network (>20,000 km) of very high-resolution

seismic reflection profiles collected from the North Carolina estuaries, shelf, and upper slope have defined over 20 regional unconformities. These physical surfaces of discontinuity were used to construct a relative chronostratigraphic framework. Well/auger/drill-hole data, onshore outcrops, open-pit mines, and 144 continental shelf vibracores were integrated for stratigraphic control. Cross-shelf unconformities were found to bind 18 Miocene sequences. Each was formed in response to large-scale sea-level changes. Fluvial paleochannels accompanying many Miocene unconformities attest to multiple subaerial exposure episodes. Benthic foraminiferal assemblages provide a semi-quantitative description of water depth at the time of deposition. Boundary current erosional scars mark flow path positions associated with highstands of sea level. Collectively, these data indicate that the amplitudes of the North Carolina Miocene sea-level cycles ranged between 40 and 100 meters/cycle.

The duration of each sea-level cycle was estimated by dividing the number of sequences plus intervening unconformities by time constraints defined in the comprehensive biostratigraphic data set of Scott W. Snyder (1988), and then calibrated via the biochronologic scheme of Haq et al. (1988). Calculations show the periodicity of Miocene sea-level oscillations to be on the order of 10^5 years or less. It is concluded that the high-frequency of high-amplitude sea-level fluctuations could only have been driven by glacioeustasy. However, more refined dating techniques capable of resolving time on scales of 10^4 years are required before these sea-level cycles can be unequivocally linked to specific orbital-perturbations. Both high-frequency (<200 kyrs/cycle) and low-frequency (about 2.3 myr/cycle) orbital-forcing are apparent in the sea-level record. They demonstrate large continental ice sheets resided on Antarctica immediately prior to the global middle Miocene $\delta^{18}O$ enrichment event. This enrichment event must therefore primarily reflect deep-water physicochemical changes, not glacial development. An alternative hypothesis for global climate change during the middle Miocene is proposed based on evidence for 1) pre-middle Miocene glacioeustasy, 2) boundary current intensification, and 3) coeval paleoceanographic and paleogeographic indices.

T25 Seismic stratigraphy within the Miocene Carolina Phosphogenic Province: chronostratigraphy, paleotopographic controls, sea-level cyclicity, Gulf Stream dynamics, and the resulting depositional framework: Snyder, Stephen W., 1982, M.S. Thesis, University of North Carolina, Chapel Hill, N.C., 183 p.

ABSTRACT

Interpretations of over 4000 km of high-resolution seismic reflection data, supplemented by litho- and biostratigraphic analyses of (9 m) vibracores, have delineated the regional distribution and local depositional patterns of the Miocene Pungo River Formation within the upper southeast North Carolina continental margin.

The Miocene section consists of over 17 discrete depositional sequences, each bound by regional unconformities and associated channels. These sequences have been grouped and mapped as 3, chronostratigraphically distinct, depositional packages on the basis of microfossil analyses. The late Burdigalian sequences form a generally NE-SW striking outcrop belt across the middle shelf of Onslow

Bay, closely paralleling the northeast limb of the underlying Mid-Carolina Platform High. Several, shallow, late Burdigalian erosional outliers, which are the surficial expression of subbottom "flexures", were identified west of the main outcrop belt in southwest Onslow Bay. The subbottom flexures seem to be coincident with mapped geophysical anomalies and are presently interpreted to be the surficial expression of differential movement along older basement structures within the Carolina Platform. Collectively, the Langhian and Serravallian sequences form a broad, N-S striking outcrop belt in central and northeast Onslow Bay. The western updip limit of these middle Miocene sequences, both in northeast Onslow Bay and on the adjacent emerged coastal plain, is directly controlled by the White Oak Lineament. In seismic view, this subbottom, elongate, N-S striking lineament appears to be a broad, monoclinal feature. Its coincidence with several prior ascribed structures suggests it may be causally related to a late early Miocene or early middle Miocene reactivation event along a rift-originated, normal fault zone. However, its present morphology can be directly attributed to severe erosional truncation associated with an ancestral Gulf Stream flow path, and the entire subbottom lineament is presently thought to be an erosional feature. North of Onslow Bay, both the Langhian and Serravallian sequences thin and/or pinch-out across the Cape Lookout High, a pre-Miocene positive topographic feature. This antecedent high is interpreted to be both constructional and erosional in origin. It appears to be part of a relict, sediment-drift system generated by early Oligocene Gulf Stream flow paths, subsequently modified by subaerial and submarine erosion associated with late Oligocene through middle Miocene sea-level fluctuations.

Previous stratigraphic studies within the adjacent emerged coastal plain have advocated depositional control through structural deformation. Here, only the Cape Fear Flexures can be attributed to deformational tectonics. Furthermore, their influence as primary depositional controls appears to be insignificant when compared to the antecedent topography developed during submarine erosional episodes. In general, the basin geometries and basin infilling histories manifested in the distribution and depositional patterns of the Miocene sequences were primarily controlled by a constant interplay between (1) high-frequency, sea-level fluctuations, and (2) changes in the position, configuration and flow dynamics of the ancestral Gulf Stream as it (3) responded to sea level induced bathymetric oscillations and (4) interacted with the antecedent bottom topography along the continental margin. During sea-level low stands, the Gulf Stream was deflected by local antecedent bathymetric highs within the continental margin, resulting in eastward migrating flow paths. Consequently, the Miocene North Carolina continental margin built seaward via a series of sequences characterized by high-angle prograding clinoforms (off-shelf sediment transport). Conversely, during the high stands of each sea-level event, the resulting paleobathymetry allowed the Gulf Stream to migrate landward, by-passing local antecedent topographic highs within the continental margin and impinging on the North Carolina continental shelf. Gulf Stream erosion associated with these sea-level high stands resulted in severe truncation and exhumation of previously deposited Miocene and/or older Tertiary sequences.

Due to the constant interplay between erosion and depositional events associated with high-frequency sea-level cyclicity, the Miocene section along the upper southeast North Carolina continental margin is represented by an extremely complex stratigraphic package, characterized by numerous truncation surfaces and highly-variable lithologies.

T26 Carbonate petrology and sedimentology of the Miocene Pungo River Formation, Onslow Bay, North Carolina Continental Shelf: Stewart, T.L., 1985, M.S. Thesis, East Carolina University, Greenville, N.C., 184 p.

ABSTRACT

The Pungo River Formation in Onslow Bay, North Carolina is predominantly a siliciclastic sediment sequence with variable amounts of authigenic and diagenetic minerals including carbonates. Based on examination of 14 of the 16 outcropping Pungo River seismic units, the dominant carbonate component is carbonate mud (low-Mg calcite, dolomite, or a mixture of the two). Calcareous fossils are the next most abundant carbonate component. Calcite cements are a very minor component and are only locally abundant.

Four patterns of carbonate sedimentation occur in the Pungo River Formation in Onslow Bay.

1. Cyclic carbonate sediments overlying noncarbonate lithologies and deposited as a couplet during the same fourth-order sea-level cycle are common. Biomicrosparites which grade into phosphorites of seismic unit FPS-1 represent deposition during a fourth-order sea-level maximum when warm Gulf Stream waters flooded the shelf. Calcite-cemented sandstone of BBS-2 grades down section into unindurated quartz sand. Unindurated, muddy, barnacle-rich sands represent fourth-order sea-level regressions. These types of carbonate cap rocks conform to the idealized lithic cycle of the Riggs model of Neogene sedimentation (1984).

2. Sediments of the OBS seismic sequence are largely carbonates in northern Onslow Bay and siliciclastics in central Onslow Bay. Carbonate content in each fourth-order seismic unit increases up section from OBS-1 to OBS-4. OBS-1 in northern Onslow Bay represents mid to outer shelf sedimentation. OBS-2 and OBS-3 contain a predominantly reworked fossil assemblage. OBS-4 is a barnacle hash, representing formation on shelf edge hardgrounds and deposition off the shelf edge.

3. Sparse fossils and minor carbonate mud occur disseminated in all predominantly noncarbonate lithologies. The major source of calcareous mud is probably from bio-mechanical degradation of larger carbonate grains, primarily shell material.

4. Predominantly carbonate beds interbedded with noncarbonate lithologies include: moldic microsparite which probably represents the carbonate cap on FPS-1 in northern Onslow Bay; moldic microsparite in BBS-1 which may be similar in origin to the carbonate cap of unit C in the Aurora Area; and echinoid-foraminiferal biosparites in FPS-6, which probably formed by winnowing of the fines by marine currents such as Gulf Stream eddies.

Diagenetic carbonates (calcite cements and dolomite) and silicates (opal-CT, microcrystalline quartz, and clinoptilolite) exhibit vertical diagenetic profiles in some cores. Where carbonate sediments are abundant, effects of fresh water calcite cementation decrease down section. Because syntaxial cement on echinoids is precipitated faster than rim cements on other fossils, it is a good indicator of the degree of diagenesis undergone by sediments. Dolomite abundance and distribution are sporadic, perhaps reflecting presence or absence of sulfate reducing bacteria in the sediment. Local chert nodule formation is related to abundance of siliceous fossils and to permeability barriers within the sediments.

T27 Foraminiferal paleoecology and biostratigraphy of the Pungo River Formation, southern Onslow Bay, North Carolina Continental Shelf: Waters, V.J., 1983, M.S. Thesis, East Carolina University, Greenville, N.C., 186 p.

ABSTRACT

The Pungo River Formation in Frying Pan Embayment, southern Onslow Bay, consists of six distinct depositional sequences (FPS-1 through FPS-6). Diastemic contacts between successive units, along with variations in their relative phosphate content, suggest a discontinuous pattern of deposition. Biostratigraphic analyses indicate a late Burdigalian (late early Miocene) age for Pungo River sediments in southern Onslow Bay. Units FPS-1 through the lower portion of FPS-6 (characterized by the co-occurrence of Globigerinoides insueta, Globigerinoides quadrilobatus altiapertura, and Catapsydrax unicavus) are assigned to planktonic foraminiferal Zone N6 (Blow, 1969). The remainder of FPS-6 (marked by the first appearance of Globigerinoides sicanus praesicanus, Globorotalia scitula praescitula, and G. acrostoma) lies within the early portion of Zone N7. When compared to global eustatic sea level curves, deposits of the Frying Pan, Pungo River Formation fall within the third order Miocene TM 1.4 transgression (Vail et al., 1977; Vail and Mitchum, 1979). Hiatuses separating these Pungo River Formation sequences are beyond the limit of biostratigraphic resolution; if related to Vail's curve, they must correspond to fourth or higher order sea level fluctuations within the larger transgressive sequence.

Moderate values of benthic species diversity (averaging 2.32) and faunal predominance (averaging 33%) characterize the Pungo River section, indicating deposition of all units on the middle to outer continental shelf. Changes in the species composition of benthic assemblages reflect variation in water mass properties and substrate type rather than directly indicating changes in paleobathymetry. Phosphatic sequences FPS-1 and FPS-2 are numerically dominated by Bolivina paula and other species associated with the high nutrient levels and low oxygen conditions typical of upwelling zones. Abundant planktonics, negligible phosphate content, and the predominance of Hanzawaia concentrica characterize Unit FPS-6. These factors indicate a well oxygenated, more typically open marine environment, probably influenced by Gulf Stream spillover associated with a westward shift in the current's axis.

BIBLIOGRAPHY OF ABSTRACTS

A. Abstracts (88)

A. ABSTRACTS

1991

A91-1 Geochemical variability of phosphate grain types within the Upper Cenozoic sediments of the Carolina Continental Margin: <u>Ames, D.V., Riggs, S.R., Crowson, R.A., and Showers, W.J., 1991</u>, **Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 3.**

ABSTRACT

Major, minor, and trace elements, rare-earth elements, structural CO_3, and various isotopic analyses have been utilized to characterize primary depositional and subsequent diagenetic overprint signals on hundreds of hand-picked, individual phosphate grains, small sample aggregates, and polished grain mounts from common stratigraphic units.

Three groups containing 7 grain types of primary phosphate characterize the Upper Cenozoic including:

1. Skeletal grains: a) pelagic bones, b) pelagic teeth, c) benthic brachiopods, and d) replaced carbonate benthic invertebrates;
2. Peloids: a) subsurface interstitial authigenic grains; and
3. Intraclasts: a) benthic interface, authigenic microsphorite surface, and b) associated rip-up clastic grains.

Each of the primary grain types form in response to specific chemical conditions in combination with distinctive processes of formation and deposition and within unique subenvironments of phosphate depositional systems. Thus, the different grain types start out with distinctive elemental, isotopic, and structural signatures.

However, subsequent episodes of nondeposition associated with sea-level highstands, weathering associated with sea-level lowstands, and erosion and reworking within different depositional environments cause diagenetic alteration of each grain type that modifies the primary chemical signal. The degree of alteration and modification of the original elemental, isotopic, and structural signal and development of a distinctive secondary diagenetic signal is dependent upon the stratigraphic location of grains relative to subsequent erosional and alteration surfaces produced by each sea-level event, as well as the number and duration of sea-level events.

A91-2 Uranium-series disequilibrium studies of phosphatic pellets from Onslow Bay, North Carolina Continental Shelf: <u>Burnett, W.C., and Riggs, S.R., 1991</u>, **Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 13.**

ABSTRACT

Uranium/thorium-series disequilibrium studies have proven useful for assessing ages and growth rates of large indurated phosphatic concretions less

than about 200,000 years old. Studies of phosphatic pellets, the principal grain type of most large-scale deposits, has not been as successful because sufficient sensitivity does not yet exist to analyze single pellets. Thus, composite samples, potentially consisting of multiple generations of grains, are required and may lead to ambiguous results.

This problem can be overcome to some degree by hand-separating similar pellets from individual sediment horizons. This approach was used in an isotopic study of vibracore samples taken in the offshore Holocene sand sheet overlying the phosphate rich Pungo River Formation. We analyzed over thirty bulk and hand-selected samples of phosphatic pellets from these cores. Our isotopic results fall into three groups: (i) bulk sediment samples containing orange-colored phosphate grains display evidence for uranium loss, perhaps by chemical leaching; (ii) separated pellets from the Miocene Pungo River Formation display equilibrium isotopic ratios suggesting that these samples are unweathered with respect to uranium-series isotopes; and (iii) samples of separated black and dark brown pellets from the Holocene sand sheet show uranium isotopic ratios significantly below equilibrium, implying that some Pleistocene phosphorite formation or "reformation" may be taking place. One possible explanation of our observations is that dissolution of underlying, older phosphorite by acidic groundwater is followed by diffusion and/or porewater advection into shallower horizons, with eventual reprecipitation of "recycled" phosphate.

A91-3 High resolution isotopic stratigraphy of phosphorites from the Miocene section, Onslow Bay, North Carolina: Crowson, R.A., Showers, W.J., and Riggs, S.R., 1991, Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 19.

ABSTRACT

Seismic-, litho-, and biostratigraphic studies of Miocene sediments exposed in Onslow Bay, NC have resulted in development of a depositional model operating within the mid-Atlantic continental margin during the Miocene. At least 18 seismic units, 3 biostratigraphic zones, and 7 lithofacies have been defined and correlated to third- and fourth-order global sea-level fluctuations during the Burdigalian, Langhian, and Serravallian. Attempts to establish a high resolution isotopic record from foraminifera-rich Miocene sediments in Onslow Bay were unsuccessful due to the diagenetic alteration of the carbonate isotopes. However, it has been demonstrated that phosphate grains, even with minor diagenetic alteration, retain their original isotopic signals. Consequently, the present study utilizes oxygen isotopes from phosphate grains that occur through the extensive stratigraphic sequence of the Miocene phosphogenic episode. Results of this study suggest the following preliminary conclusions.

1. Individual phosphate grain types have resolvable isotopic signals that reflect their specific mode of formation and depositional history.
2. By comparing isotopic values from contemporaneous grain types, environmental information has been developed concerning differences between subbottom, bottom and surface water temperatures, as well as information on the history of subsequent sediment mixing.
3. Since isotopic offsets occur between phosphate grain types as they do in carbonates (i.e., vital effects between species in forams),

construction of an isotopic stratigraphy requires comparison of isotopic data from monospecific phosphate grain types.

4. Phosphate isotopic values can be utilized to establish a high resolution isotopic stratigraphy that does reflect global sea-level change.

A91-4 Variations in francolite mineralogy with stratigraphic position in phosphorites: McClellan, G.H. and Fountain, K., 1991, Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 100.

ABSTRACT

Systematic crystallographic variations in francolites were established some 20 years ago and have been used to understand many practical problems in the industrial uses of phosphorites. In the past 5 years, these mineralogical relationships have been applied to selected stratigraphic problems where francolites occur (Florida, Togo, North Carolina).

Stratigraphic samples were collected and the detailed mineralogy of the francolites was determined on bulk francolite samples as well as selected particle sizes. The results have shown that francolite composition varies with position in stratigraphic sections as well as with decreasing particle size. In general, the degree of alteration (i.e. decarbonation of francolite) decreases with depth in sections. Francolites show the greatest degree of alteration in particles that are less than 100 microns in diameter. Unconformities in stratigraphic sections also provide opportunities for francolite alteration.

In deposits with more than one phosphate grain type (pellets, ooids, microsphorite, lithoclasts, etc), francolite compositions can vary with morphology as well as with particle size. The genetic significance of the various grain types and their post-depositional alteration (reworking and other processes) can provide new insights into phosphogenetic processes and facilitate the understanding of these deposits.

These detailed mineralogical studies complement parallel isotope geochemistry studies on some of these samples.

A91-5 Relationship of phosphate geochemistry to cyclic continental margin deposition during the Upper Cenozoic: Onslow Bay, North Carolina: Riggs, S.R., Crowson, R.A., and Showers, W.J., 1991, Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 119.

ABSTRACT

Detailed studies of individual phosphate grain types have demonstrated systematic stratigraphic variations in both types and geochemical composition that are stratigraphically controlled. Upper Cenozoic, fourth-order depositional sequences resulted from high-frequency, transgressive and regressive sea-level events that 1) repeatedly moved depositional and erosional processes across the Carolina continental margin; 2) deposited a complex sequence of siliciclastic, biogenic, and authigenic--diagenetic sediments that were 3) interrupted by episodes of non-deposition, erosion, and reworking of previously deposited

sediments and 4) periods of late diagenesis that complicated primary sediment patterns and altered mineralogic components.

Consequently, specific phosphate grain types within each depositional sequence are characterized by systematic variations in: 1) occurrence and concentration; 2) elemental and isotopic composition; and 3) diagenetic alteration. These distribution patterns of phosphate grain types with distinct geochemical signatures are interpreted to reflect specific modes of formation and changing depositional histories through a depositional sequence as follows.

I. Transgressive facies: phosphate consists of basal reworked intraclasts (formed at sediment-water interface) that grade upward to in situ peloids (formed below sediment-water interface); skeletal grains (formed in benthic and pelagic water column environments) are disseminated throughout.

II. High-stand condensed section facies: phosphate occurs as microsphorite surfaces with rip-up intraclasts and skeletal grains.

III. Regressive facies: phosphate consists of reworked mixtures of intraclasts, peloids, and skeletal grains.

IV. Low-stand hardground facies: surfaces with local developments of in situ microsphorite and reworked intraclasts and skeletal grains.

A91-6 Depositional environments of Neogene phosphatic facies of North Carolina based on benthic foraminiferal assemblages: Snyder, Scott W., 1991, Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 131.

ABSTRACT

Numerous episodes of cyclic sedimentation are recorded in the Miocene Pungo River and Pliocene Yorktown Formations. Miocene sediments occur in the subsurface of the modern North Carolina coastal plain and in outcrop-shallow subcrop across the continental shelf of Onslow Bay. Yorktown sediments crop out across the central coastal plain and dip eastward beneath younger deposits. Sediment cycles, although largely siliciclastic, include phosphate-rich intervals, many of which are immediately overlain by indurated carbonate caprock.

Phosphatic horizons are generally characterized by benthic foraminiferal assemblages that are numerically dominated by Bolivina paula, Buliminella elegantissima, and Bulimina elongata. Elphidium sp. may also be numerically important in marginal marine environments. Analogous assemblages in modern seas occur in oxygen-minimum zones and nutrient-enriched, oxygen-depleted environments associated with sewage outfalls. Hence, low diversity assemblages predominated by species of Bolivina, Buliminella, and Bulimina suggest that ancient phosphatic sediments accumulated in nutrient-enriched environments, presumably associated with coastal marine upwelling. Intervening well-oxygenated quartz and carbonate sands contain faunas predominated by species of Cibicides, Valvulineria, and Hanzawaia.

The relationship between benthic foraminiferal assemblages and phosphate content is not entirely predictable because benthic foraminifera are affected by other factors: total organic carbon content, substrate type, microhabitat preference, among others. However, generalized, larger-scale distributional patterns are reliable indicators of depositional environment.

A91-7 Paleo-productivity controlled by sea-level cyclicity: Miocene upwelling episodes on the Carolina Platform: Snyder, Stephen W., 1991, Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 131.

ABSTRACT

Stratigraphic analyses from a dense grid of over 21,000 km of seismic reflection data, supplemented by detailed biostratigraphic analyses of planktic fauna and flora, have delineated a very high-resolution Miocene chronostratigraphic framework consisting of 18 sequences bound by physical unconformities. The unconformities are chiefly erosional, and can be attributed to subaerial (fluvial channel scars) or submarine (boundary current scour) processes -- both regulated by changes in sea-level. The Miocene sea-level cycles are inferred to be of high-amplitude (> 60 m), and the dominant periodicity appears to lie within the Milankovitch realm (<500 ka). Sea-level events grossly simulate the ice growth/decay cycles of the last 700 ka.

Lithostratigraphic and benthic community studies of core materials recovered along the seismic lines were completed by Stanley R. Riggs, Scott W. Snyder, and their students. The results of these studies were integrated with the seismic data to define the distribution of organic-rich, oxygen-depleted depositional regimes. This approach has revealed a unique pattern; intense upwelling apparently reoccurred episodically within specific sites on the Carolina Platform. Most sites lie adjacent to antecedent bathymetric features scarred by boundary current erosion. It is hypothesized that the ancestral Gulf Stream migrated landward with transgressing sea-levels, interacting with bathymetric hills lying along the continental margin. Frictional effects along the western wall of the boundary current altered the flow dynamics. As a consequence, counter-clockwise spinning gyres developed. Deep, nutrient-rich, slope waters upwelled within the gyres as they spun onto the continental shelf. This elevated primary productivity within continental shelf waters. Phosphate and isotopically-light carbon were extracted from seawater and stored in shelf sequences. This scenario was repeated multiple times through the early Miocene. Only the position of boundary current upwelling changed because the Gulf Stream interacted with different seafloor bumps as it migrated landward and seaward in response to the oscillating sea-levels. Paleo-productivity cycles were therefore uniquely paced by sea-level change. Some appear to be synchronous with $\delta^{13}C$ enrichment-depletion cycles identified in the Pacific Ocean. If a link can be established (synchroniety), it would imply that the phosphogenic events extracted a significant volume of carbon from the global ocean reservoir during high-stands, and the carbon returned to the ocean during low-stands of sea-level via epidiagenetic oxidation of organic-rich shelf sequences.

A91-8 Nd and Sr isotope stratigraphy of phosphates from the North Carolina Continental Margin: **<u>Stille, P., Riggs, S., and Clauer, N., 1991</u>, European Union of Geologists, Terra, v. 3, no. 1.**

ABSTRACT

More than twenty Upper Cenozoic depositional sequences bound by cross-shelf unconformities have been defined for the North Carolina continental margin. Different phosphate grain types from specific planktonic biochronozones were used for Sr and Nd isotope investigations. The average $^{87}Sr/^{86}Sr$ isotopic composition value of different grain types from the same phosphatic sample (peloids, intraclasts, brachiopods, bone splinters, and vertebrae) is 0.70864 ± 4. The analytical spread corresponds to a middle Miocene age (15.3 to 16.5 Ma), using the secular variation curve of Sr in seawater (DePaolo and Ingram, 1985), and is in excellent agreement with the ages deduced from planktonic biochronozones. Diagenetically altered Miocene peloid grains, that have been eroded and reworked during the Quaternary and Holocene, yield Sr isotopic compositions identical with that of the pristine Miocene phosphate samples. This suggests that even the reworked phosphate samples did apparently not record diagenetic $^{87}Sr/^{86}Sr$ imprints and did not suffer interaction with high $^{87}Sr/^{86}Sr$ typical for continent derived material. Therefore, similar to marine carbonates, phosphates can be very powerful material for Sr high-resolution stratigraphy. The average ΣNd values of the different Miocene phosphate grain types in the samples studied for Sr show a narrow variation between -6.3 and -6.5. They are identical with the Atlantic seawater Nd isotopic composition at that time. Peloids in the Quaternary sediments that have been reworked from the Miocene show ΣNd values identical with the pristine Miocene phosphates. This indicates that they did not undergo diagenetic alteration with new $^{143}Nd/^{144}Nd$ imprint and may be potentially used for stratigraphic purposes when the secular variation of Nd in seawater will be more constrained.

<u>1990</u>

A90-1 Oxygen isotope geochemistry of Miocene phosphate grains from Onslow Bay, N.C.: evidence for Miocene Western Boundary Current induced upwelling: **<u>Crowson, R.A., Showers, W.J., and Riggs, S.R., 1990</u>, Geological Society of America, Abstracts with Programs, v. 22, no. 7, p. A354.**

ABSTRACT

Extensive deposits of phosphorite (>50% phosphate grains) formed during the early to middle Miocene in Onslow Bay, North Carolina. These phosphorite deposits are exposed on the sea floor and are contiguous with those deposits currently being mined by Texasgulf, in Aurora, NC. A detailed petrographic examination of these deposits reveal a composition of at least 12 distinct phosphatic grain types, which are represented by 6 major forms: 1) Peloids--spherical to oblate grains, 2) Intraclasts--irregularly shaped grains, 3) inarticulate brachiopod shell fragments, 4) small fish vertebrae of unknown

speciation, 5) elongate bone splinters, and 6) fish teeth. Peloids formed beneath the sediment-water interface and represent the interstitial water record. Brachiopods and intraclasts formed at the sediment-water interface and represent the benthic water record. Small fish vertebrae, bone splinters and fish teeth formed in the overlying water mass and represent the pelagic realm.

Oxygen isotopic analysis was conducted on a two meter core from the Burdigalian section near Frying Pan Shoals, Onslow Bay, North Carolina. Isotopic analyses were completed on the six major grain types downcore at a 20 cm interval using a modified silver phosphate ion exchange technique originally developed by Wright and Hoering (1989). Results of these analyses indicate that brachiopod shells and intraclasts are consistently isotopically heavier than peloids and skeletal grains (vertebrae and bone splinters). Differences of 10°C were obtained between surface and bottom water temperatures based upon the relative oxygen isotopic difference between brachiopods and fish vertebrate. The postulated isotopic thermal gradient between Miocene surface waters and bottom waters is consistent with the thermal gradients observed in modern high organic productivity upwelling sites originating from strong western boundary currents (Pietrafesa, 1990).

A90-2 Late Quaternary glacio-eustatic sea-level fluctuations: what are the sedimentological processes and stratigraphic responses on continental margins?: Riggs, S.R., Snyder, Stephen W., and Hine, A.C., 1990, EOS, v. 71, no. 2, p. 167.

ABSTRACT

Published stable isotope data from deep-sea sediments clearly show that the earth's climatic cycles have oscillated through at least 10 major glacial and interglacial episodes during the last million years. These high-frequency, orbitally-forced events should have resulted in major glacioeustatic sea-level fluctuations on the continental margins with dramatic sedimentologic effects and stratigraphic responses. However, such high-frequency events have proven difficult to resolve. Are they too short-lived to be recorded, too complex to decipher, or have traditional stratigraphic tools not been adequate to recognize them in continental margin sequences? A detailed, multidisciplinary study of various continental margins is necessary to test the sensitivity of sedimentologic systems and response in stratigraphic records. This study must utilize 1) high-resolution event stratigraphy to define the depositional and erosional sediment sequences; 2) sediment analyses to delineate depositional environments and characterize lithofacies of specific system tracts; and 3) biostratigraphic and geochronologic analyses to place the depositional sequences in time. Integration of these data sets will 4) determine the resolving power of sequence stratigraphy; 5) develop working stratal models for recognizing short-pulsed, glacioeustatic sea-level events within the stratigraphic record; and 6) define a chronostratigraphy of changing paleoclimatic and paleoceanographic events operating on continental margin systems during the late Quaternary.

A90-3 Miocene glacio-eustasy, phosphogenesis, and climate change: Snyder, Stephen W., Compton, J.S., Hodell, D.A., and Riggs, S.R., 1990, Geological Society of America, Abstracts with Programs, v. 22., no. 7, p. A196.

ABSTRACT

Seismic, isotopic, and lithostratigraghic studies of Miocene sections from the Carolina Platform and the Florida Platform indicate primary phosphogenesis was generally limited to the Burdigalian and Langhian Stages (N-6 through N-9 Zones of Blow, 1969). Most Serravallian phosphates appear reworked. The timing of these primary phosphogenic events is synchronous with a pronounced enrichment of $\delta^{13}C$ in global seawater (i.e., the "Monterey" excursion). Moreover, lithostratigraphic sections from the Jacksonville Basin, FL, and Onslow Bay, NC, are relatively rich in phosphate, glauconite, siliceous muds, dolomite, and other sediments indicative of intense upwelling. Yet, organic carbon and pyrite constituents are well below that expected for a ancestral upwelling site. The phosphatic sections are also separated from younger sequences by a long-standing hiatus (about 2 ma in duration) interpreted to be the consequence of falling global sea-levels. Epidiagenetic episodes during this early Serravallian lowstand interval are suspected to have oxidized and removed most of the organic carbon originally buried.

Miocene upwelling episodes cumulatively produced at least 10^{11} metric tons of phosphate concentrate (30 to 35% P_2O_5) within the southeastern U.S. continental margin. We believe the burial of light carbon within the SE USA during the early Miocene resulted in a global $\delta^{13}C$ enrichment event. The removal of carbon from ocean/atmosphere reservoirs amplified global Miocene cooling via a reverse greenhouse effect. Antarctic ice-sheets enlarged ($\delta^{18}O$ enrichment event), and sea-level fell. Epidiagenesis during the subsequent prolonged lowstand oxidized much of the buried early Miocene organics. This resulted in a global shift back toward a lighter $\delta^{13}C$ (preexcursion values). We therefore believe the southeastern USA provides a better explanation for the Monterey excursion than Pacific margin phosphates because (1) the timing of primary phosphogenesis and subsequent epidiagenesis closely match the $\delta^{13}C$ excursion; and (2) boundary current upwelling is not wind-driven and therefore does not require global cooling (intensification of zonal winds) prior to the initiation/intensification of upwelling regimes.

1989

A89-1 Miocene clay mineral facies: inter-relationships between phosphorite and dolomite formation and siliciclastic sedimentation, mid-Atlantic U.S. Continental Margin: Riggs, S.R., and Allison, M., 1989, Proceedings, 9th International Clay Mineralogy Conference, Strasbourg, France, Abstracts, p. 457.

ABSTRACT

The Miocene section on the mid-Atlantic United States continental margin is characterized by moderate concentrations of organic matter; very high

concentrations of a suite of abnormal authigenic and early diagenetic minerals that include phosphate, dolomite, silica polymorphs, clinoptilolite, and Mg-rich clay minerals; all complexly inter-mixed with a suite of more normal biogenic carbonates and siliciclastics. During a 6 million year portion of the Miocene (from 18 to 12 mya), sedimentation was characterized by at least 18 high-frequency (< 200 Ky), high-amplitude (> 50 m) episodes of deposition alternating with episodes of nondeposition, erosion, and late diagenetic alteration that complicated the primary sediment patterns and altered many of the mineralogical components. These fourth-order depositional sequences are interpreted to be sedimentological responses to high-frequency climatic and glacio-eustatic sea-level cycles and associated changing paleoceanographic conditions. The regional patterns of phosphate, carbonate, and siliciclastic sedimentation are directly related to the changing interaction between the paleotopographic and paleogeographic setting and paleoceanographic conditions through each transgressive-regressive cycle.

X-ray, chemical, and electron microscope examination of clay-sized minerals from lithologically diverse shelf and upper slop sediments of the Miocene section reveal strong environmental zonations. Three distinct clay mineral suites are recognized. 1) Detrital illite and smectite are chemically variable, occur together in approximately equal proportions, and are the dominant clay minerals occurring throughout all lithofacies and crossing regional lithofacies boundaries. 2) Muddy quartz sand lithofacies deposited proximal to siliciclastic point sources contain clay mineral suites with significant concentrations of detrital kaolinite and chlorite. This assemblage reflects the intense chemical weathering from the adjacent coastal plain and piedmont province source area. 3) Authigenic or very early diagenetic dolomite lithofacies contain a clay mineral suite distinguishable by the presence of sepiolite and palygorskite. These Mg-clay minerals appear to be penecontemporaneous with dolomite formation and therefore, are either authigenic or very early diagenetic in origin. Contemporaneous diatom dissolution provided the silica source. Phosphatic lithofacies, which occur primarily within the transition zone between the muddy quartz sand and dolomite lithofacies, are characterized by the detrital illite-smectite clay suite. Clay mineral assemblages in the Miocene sediments display no evidence of late diagenetic alteration; thus, they appear to be 'original signal' depositional indicators. If this is the case, the clay mineral facies provide an important index of changing depositional environments and sea level events. This is particularly important in interpreting the complex Miocene stratigraphic sequence since the depositional units have been severely complicated by episodes of late diagenesis and erosion by subsequent transgressive-regressive events.

A89-2 Mid-Cenozoic glacio-eustacy: detailed record of high-frequency sea-level changes from the North Carolina Continental Margin: Snyder, Stephen W., Hine, A.C., Snyder, Scott W., and Riggs, S.R., 1989, 28th International Geological Congress, Washington, D.C., Abstracts, v. 3, p. 144.

ABSTRACT

Interpretations from a dense network (20,000 km) of very high-resolution seismic reflection profiles collected from the North Carolina estuaries, shelf,

and upper slope have defined over 30 regional unconformities. These physical surfaces of discontinuity were used to construct a relative chronostratigraphic framework by stacking the unconformities and intervening sequences vertically according to superposition. Correlations to well, auger, and drill hole data were used to establish initial age relationships. These correlations were confirmed by penetrating stratigraphic targets along the seismic lines via 140 continental shelf vibracores. Eighteen Miocene and eight Oligocene sequences have been identified.

A comprehensive biostratigraphic study (planktic foraminifera, nannofossils, radiolarian, and diatoms; Scott W. Snyder, 1988) of the shelf vibracores has rendered relatively tight constraints on the timing of Miocene depositional and erosional events. Biochronologic constraints on the Oligocene sequences are not as well defined. Herein, absolute values of time are relative only to the calibrated biogeochronologic time scheme of Haq et al. (1987).

Four biostratigraphic gaps divide the composite Miocene record into three distinct stratigraphic sections.

1. Mid-Burdigalian section consists of 6 distinct shelf sequences; deposition started near the N-5/N-6 boundary of Blow (1969) (ca. 18.7 ma) and continued until NN-3/NN-4 boundary of Martini (1971)(ca. 17.6 ma).
2. Langhian section consists of several outliers and 4 prograding shelf-margin sequences; deposition started near the NN-4/NN-5 nannofossil boundary (ca. 16 ma) and lasted until the boundary between N-9/N-10 (ca. 14.8 ma); the 4 shelf margin sequences are confined to zone III of Abbott's (1978) Atlantic Margin Diatom Zonation scheme (AMDZ), which is approximately equivalent to the N-9 global biochron (ca. 0.5 ma in duration).
3. Serravillian section consists of 8 depositional sequences, although the upper 3 sequences were found to be nearly barren of index microfossils; deposition began near the N-11/N-12 biochron boundary (ca. 13.2 ma); the upper age limit for the lower 5 Serravallian sequences is placed just below the N-12/N-13 boundary (ca. 12.1 ma) based on the identification of diatom species from Atlantic Margin Diatom Zone VI; the upper limit of all 8 sequences is not defined.

A large hiatus separates the Miocene and Oligocene deposits. It spans the NN-1 through NN-2 biochrons (ca. 6 ma in duration). Available biostratigraphic data also indicate that the Oligocene sequences can be divided into at least two sections separated by hiatuses.

1. The Chattian section consists of five shelf sequences containing nannoplankton assigned to zone NP-25 and planktic foraminifera assigned to the P-22 through N-4 biochrons (latest Oligocene).
2. The Rupeilan section consists of three prograding shelf-margin sequences deposited in association with the ancestral Gulf Trough, an Oligocene Seaway connecting the Gulf of Mexico with the North Atlantic Ocean. Fletcher (1986) and Jones (1983) found the Rupeilan sequences to contain planktic foraminifera assigned to biochron P-19/P-20 (early Oligocene).

All of the mid-Cenozoic sequences are bound by cross-shelf unconformities. They are therefore interpreted to be the products of discrete sea-level fluctuations. Many of the unconformities are marked by paleofluvial channels that indicate subaerial exposure and render some constraints on the minimum elevation of lowstand events. Benthic foraminiferal assemblages give a semiquantitative description of water depth at the time of deposition; they have been used to help quantify the highstand sea-level positions. Collectively, these data suggest that the amplitudes of the sea-level cycles ranged between ± 50 and ± 200 m. The duration of the Miocene sea-level fluctuations is estimated by dividing the number of sequences by the time limits defined in the biostratigraphic data set. This calculation renders the periodicity for Miocene sea-level oscillations on the order of 10^5 years (4th order). We conclude that this high frequency of high-amplitude sea-level fluctuation could only be driven by glacioeustacy associated with climatic changes forced by the orbital-perturbations described by Milankovitch (1941). Better resolution in time is required before the periods of the Oligocene sea-level cycles can be quantified.

While most of the mid-Cenozoic sequences are believed to be the products of glacioeustacy, the origin of all five sections and their intervening hiatuses remains more speculative. Each section spans over 1 ma in duration is separated by hiatuses lasting up to 6 ma. They may be the products of lower-frequency sea-level oscillations; however, correlations with the 3rd-order cycles of Haq et al (1987) is poor. Many of the hiatuses may have been generated or modified by significant erosional episodes associated with extended lowstand events or Gulf Stream scour. These erosional events could have removed the stratal products of prior sea-level events. Numerous scars of the western boundary current have been identified in the seismic sections. Their role in exhuming and removing records of older sea-level events from the North Carolina margin needs to be quantified by extending the seismic network farther seaward across the slope and Northern Blake Plateau.

A89-3 Subsidence versus eustatic flooding rates: their relative roles in controlling the preservation of coastal and shelf sequences: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1989, 28th International Geological Congress, Washington, D.C., Abstracts, v. 3, p. 145

ABSTRACT

Recent stratal models offered by Exxon Production Research (EPR) depict the depositional products of a generic sea-level cycle as a thick aggradational wedge consisting of coastal, shelf, and shelf margin lithosomes or "system tracks" (Haq et al, 1987). In contrast, stratigraphic studies from the North Carolina coast and continental shelf show that the depositional records of Quaternary glacioeustatic sea-level cycles are generally confined to estuarine-filled paleofluvial channels.

Interpretations of high-resolution seismic profiles and vibracores, supplemented by auger data and ^{14}C and amino acid racemization dates from the shelf-barrier-lagoon complex off Bogue Banks, North Carolina (USA), have demonstrated that stratigraphic incision by the shoreface profile has exhumed and removed almost the entire sedimentary record of the Holocene Transgression. Only Tertiary and early Pleistocene sequences crop out on the continental shelf. The erosional mode of this transgression is presently captured by the modern shoreface that is actively exhuming a stacked sequence of barrier-backbarrier

coastal lithosomes. These include (1) a basal Pleistocene sequence cut by (2) fluvial channels filled with early Holocene estuarine sediments, which are overlain by (3) a Holocene lagoonal section heavily dissected by a series of tidal inlet channels, and finally capped by (4) a relatively thick section of late Holocene regressive shoreface sands. Lagoonal and inner shelf seismic profiles demonstrate that none of the Holocene barrier-backbarrier lithosomes underlying Bogue Banks will be preserved because they all lie above the depth of stratigraphic incision by the shoreface. Only a few early Holocene paleofluvial channels, which have cut stratigraphically lower into the Pleistocene and Tertiary sequences, have the potential to be preserved as the shoreface continues to migrate landward with sea-level rise.

Analyses of the composite seismic network from the adjacent continental shelf demonstrates that paleofluvial channel-fill lithosomes of Quaternary age are quite abundant. Their surface outcrops cover approximately one-third of the seafloor of the shelf embayment of Onslow Bay. Profiles from inland rivers and estuaries depict the composite Pleistocene section as a mosaic of fluvial and estuarine sediments dissecting a few isolated highstand shorelines. Amino acid racemization dates from in situ mollusca demonstrate that these limestones represent the stratigraphic products of at least eight different Pleistocene sea-level events.

Poor seismic coverage and the lack of drill/vibracore data have limited our analyses of Quaternary records along the outer shelf and upper slope. Existing data depict a series of prograding shelf-margin sequences consisting of oblique clinoforms downlapping onto Tertiary outcrops within the Northern Blake Plateau. A few channels oriented parallel to the shelf margin truncate these progradational wedges. The channels were probably cut by currents associated with the Gulf Stream.

The depositional record of Quaternary glacioeustatic sea-level oscillations along the North Carolina continental margin can be summarized as consisting of a few paralic highstand shorelines separated from a series of prograding shelf margin wedges by paleofluvial channel-fill lithosomes buried in Tertiary continental shelf outcrops. The most complete record of the glacioeustatic sea-level fluctuations is probably preserved in the paleofluvial channels, because successful erosional transgressions have consumed many former highstand shoreline deposits, and Gulf Stream scour has repeatedly attacked the shelf-margin records. The difference between this record and the thick aggradational sequence proposed in the stratal model of Haq et al. (1987) is related to absolute shelf flooding rates.

Using the sea-level curve from Bermuda (Neumann, 1971) as a record of Holocene eustacy, maximum flooding rates are calculated as exceeding 800 cm/Ka. Stable passive continental margins overlying continental crust or old, thermally contracted, rift-stage crust is subsiding at rates less than 1 cm/Ka. This is the case for the Carolina Platform. The effective maximum flooding rate is therefore estimated at 801 cm/Ka for the North Carolina margin. At that rate, the shoreline is capable of crossing the continental shelf dozens of times before the margin subsides a few meters. Stratigraphic incision by the shoreface during each cross-shelf transit reworks and removes all coastal and shelf lithosomes, leaving only a few channels cut deeply into the older shelf outcrops.

In contrast, the maximum flooding rate of any Cenozoic 3rd-order sealevel cycle delineated in the curve of Haq et al. (1987) was calculated to be 13 cm/Ka (cycle TB 2.3 at 100 m/800 Ka). Subsidence along a stable continental platform margin such as North Carolina (1 cm/Ka) would lower the shelf approximately 10 m during this 3rd-order sea-level event. Thus, some of the coastal and shelf lithosomes would be capable of subsiding below the depth of stratigraphic incision by the shoreface. Along younger continental margins (overlying hot rift-stage crust), or areas of severe isostatic loading (Mississippi delta and fan), subsidence rates range between 50 and 1000 cm/Ka. This significantly increases the potential for preservation of all the system tracks, regardless of the eustatic flooding rate. Thus, the rates of eustatic flooding and regional subsidence can be used to help determine the mode of any transgressive sea-level event; erosional (mostly channels preserved) versus depositional (preservation of a vertical succession of transgressive and highstand system tracks).

1988

A88-1 Distribution patterns and environmental controls on clay sedimentation in the Miocene Pungo River Fm., North Carolina Continental Margin: Allison, M.A., and Riggs, S.R., 1988, Geological Society of America, Abstracts with Programs, v. 20, no. 4, p. 252.

ABSTRACT

X-ray diffraction, SEM, EDX and chemical analysis of clay minerals in the Pungo River Formation indicate that smectite, illite, kaolinite and chlorite are of detrital origin, whereas palygorskite and sepiolite exhibit authigenic textures. Smectite and illite, the dominant clay minerals, always occur together in approximately equal proportions which remain constant across regional lithofacies and depositional sequence boundaries. Kaolinite and minor chlorite occur together in variable concentrations. They are generally confined to muddy quartz sand lithofacies that were deposited on the inner-shelf, proximal to major clastic point sources. Palygorskite and sepiolite typically co-occur associated with the dolomite-rich lithofacies. These Mg-clays appear to have formed penecontemporaneously with dolomite in oxygen deficient, outer-shelf environments. The phosphorite lithofacies contains a non-distinctive, smectite-illite assemblage with minor amounts of other clays. Clay mineral data support the following conclusions.

1. Vertical patterns between inner-shelf kaolinitic assemblages and outer-shelf Mg-clay assemblages reflect portions of transgressive and regressive cycles.
2. Clay minerals show no alteration associated with lowstand diagenesis during multiple Miocene sea-level events.
3. Illite in deeper-water facies appears to be undergoing structural rebuilding to a well-crystallized, possible "precursor glauconite".
4. Scarcity of detrital 4-layer clays and lack of large-scale variations in clay mineralogy suggest that warm, stable climatic conditions existed on the adjacent continent from late-early through middle Miocene.

A88-2 Trace element and stable isotopic trends associated with diagenesis of selected benthic foraminifers from Miocene sediments: Jones, W.E., Snyder, Scott W., Moretz, L.C., Bray, J.T., and Showers, W.J., 1988, Geological Society of America, Abstracts with Programs, v. 20, no. 4, p. 273.

ABSTRACT

Analyses of the benthic foraminifers Hanzawaia concentrica, Bolivina paula and Florilus pizarrensis from one fourth-order seismic sequence in the lower Miocene section of the Pungo River Formation provide a record of the type and pattern of diagenesis. Vibracores spanning the entire outcrop and shallow subcrop extent of this sequence on the North Carolina continental shelf were sampled at one-half meter intervals. Trends in Sr/Ca ratios provide the most useful geochemical record of diagenesis. From south to north within the sequence, Sr/Ca ratios decrease as both the intensity of recrystallization of foraminiferal tests and the mean grain size of sediments increase, all of which reflects increased diagenesis toward an early Miocene point-source for siliciclastics. Sr/Ca ratios also decrease upward within the sequence along its entire extent, revealing a diagenetic profile in which the intensity of alteration diminishes downward from the overlying unconformity. Trends in Sr/Ca ratios are similar for all three species, suggesting that each has been subjected to a diagenetic history similar in type but not necessarily in intensity. Compared to the other two species, smaller scale changes in ratios for Bolivina paula suggest less intense alteration. All three species show very little stratigraphic isotopic variation, so that trends upward within the sequence are difficult to relate in any meaningful way to other indicators of diagenetic intensity. Isotopic data are generally consistent with diagenesis in a marine pore-water environment.

A88-3 Recrystallization, mineralization and diagenetically induced geochemical change in benthic foraminifers from Miocene sediments of the North Carolina Continental Shelf: Moretz, L.C., Snyder, Scott W., and Bray, J.T., 1988, Geological Society of America, Abstracts with Programs, v. 20, no. 4, p. 282.

ABSTRACT

Analyses of foraminifers from 25 vibracores representing seven fourth-order Miocene seismic sequences, which range in age from middle Burdigalian to middle Serravallian, reveal several types of diagenesis with varying degrees of intensity. The degree of recrystallization, assessed by comparison to an experimentally derived index, increases upward within each sequence toward the overlying unconformity. Relative changes in Sr/Ca ratios, based on energy dispersive x-ray fluorescence analyses of Hanzawaia concentrica and Bolivina paula, exhibit a corresponding decrease. Used in conjunction with one another, trends in recrystallization and Sr/Ca ratios are useful for delineating unconformities, even those difficult to recognize lithologically. In addition to vertical variations within a given seismic sequence, both intensity of

recrystallization and Sr/Ca ratio values differ significantly from one lithology to another (phosphorites versus carbonate and siliciclastic sands versus siliciclastic and organic-rich muds). Sediment grain size appears to be the primary controlling factor. Post-depositional mineralization, which occurs largely within the vacant chambers of foraminiferal tests, is associated with organic-rich sediments. The zeolite mineral clinoptilolite occurs primarily in the organic-rich muds of southern Onslow Bay, whereas pyrite is less abundant but more widespread. Regionally, most types of diagenesis decrease southward as sediments fine away from a Miocene siliciclastic point-source. The common occurrence of isopachous cements low in Fe and Mg indicates early diagenesis in a marine environment.

A88-4 Relationship of organic carbon to lithofacies and cyclic deposition in the Miocene Pungo River Fm., North Carolina Continental Margin: Powers, E.R., Riggs, S.R., and Maxwell, E., 1988, Geological Society of America, Abstracts with Programs, v. 20, no. 4, p. 309.

ABSTRACT

Total organic carbon (TOC) and major element analyses were performed on over 250 samples of all major lithofacies. Major elements were assigned to three sediment categories and normalized to 100% as follows: % SiO_2 + % Al_2O_3 = % terrigenous sediment; % CaO (corrected for CaO in phosphate and dolomite) = normal authigenic sediments (calcite); and % P_2O_5 + % MgO (dolomite) = abnormal authigenic sediments. The results were correlated with TOC and integrated with the lithostratigraphy. Cluster analysis defined seven major facies, each characterized by distinctive lithology and chemistry and reflecting different depositional environments.

Highest TOC values (mean = 1.6 wt. %) occur in very muddy facies rich in diatoms and foraminifera. Intermediate TOC values (mean = 1.2 wt. %) occur in facies containing high concentrations of primary phosphate and dolomite. In contrast, facies dominated by quartz sand and macrofossiliferous biogenic calcite, have the lowest TOC values (means = 0.8 and 0.4 wt. %, respectively). Lithostratigraphic analysis of third- and fourth-order sea-level events suggests sediments with high TOC values (1 to 6 wt. %) and significant concentrations of primary phosphate and dolomite occur primarily in transgressive portions of depositional sequences. Facies associated with regressive portions are characterized by a) low TOC values (< 1%), b) reworked and secondary phosphate and dolomite, and c) quartz sand and biogenic calcite as the dominant components. Also, associated sediment structures and fossils suggest that most transgressive facies are characterized by dysaerobic benthic environments and regressive facies by aerobic conditions.

A88-5 Present status of offshore phosphate deposits, U.S. Atlantic Continental Margin: Riggs, S.R., 1988, Proceedings, 20th Underwater Mining Institute, Woods Hole, Massachusetts, Abstracts, v. 20, p. 8-9.

ABSTRACT

Phosphate deposits on the southeastern U.S. coastal plain have long been the major force in world phosphate markets. World markets continue to grow, but the role of U.S. resources is rapidly declining. This situation results from a complex interaction of economic, political, and environmental factors. Causes for this ongoing erosion of the U.S. market include:

1. escalating costs;
2. changes in land-use patterns;
3. environmental pressures on conventional mining techniques;
4. exhaustion of shallow, high-grade resources in Florida; and
5. increased, low-cost production in other countries throughout the world.

In fact, some agencies and commodity personnel predict that the U.S. will become a net phosphate importer early in the next century.

If this projection is correct, the U.S. industry must look towards major changes in the near future in order to continue to compete in the world market. One possible change includes development and application of unconventional mining techniques to cheaply recover vast 'new' potential resources in areas with lower land-use pressures. These 'new' resources include:

1. deep phosphorites within major sediment basins of the southeastern coastal plain and
2. subsurface phosphorites on the continental shelf and within the EEZ.

These latter resources include extensive deposits in Onslow Bay, N.C.; broad regions offshore of Savannah, Ga. and Cape Canaveral, Fla.; and the central portion of the west Florida shelf. Little research and exploration has been done on these poorly known offshore resources due to the prior healthy economic situation of land-based mining and short-term attitudes of both industry and government. Recent ongoing research has demonstrated that specific target areas do contain or have a high probability of containing quantities of phosphate similar to that estimated for the entire recoverable resource base of the southeast with a quality similar to that presently being mined in N.C. and the southern portion of central Florida.

In 1987, an Economic Feasibility Study of mining phosphate in the U.S. EEZ adjacent to North Carolina was completed by Development Planning and Research Associates, Inc. This study, contracted by the U.S. Department of the Interior and the State of North Carolina, was to be the basis for making decisions regarding future research tasks necessary for possible future development of the resource. A similar study is presently in progress by Zellers-Williams, Inc. concerning the State of Georgia and similar continental shelf deposits adjacent to Georgia.

The preliminary resource assessment by the DPRA study provided an independent evaluation of the quantity and quality of the known phosphate deposits. Based upon this evaluation, the report concluded that "several geologic units contain phosphate ores that have the potential to be developed into a commercial mining operation." However, they also stressed that in spite of the extensiveness of the existing data base, it was collected to fulfill other

research objectives. Thus, this data base represents early stage continental margin exploration and does not contain enough specific information within the potential areas to carry out detailed economic studies essential for mining. Consequently, the report also concluded that "additional sampling and particularly deep drilling are critical to further delineate this substantial phosphate resource" and is the appropriate next step towards future development.

1987

A87-1 Stable isotopes and cyclic deposition in the Miocene Pungo River Formation, North Carolina Continental Margin: Crowson, R.A., Showers, W.J., and Riggs, S.R., 1987, Marine Geochemistry Volume of Abstracts, Gordon Conference on Marine Geochemistry, p. 13.

ABSTRACT:

Previous work in the Carolina Neogene phosphatic shelf sequences have resulted in critical baseline sedimentation models developed from a synthesis of seismic-, lithic-, and biostratigraphic data. These shelf sequences reveal major fluctuations in sea level, paleoclimatic, and paleoceanographic conditions which have occurred during the deposition of discrete seismic units. These depositional units are characterized by a recognizable lithological progression and a repeated diagenetic signature with diagenetic intensity decreasing downsection through each fourth-order depositional cycle. Preliminary isotopic and geochemical data suggests that we can define and decipher the syndepositional and post-depositional diagenetic profiles. We now propose to generate detailed geochemical profiles of $\delta^{18}O$ phosphates, $\delta^{18}O$ and $\delta^{13}C$ of carbonates, and $\delta^{15}N$ and $\delta^{13}C$ of organic material, associated organic content data, and trace element data to test the depositional models for the Miocene phosphogenic sediments on the Carolina continental margin. These records can then be compared to the high-resolution, deep-sea paleoceanographic records currently being generated to develop a more detailed understanding of global Miocene paleoceanography during the early to middle Miocene $\delta^{13}C$ cycle.

A87-2 Continental margin sedimentation and sea-level cyclicity: complex depositional and erosional responses: Riggs, S.R., Snyder, Stephen W., and Hine, A.C., 1987, Geological Society of America, Abstracts with Programs, v. 19, no. 2, p. 126.

ABSTRACT

The Carolina continental margin has been dominated by major glacio-eustatic sea-level fluctuations for at least 20 million years. Climatic and oceanographic forces produced allocyclic responses in the deposition of multiple, high-resolution stratigraphic sequences which were modified and complicated by the interaction of various erosional processes. The resulting continental margin sediment sequences are characterized by the following.

1. Multiple sediment units were deposited cyclically at several different

spatial and temporal scales with specific lateral and vertical facies relationships that were often repeated through many sea-level events.

2. Associated processes of erosion and diagenesis operated at various stages through each sea-level event, modified each depositional unit, and complicated the geometry, facies patterns, and sediment components as follows.
   A. During low sea-level stages, previously deposited depositional sequenceswere subaerially weathered, diagenetically altered, and extensively eroded and channeled by fluvial drainage systems extending across the margin.
   B. Through each transgression, shore-face retreat across the shelf eliminated most depositional facies representing the coastal environments.
   C. During transgressions, the Gulf Stream interacted with continental margin environments by locally truncating seaward portions of depositional sequences on the slope; eroding and channelling the sediments on the shelf; and modifying paleoceanographic conditions of deposition in the shelf environments.

Thus, each unit may have been partially or totally removed by subsequent erosion and, if preserved, may contain an alteration profile reflecting the post-depositional history.

A87-3 Benthic foraminifera as indicators of Pliocene oceanography in the Mid-Atlantic coastal zone: Snyder, Scott W., and Mauger, L.L., 1987, Geological Society of America, Abstracts with Programs, v. 19, no. 2, p. 130.

ABSTRACT

Pliocene deposition in eastern North Carolina is represented largely by the Yorktown Formation. Muddy, phosphatic quartz sand of the lowermost Yorktown grades upward into muddy, quartz sand capped by partially indurated, carbonate-cemented sand in which fossils have been mostly dissolved. The middle Yorktown consists of sandy mud with an upper carbonate zone characterized by minor dissolution. Mud content decreases abruptly in quartz sand of the upper Yorktown. Cluster analysis reveals that benthic foraminiferal assemblages are related to specific lithostratigraphic sequences. Lower Yorktown assemblages contain relatively high percentages of taxa known to tolerate organic enrichment and oxygen depletion. *Nonionella miocenica* is predominant, followed by *Florilus pizzarensis* and *Bulimina elongata*. Middle and upper Yorktown assemblages are predominated by *Cibicides lobatulus*, particularly in the uppermost quartz sands which contain little mud. *C. lobatulus* is the most abundant species in muds of the middle Yorktown, but *Parafissurina bidens*, *Elphidium excavatum*, *Globocassidulina crassa* and *Buccella frigida* are also numerically important. Assemblages predominated by *C. lobatulus* suggest more highly oxygenated bottom conditions than those indicated for the lower Yorktown.

Trends in sediment composition, grain size and benthic foraminiferal assemblages suggest the following sequence of events:

1. initial coastal onlap with waters of moderate nutrient enrichment that may have been associated with a minor episode of phosphate formation,
2. abrupt coastal offlap marked by a period of dissolution,

3. coastal onlap during which muds accumulated, and

4. brief offlap followed by deposition in highly oxygenated waters.

Sea level fluctuations implied by this scenario generally agree with those suggested by the most recently published chart of Haq et al. (1986).

1986

A86-1 **Offshore phosphate deposits: new developments in U.S. waters:** Burnett, W.C., and Riggs, S.R., 1986, **Underwater Mining Institute, Abstracts, v. 18, p. 18-19.**

ABSTRACT

The land phosphate deposits of the U.S. southeastern coastal plain have long been a major factor in the world trade of phosphate rock (Fig. 1). As recently as 1979, deposits of North Carolina and Florida alone accounted for about 33 percent of the entire world's phosphate exports. This situation is changing, however. World production increased by about 9%, yet the U.S. share was down to about 28% in 1984. A complex interaction of economic and political factors combined with increasing costs of raw materials, production, and transportation have led to this systematic erosion of the U.S. market share. Changing land-use patterns within the southeast, environmental pressures, exhaustion of shallow high-grade resources in Central Florida, and the increased pressure from expanding low-cost production in other countries throughout the world account for much of the present difficulty in the U.S. phosphate industry. Considering this depressed environment -- what are the prospects for development of offshore resources? A summary of new research on offshore phosphorite within the U.S. Exclusive Economic Zone (EEZ), as well as an attempt to place possible development of these resources within the current economic setting, is the purpose of this presentation. We will emphasize work in progress on a major offshore deposit along the U.S. Atlantic Margin as well as new research on Pacific Ocean occurrences of phosphorite on seamounts and insular slopes within U.S. waters.

Research on the southeastern U.S. continental margin has led to a series of important scientific developments which demonstrate the potential for extensive, high-grade phosphate deposits within our EEZ. For example, recent research in the Onslow Bay, North Carolina area has delineated extensive submarine phosphate deposits of Neogene age in the shallow subsurface of the continental shelf. Geologically, these deposits are an extension of the coastal plain deposits currently being mined. The deposits on land apparently represent only a very small updip portion of the total volume of phosphate-enriched sediments which were deposited on the Miocene continental shelf. Subsurface, poorly documented Miocene sediments are known to extensively occur on continental shelves in many areas throughout the world. These represent a potentially vast additional resource of sedimentary phosphate. Before this possibility can be realized, however, a thorough three-dimensional evaluation of the offshore areas is required. Evaluations utilizing high-resolution seismic stratigraphy and deep drilling together with continued developments in offshore mining technology, have the best hope of expanding the phosphate resource base.

Recent expeditions in the Pacific Ocean have shown that phosphorite occurrences on seamounts and other raised portions of the sea floor are more common than previously thought. Theories suggest that these "open-ocean" phosphorites originate by either marine replacement of limestone, hyaloclastite, etc., or by submergence of a previously existing insular phosphate deposit. Our studies indicate that both processes produce these deposits with the marine type predominant.

A86-2 Bioerosional development of submarine scarps in Onslow Bay, North Carolina: Carter, J.G., and Mearns, D.L., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 19-20.

ABSTRACT

Submarine scarps at depths of 25 to 30 meters in Onslow Bay, North Carolina, reflect differential bioerosional undercutting and structural failure of calcarenites and concomitant differential preservation of bioerosion-resistant siliciclastic hardgrounds. Scarp faces of 4 to 8 meters relief are produced by localization of predominantly chemically boring bivalves to the more sediment-free vertical faces and undersides of the calcareous substrata.

Bivalved molluscs are quantitatively more important than clionid sponges as agents of bioerosion in Onslow Bay. Despite the occurrence of varied substrata, chemically boring bivalves such as lithophaginids and gastrochaenids are far more numerous than more strictly mechanically boring bivalves such as Petricola typica, Jouannetia quillingi and Hiatella arctica. The primary agents of chemical bioerosion in Onslow Bay are, in decreasing order of abundance, Lithophaga bisulcata, Gastrochaena stimpsonii, G. ovata, L. aristata, clionid sponges, L. antillarum, Botula fusca, Gregariella coralliophaga, Spengleria rostrata, and G. hians. Except for the absence of Lithophaga nigra, this is a typical tropical endolithic bivalve fauna. Infestation of these bivalves on exposed surfaces of the coral Solenastrea hyades suggest bioerosion rates of 0.5 to 1.5 cm/year. This rate can account for most of all the apparent 80 meter recession of the scarp faces during the past 5,000 to 7,000 year.

A86-3 Stratigraphy and diagenesis of carbonate sediments in the Miocene Pungo River Formation, Aurora Phosphate District, North Carolina: Forgang, J.A., and Riggs, S.R., 1986, SEPM Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts v. 3, p. 39.

ABSTRACT

The Pungo River Formation in the Aurora Phosphate District (APD) consists of four depositional units, each characterized by an upper omission surface. Significant differences occur in carbonate composition and diagenesis between depositional units; however, the lateral character within each unit is consistent throughout the APD. Carbonate sediments are composed of a) calcitic lime mud, b) biogenic skeletal material, c) dolomite and d) local carbonate cements. All carbonate components are either low magnesium calcite or nonferroan, Mn^{2+} depleted, calcium dolomite. Carbonate sediments range from unconsolidated to

indurated units and occur as a) laterally continuous beds capping depositional units; b) thin interbeds with phosphorite and siliciclastic sands; c) local, isolated nodules and lenses; and d) subordinate components disseminated within phosphorite and siliciclastic sands.

Petrographic analysis reveals the following textures associated with calcite and dolomite components:

1. pervasive development of molluscan-moldic porosity and later occlusion of porosity by sparite cementation,
2. intra- and intergranular sparite and skeletal bladed to blocky sparite cementation,
3. echinodermal syntaxial rim cementation, and
4. equant to subequant to radiaxial poikilotopic calcite cementation.
5. dolomitization of precursor skeletal and nonbiogenic carbonate,
6. intracrystalline dissolution of multi-zoned, calcian dolomite which is compositionally controlled,
7. relict intracrystal dolomite porosity commonly filled with calcite cement,
8. dedolomitization of grains occurring in burrow in-fill structures, and
9. local silicification of carbonate components occurring as a later-stage textural fabric.

A86-4 A model for the occurrence of glauconie on the modern and Miocene North Carolina Continental Shelf/Slope: Mallinson, D.J., and Otte, L.J., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 70.

ABSTRACT

The extremely low concentration of Fe within marine water necessitates the existence of a terrigenous Fe source for the formation of glauconitic sediments. Iron is rapidly removed from solution as salinities and pH increase during estuarine mixing. A mechanism to transport this Fe to deeper water environments, where glauconitic sediments commonly occur, may be found in fourth-order eustatic sea-level fluctuations. During regressive phases Fe-rich transitional environments are "flushed" and their Fe, clays and organics are deposited in deeper waters. The position of deposition on the shelf or slope should largely depend on the amplitude of regression. Organic and Fe reduction, transgressing seas and development of a downlap surface (low sedimentation rates) permit the concentration of Fe within substrate pore spaces and the precipitation of glauconie. The efficiency with which Fe may be concentrated and the abundance of reducing micro-environments should increase upsection with transgressing seas and lessening disturbance and oxidation of the substrate pore water. This should correspond with an upsection increase in the abundance of glauconie. In the Miocene Pungo River Formation (North Carolina Continental Shelf) glauconie is sparse to absent in all but one seismic sequence. This one shows an upward increase in glauconie abundance and a decrease in overall clay content. In this case the trend may be related to a previous low amplitude regressive phase leaving Fe stranded on the outer shelf. On the modern Northern Blake Plateau glauconie precipitation is occurring, probably as a result of the deposition of Fe-rich sediments well downslope during the last major regression. Glauconie

distribution and petrology in the Eocene Castle Hayne Fm. (N.C. Coastal Plain) also supports the terrigenous Fe-source model.

A86-5 A direct comparison of sonograph images of Onslow Bay prior to and following Hurricane Diana, Sept. 11-13, 1984: profile of a high-energy, storm-resistant shelf: Mearns, D.L., Hine, A.C., and Riggs, S.R., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts v. 3, p. 76.

ABSTRACT

Hurricane Diana was a small but intense storm that circulated in southern Onslow Bay for 33 hours before making landfall at Cape Fear, North Carolina. Previously, seafloor mapping exercises with side-scan sonar were conducted in the same area of the middle continental shelf where Diana remained nearly stationary while exhibiting her maximum force (sustained surface winds of 217kph/135mph). Shortly after the storm, a second sonograph mosaic was obtained to investigate the possible impact to the shelf surface.

The resulting mosaics delineated a rugged seafloor characterized by extensive zones of high-relief hardbottom/livebottom, bioeroded rock debris, outcropping Miocene muds and reworked Holocene sands. In each instance, however, direct comparison of the pre-storm and post-storm sonographs failed to reveal any measurable change. Overhanging scarps were believed to be particularly susceptible to failure if upwards (or downwards) water thrust and erosional scour had further weakened their bases. However, close comparison of the blocks forming the most proximal and recently eroded row of debris revealed no additional failure. Distinct spatial patterns representing textural variations between the Miocene muds and Holocene sands, and fields of loose rock debris appeared exactly alike in both mosaics as well.

The resistant nature of the shelf surface in Onslow Bay reflects its ambient, high-energy setting, which includes periodic exposure to tropical cyclones and severe winter storms (northeasters). Prior frequent disturbances have apparently modified the shelf and its associated livebottom community whereby erosion, transport and biological mortality was negligible.

A86-6 Hardbottom distribution and geomorphology as seen in side-scan sonographs of Onslow Bay, North Carolina Continental Shelf: Mearns, D.L., Hine, A.C., and Riggs, S.R., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 76.

ABSTRACT

High-resolution seismic and side-scan sonar profiling, in addition to vibracoring and rock dredging, reveals that morphologically complex hardbottoms (exposed rock surfaces) extensively crop out on the inner and middle continental shelf of Onslow Bay, North Carolina. The hardbottoms are of two types:

1. outcroppings of calcareous quartz sandstones associated with regionally southeast dipping Paleogene/Neogene stratigraphic sequences, and

2. outcroppings of heavily bored and stained fossiliferous calcarenites unconformably overlying these upper Tertiary sequences.

Within Onslow Bay, their distribution is controlled such that the two types primarily occupy different regions: the former the northeast and the latter the southwest.

Both types of hardbottom share similar morphologies, the main elements of which are erosional escarpments and unlithified ramps, preferentially oriented in a southwest and northeast facing direction, respectively. Convoluted scarp margins are the result of intensive bioerosion, excavation and structural failure, primarily mediated by endolithic bivalves. Commonly reaching between 4 and 8 meters in height, they serve as the focal point for a tropical livebottom community including bottom reef fishes. Zones of massive boulder debris as wide as 80 meters flank the scarp margins and are indicative of the rapid erosion.

Hardbottom development and the processes leading to their degradation play an important role in the formation of shelf unconformities, and ultimately sequence boundaries. Ancient hardbottoms exposed throughout the coastal plain, in addition to subsurface data from Onslow Bay, represent a record of these processes as far back as the Eocene.

A86-7 Patterns of benthic foraminiferal diagenesis in relation to cyclic sedimentation in the Miocene Pungo River Formation, North Carolina Continental Shelf: Moretz, L.C., Snyder, Scott W., and Jones, W.E., 1986, SEPM Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts v. 3., p. 80-81.

ABSTRACT

Benthic foraminifera within Pungo River sediments of Onslow Bay exhibit various types and degrees of diagenetic alteration that relate to patterns of cyclic sedimentation within the formation. The upper surfaces of seismic sequences are commonly diastemic. Diagenetic intensity changes with increasing distance downward from such surfaces. Within any given sequence, types of diagenesis may include:

1. dissolution profiles in which foraminiferal molds, usually of clinoptilolite and sometimes of phosphate, occur in the upper portion of a sequence while preservation of tests improves downward;
2. overgrowths of calcite or dolomite that become less pronounced downward;
3. recrystalization of foraminiferal tests accompanied by growth of secondary minerals such as clinoptilolite, pyrite, calcite, dolomite and glauconite within test chambers.

Precipitation of clinoptilolite within tests is restricted to southern Onslow Bay where dissolution of diatoms provided a source of silica. Framboidal pyrite, often found in association with clinoptilolite, occurs within test chambers and on the exterior surfaces of tests. SEM and thin-section analyses confirm that pyrite formation postdates precipitation of clinoptilolite, as does the dissolution of foraminiferal tests. Calcite and dolomite overgrowths are predominant in central and northern Onslow Bay. Dissolution of surrounding carbonate sediments supersaturated marine phreatic waters with calcium carbonate, allowing isopachous calcite and dolomite cements to grow on interior and exterior surfaces of test walls.

A86-8 Biostratigraphic correlation of Miocene phosphorites on the North Carolina Coastal Plain and Continental Shelf based on diatoms and silicoflagellates: Powers, E.R., 1986, **SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 91.**

ABSTRACT

Diatom and silicoflagellate floras indicate that Miocene Pungo River sediments near Aurora, NC correlate with Miocene sequences which crop out on the continental shelf in Onslow Bay. High resolution seismic profiles delineate three third-order depositional sequences within the Pungo River Formation of Onslow Bay. They have been informally named the FPS, OBS, and BBS sequences, from oldest to youngest. Diatom and silicoflagellate floras from these sequences indicate deposition during the late Burdigalian, Langhian and early Serravallian stages, respectively. Lithostratigraphic studies have informally designated four depositional units in the Aurora Phosphate District (A, B, C, and D from oldest to youngest). Regional correlations of floras from both areas indicate the following:

1. Species common to the Actinoptychus heliopelta zone of Abbott (1978) occur in unit A in Aurora.
2. Unit B in Aurora contains floras representative of the A. heliopelta zone and the Naviculopsis navicula silicoflagellate zone of Martini and Muller 1976. These zones also occur in the FPS sequences in Onslow Bay.
3. Units C and D in Aurora are assigned to the D. ovata and Delphineis ovata/D. penelliptica zones. These zones also occur in the uppermost FPS and lowermost OBS sequences of Onslow Bay.

These assignments indicate the following interpretations:

1. Units A and B in Aurora were deposited during the late Burdigalian stage and were deposited contemporaneous with FPS sequences in Onslow Bay.
2. Units C and D were deposited during the Langhian stage and are thus correlative with the OBS sequences of Onslow Bay.
3. Strata equivalent to the uppermost sequence (BBS) in Onslow Bay have not been recognized at Aurora.

These biostratigraphic relationships demonstrate that the major phosphate deposit in Onslow Bay (lower FPS sequences) is equivalent in age to the lowermost deposits at Aurora (units A and B), but is older than the upper phosphate bed (unit C).

A86-9 Diatom biostratigraphy of the Miocene Pungo River Formation, Onslow Bay, North Carolina Continental Shelf: Powers, E.R., 1986, **American Association of Petroleum Geologists, Bulletin, v. 70, no. 5., p. 634.**

ABSTRACT

Diatom floras in the Miocene Pungo River Formation of the North Carolina continental margin indicate deposition from the late Burdigalian to middle Serravallian stages. Assemblages from 15 vibracores from the continental shelf in Onslow Bay, N.C. and one stratigraphic section from the phosphate mine at Aurora, N.C. provide the basis for biostratigraphic interpretations. High-resolution seismic profiling in Onslow Bay has delineated at least eighteen fourth-order seismic sequences, each bounded by unconformities, which can be grouped into third-order sequences named FPS, OBS, and BBS from oldest to youngest. Biostratigraphic age assignments are based on indicator species of Abbott's 1978 Atlantic Miocene diatom zonation, in which Actinoptychus heliopelta and Delphineis ovata do not co-occur. The A. heliopelta zone spans the Burdigalian, and the D. ovata zone is early Langhian. Their co-occurrence in the lowermost third order sequence (FPS) in Onslow Bay suggests a late Burdigalian age. The overlying OBS sequence contains species common to the D. ovata / D. penelliptica zone. The concurrent range zone of these species indicates the Langhian stage. The uppermost BBS third-order sequence contains definitive species of the Coscinodiscus plicatus zone of the middle Serravallian stage. The intervening D. penelliptica and D. penelliptica / C. plicatus zones have not yet been observed in the BBS sequence. Samples from the lower Pungo River Formation at Aurora contain abundant specimens of A. heliopelta and other species characteristic of the Burdigalian, suggesting correlation with the FPS sequence of Onslow Bay. Upper Pungo River sediments at Aurora yielded no diatoms.

A86-10 Future U.S. phosphate resources: a new perspective: Riggs, S.R., 1986, American Institute of Mining Engineers Program, Proceedings Abstracts, p. 4.1.

ABSTRACT

Extensive phosphate resources occur within the Miocene Hawthorn and Pungo River Formations which have not been considered in the past since they were poorly known and were not available to conventional mining. These resources include 1) deep phosphates that occur below 75 meters of overburden within major sediment basins throughout the southeastern coastal plain, and 2) offshore phosphates that occur on the continental shelf and within the U.S. Exclusive Economic Zone (EEZ). The future potential of these two vast resources will be realized with development of new mining technologies such as hydraulic slurry mining and integrated with advanced technology already being utilized in the offshore petroleum industry.

A86-11 Cyclical patterns of diagenetic alteration associated with multiple episodes of deposition and erosion within the Miocene Pungo River Formation, southeastern United States: Riggs, S.R., and Snyder, Scott W., 1986, 12th International Sedimentological Congress, Canberra, Australia, Abstracts, p. 258.

ABSTRACT

Differentiating diagenetic from synsedimentary processes is fundamental to unraveling the depositional history of continental margin sedimentation during

the Miocene and to resolving the controversial problem of phosphate genesis. The Miocene Pungo River Formation of the North Carolina continental margin is characterized by the following.

1. Cyclical sedimentation of depositional units occurred at several different spatial and temporal scales.
2. An anomalous suite of authigenic sediments was formed, including multiple episodes of phosphogenesis with specific vertical and lateral facies relationships.
3. Nondepositional and erosional episodes followed the deposition of each unit, complicating both the sediment patterns and components.
4. Due to sea-level cyclicity and associated changes in paleoceanographic processes that produced the Neogene sediments, a diagenetic phase of sedimentation was systematically overprinted on most depositional units.

Three types of diagenetic signatures are recognized within most depositional units, with the intensity of alteration generally decreasing downward from each upper diastemic surface:

1. modification of foraminiferal tests,
2. modification of phosphate grains, and
3. new mineral formation.

The simple, primary mineralogy and chemistry of foraminiferal tests are sensitive indicators to post-depositional alteration by 1a) dissolution, and 1b) recrystallization, and 1c) mineralization. Phosphate grains display processes of 2a) dissolution, 2b) recrystallization, 2c) rimming, and 2d) distinct trace element profiles. New mineral formation includes 3a) carbonate fluorapatite, 3b) clinoptilolite, 3c) dolomite, 3d) glauconite, 3e) opal, 3f) calcite cements, and 3g) siderite- magnesite. Each unit, if not partially or totally removed by subsequent erosion, is characterized by alteration profiles which reflect its specific post-depositional history (ie., degree and type of geochemical processes that have affected the sediment components and extent of sediment removal by erosion from each depositional unit).

A86-12 SEM-BSE observations, isotopic stratigraphy and trace element geochemistry--qualification of diagenesis of benthic foraminifera in the Pungo River Formation, North Carolina: Showers, W.J., Lent, R.M., Margolis, S.V., Snyder, Scott W., and Baker, P., 1986, EOS, Transactions of the American Geophysical Union, v. 67, no. 16, p. 296.

ABSTRACT

The isotopic stratigraphy of three benthic foraminifera have been investigated in the phosphate-bearing Pungo River Formation, North Carolina. The two coarsely perforate epifaunal species, *Siphogenerina lamellata* and *Hanzawaia concentrica*, show little stratigraphic isotopic variation and the isotopic data suggest that diagenesis has occurred associated with a fresh water dispersal system. The finely porous infaunal species, *Bolivina paula*, shows a definitive isotopic stratigraphic signal, with more negative $\delta^{13}C$ values associated with higher sedimentary phosphate content. Strontium trace element geochemistry of the larger two species of epifaunal benthic foraminifera suggest that these species have undergone 50 to 80% bulk recrystallization. SEM-BSE

(back scattering electron) analysis shows that this recrystallization has occurred as solution in the walls of the epifaunal foraminifera and precipitation of crystals in the walls and on the inner chamber surfaces. Recrystallized carbonate material is brightly luminous under SEM-BSE. In contrast, the infaunal species, B. paula, shows no evidence of recrystallization under SEM-BSE examination. The isotopic data from this species can therefore be used for paleoceanographic interpretations. SEM-BSE examination can be used prior to isotopic analysis to qualify diagenesis in biogenic carbonates.

A86-13 Paleofluvial channel-fill sequences: keys to resolving Quaternary glacio-eustatic sea-level events: Snyder, Stephen W., Hine, A.C., and Belknap, D.F., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 104.

ABSTRACT

Stratigraphic interpretations from over 21,000 km of high-resolution seismic reflection profiles within the North Carolina continental margin have delineated a complex mosaic of subbottom channel-fill sequences. Detailed mapping exercises have demonstrated that these lithosomes are:

1. volumetrically important occupying over 40% of the modern sea-floor; and
2. the only Quaternary stratigraphic record that is preserved on the continental shelf of Onslow Bay.

Vibracores penetrating these sequences have recovered sediments representing a variety of fluvial (point bar/overbank) and estuarine paleoenvironments, each having its own distinct seismic facies. Amino acid racemization dates from in situ mollusc shells indicate that channel cutting occurred in association with at least 7 different low-stand events, and multiple estuarine infilling episodes appear to have been coincident with interglacial isotope stages 5, 7, 9, 11, 13, 15, 19, and 21.

Shoreface profiles show stratigraphic incision by the nearshore profile is exhuming all the Holocene coastal lithosomes beneath Bogue Banks (e.g., barrier, lagoon, tidal delta, and tidal inlet facies). However, paleofluvial channels filled with early-mid Holocene estuarine sediments are being preserved. Considering the a) number of transgressions which have traversed the continental margin during the Quaternary, b) erosional nature of these transgressions, and c) the generally poor-preservation potential of coastal lithosomes; then, collectively, the channel-fill sequences probably hold the most complete stratigraphic record of Quaternary sea-level fluctuations within the North Carolina continental margin.

A86-14 Shifting sites of Miocene phosphorite deposition: the critical depth hypothesis: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1986, SEPM Annual Midyear Meeting, Society of Economic Paleontologists and Mineralogists, Abstracts, v. 3, p. 105.

ABSTRACT

The sites of primary Miocene phosphogenesis within the North Carolina continental margin shifted between at least 3 distinct depocenters. These phosphogenic episodes are interpreted to be a consequence of topographically-induced upwelling which requires the Gulf Stream (GS) to be deflected by bathymetric highs. Modern studies of GS flow dynamics depict similar upwelling events occurring within cyclonic meander eddies generated by a vorticity imbalance acquired via frictional effects. The resulting upwelled waters occupy areas 50 to 110 km in diameter along the outer shelf and upper slope, and are always found 100 to 200 km downstream from the deflection site. Application of these modern GS flow criteria to our Miocene stratigraphic studies helps explain both the episodic nature of phosphogenesis as well as the frequent shifts in the position of phosphorite deposition.

All 3 Miocene phosphorite depocenters are located within 200 km of inferred deflection sites. Deposition within these areas occurred during successive 4th-order (10^5 yrs) glacioeustatic sea-level events. However, phosphogenesis occurred only when the paleobathymetry forced the Gulf Stream to be deflected by topographic highs. If sea level was too low, then the GS was positioned seaward of the potential deflection site. If sea level was too high, the GS could over-ride the bathymetric high without any deflection or frictional effects. Thus, there was a critical depth range at which topographically-induced upwelling occurred with respect to each local bathymetric high. Miocene shifts in the position of phosphogenesis probably reflect changing deflection sites as the GS interacted with different bathymetric highs while migrating landward and seaward in concert with each 4th-order sea-level cycle.

A86-15 Miocene unconformities, chronostratigraphy, and sea-level cyclicity: fine-tuning the early Neogene relative coastal onlap curve for the North Carolina Continental Margin: Snyder, Stephen W., Hine, A.C., Riggs, S.R., and Snyder, Scott W., 1986, American Association of Petroleum Geologists, v. 70, no. 5, p. 651.

ABSTRACT

Stratigraphic interpretations of over 21,000 km of high resolution seismic reflection data have identified at least 18 discrete depositional sequences within the Miocene section of the North Carolina continental margin. Each sequence is bounded by erosional unconformities and/or condensed sections. These Miocene unconformities have been traced and mapped throughout the North Carolina continental margin, which demonstrates that they are regional chronostratigraphic hiatuses.

Biostratigraphic analyses (planktonic foraminifera and calcareous

nannofossils) from over 900 meters of stratigraphic section recovered from 140 vibracores penetrating Miocene sequences on the continental shelf have identified significant biostratigraphic gaps associated with four of the Miocene unconformities. These four major unconformities divide the Miocene sequences into three distinct ages, each generally correlative to third-order cycles of relative coastal onlap proposed by Vail and Hardenbol (1979).

Each third-order sequence consists of several fourth-order sequences. These higher frequency sea level events are interpreted to be driven by glacioeustatic fluctuations throughout the Miocene Epoch. The duration and amplitude of each third- and fourth-order sea level event will be presented. They are based on the biostratigraphic constraints, the identification of type 1 unconformities (marked by paleofluvial channels) versus type 2 unconformities (recognized by condensed sections characterized by bored, indurated carbonate hardgrounds), as well as paleoenvironmental interpretations of benthic foraminiferal assemblages (maximum amplitudes).

Thus, these data have allowed us to approximate the duration and amplitude of Miocene sea level events identified within North Carolina, and to fine tune the early Neogene relative coastal onlap curve for this segment of the western North Atlantic continental margin.

1985

A85-1 High-resolution seismic stratigraphy of the North Carolina Continental Margin, Cape Fear Terrace: sea-level cyclicity, paleobathymetry, and Gulf Stream dynamics: Matteucci, T.D., Hine, A.C., Snyder, Stephen W., and Riggs, S.R., 1985, American Association of Petroleum Geologists, Bulletin, v. 69, no. 2, p.284.

ABSTRACT

A high-resolution seismic stratigraphic study of the Cape Fear Terrace (outer continental shelf off North Carolina) combined with bio- and lithostratigraphic data has yielded a chronostratigraphic framework of the Quaternary sequences that comprise this portion of the North American continental margin. The Cape Fear Terrace is an anomalous, point-source prograding shelf-margin feature that has experienced positive relief through much of the Quaternary. This upbuilding or outbuilding followed a period of active early Pliocene submarine erosion in which the ancestral Gulf Stream cut an erosional path beneath the present shelf margin. The terrace was originally built up during a relative lowstand of sea level with the construction of a shelf-edge deltaic feature. Severe modification of this delta front occurred during a relative highstand of sea level as the Gulf Stream began to impinge upon the margin. The anomalously thick accumulation of shelf-edge sediments acted as a barrier to flow, inducing complex flow patterns of the Gulf Stream. Excavation of these sediments yielded a terrace feature with preferential erosion on the upstream side.

Subsequent deposition in the terrace region may have resulted during fairly high stands of sea level as evidenced by the presence of active seaward-prograding sand waves in the terrace region today. Once this shelf-edge bathymetric irregularity (the terrace) had been established the Gulf Stream acted

as a dynamic force inducing cellular flow structures within the shelf environment, which enabled sediments to be transported seaward along the paleo-shoals complex.

A85-2 Direct evidence of a hurricane's impact on a continental shelf: Hurricane Diana in Onslow Bay, North Carolina, Sept. 11-13, 1984: Mearns, D.L., Hine, A.C., Riggs, S.R., and Snyder, Stephen W., 1985, Geological Society of America, Abstracts with Programs, v. 17, no. 2, p. 125.

ABSTRACT

Hurricane DIANA was a small but intense storm (maximum sustained winds of 217 kph; 135 mph) that circulated in southern Onslow Bay for 32 hours before striking the North Carolina coastline. One hundred days earlier, we had obtained a tight grid of side-scan sonar profiles from the exact area of the middle continental shelf where DIANA remained nearly stationary while exhibiting her maximum force. The resulting sonograph mosaic provided an excellent database from which to compare a second mosaic, obtained from the same area shortly after the storm.

Comparison of the two mosaics indicated that the hurricane had little effect on the sea floor despite the expected 8 meter and higher wave heights. Spatial patterns in surface reflectivity, due to variations in grain size remained the same in both mosaics. Post-storm TV imagery and rock dredgings indicated that the biological community, consisting largely of soft corals, hard corals and sponges, remained intact and did not appear to be stressed. Finally, bioeroded scarps incised into the limestone outcrop, as well as the adjacent zones of boulder-debris, showed no recognizable change in their configuration, pattern and orientation.

The apparent insignificant effect of this hurricane on this portion of the continental shelf is due in part to:

1. DIANA's small size,
2. limited fetch available to generate long-period swells, and
3. the relatively resistant nature of the seafloor geology.

A85-3 The geomorphology and biological erosion of continental shelf hardbottoms as seen in side-scan sonar mosaics: Onslow Bay, North Carolina: Mearns, D.L., Hine, A.C., and Riggs, S.R., 1985, Geological Society of America, Abstracts with Programs, v. 17, no. 2, p. 125.

ABSTRACT

Extensive high-resolution seismic and side-scan sonar profiling, in addition to vibracoring and rock dredging, have shown that topographically and morphologically complex hardbottoms (exposed rock surfaces) extensively crop out on the inner and middle continental shelf off North Carolina. The hardbottoms are of two types:

1. outcroppings of calcareous quartz sandstones associated with the regionally southeast dipping Paleogene/Neogene stratigraphic

sequences, and

2. outcroppings of Quaternary, well-lithified calcarenites unconformably overlying these Tertiary sequences.

The Quaternary hardbottoms exhibit the highest relief (from 2 to 8 m), represented primarily by the steep, bioeroded scarps which serve as the focal point for a tropical community of algae, sponges, coral, epibenthic encrusters, benthic infauna and bottom reef fishes. Scarp formation involves a steady process of intensive bioerosion by boring molluscs which yields an overhanging, undercut cliff that eventually fails under its own weight. The resultant rock-debris initially takes the form of immense rectangular blocks (5 m by 10 m) which flank the hardbottom margins while continually providing coarse material to the shelf as they are further degraded. Hardbottom development and the processes leading to their degradation play an important role in the formation of shelf unconformities, and ultimately sequence boundaries. Ancient hardbottoms exposed throughout the coastal plain, in addition to subsurface data from Onslow Bay, represent a record of these processes as far back as the Eocene.

A85-4 Benthic foraminiferal paleoecology of Miocene deposits in central and northern Onslow Bay, North Carolina Continental Shelf: Moore, T.L., and Snyder, Scott W., 1985, Geological Society of America, Abstracts with Programs, v. 17, no. 2, p. 126.

ABSTRACT

Three third-order seismic sequences (correlative to third-order sea level changes) constitute the sediments of the Miocene Pungo River Formation in central and northern Onslow Bay. Benthic foraminiferal associations vary with sediment type through each seismic sequence. One association comprises species known to thrive in high-nutrient, low oxygen conditions (Bolivina paula, Buliminella elegantissima, Florilus pizzarensis). These species typically abound where phosphate, which forms in zones of nutrient enrichment, is plentiful. The other association, predominated by Valvulineria floridana, Hanzawaia concentrica, and Cibicides spp., characterizes more normal marine environments. The FPS sequence, stratigraphically lowest of the three sequences, grades upward from moderate to low phosphate content. Buliminella elegantissima predominates in the phosphatic portion; it is gradually replaced by Valvulineria and Hanzawaia as phosphate decreases. The overlying OBS sequence is carbonate-rich and generally devoid of phosphate. The most abundant foraminiferal species are Cibicides lobatulus and C. americanus. This sequence contains discrete horizons with low phosphate content but an unexpected abundance of Bolivina paula and Buliminella elegantissima. The presence of diatoms in these intervals does, however, indicate that nutrient-rich conditions, although not associated with phosphate formation, did prevail. The BBS sequence is the youngest and most lithologically variable. Phosphate-rich and diatom-rich portions contain abundant Bolivina paula. Non-phosphatic and non-diatomaceous intervals are marked by abundant Hanzawaia, Cibicides and Valvulineria. The uppermost BBS sediments contain phosphate in association with Valvulineria and Hanzawaia, an unexpected affiliation suggesting the phosphate has been transported from its site of origin.

A85-5 Planktonic foraminiferal biostratigraphy of cyclical Miocene deposits in central and northern Onslow Bay, North Carolina Continental Shelf: Snyder, Scott W., and Moore, T.L., 1985, Geological Society of America, Abstracts with Programs, v. 17, no. 2, p. 137.

ABSTRACT

Miocene Pungo River sediments in Onslow Bay comprise at least 18 seismic sequences, each related to fourth-order sea level cyclicity, which can be grouped into three third-order seismic sequences (informally designated FPS, OBS and BBS, from oldest to youngest). Seismic, lithologic and benthic foraminiferal data indicate cyclic deposition, with each fourth-order sequence being separated from the one above by an unconformity. The FPS sequence correlates with planktonic foraminiferal Zones N6/N7 (Burdigalian). Sediments assigned to Zone N6 are characterized by the co-occurrence of Globigerinatella insueta, Globigerinoides quadrilobatus altiapertura and Catapsydrax unicavus; those assigned to Zone N7 are marked by the first appearances of Globigerinoides sicanus praesicanus, Globorotalia scitula praescitula and G. acrostoma. The OBS sequence, which lies within the N8-N10 zonal interval (Langhian), is recognized by the disappearance of diagnostic early Miocene taxa (Globigerinoides quadrilobatus altiapertura, G. q. primordius, species of Catapsydrax), the transition from Globigerinoides sicanus praesicanus to typical G. sicanus sicanus and the appearance of rare specimens of Orbulina universa. The BBS sequence contains a foraminiferal association indicating the N11-N14 zonal interval (Serravallian). This age assignment is based on the co-occurrence of common, well preserved specimens of Globigerinoides bollii (not seen in the OBS sequence) and Globorotalia siakensis. Also, the Globigerinoides sicanus complex, consistently present in the OBS sequence, does not occur in the BBS sequence. Biostratigraphic age assignments, in conjunction with the regional seismic data base, are the basis for detailed correlation of Pungo River cyclic sediment patterns with relative changes of eustatic sea level.

A85-6 More evidence for a glacial world prior to the middle Miocene oxygen isotope enrichment event: resolution of early Miocene glacio-eustatic sea-level cyclicity from North Carolina: Snyder, Stephen, Snyder, Scott, Waters, V.J., Steinmetz, J.C., Hine, A.C., and Riggs, S.R., 1985, Geologic Society of America, Abstracts with Programs, v. 17, no. 7., p. 721.

ABSTRACT

Benthic $\delta^{18}O$ analyses from DSDP sites worldwide have documented a positive excursion (≈+1.5 o/oo) through the early-middle Miocene. These data are traditionally interpreted as marking the transition from an "ice-free" world to one that was extensively glaciated. Recently, however, this doctrine has been challenged, and an alternative hypothesis suggests the benthic $\delta^{18}O$ excursion primarily reflects a temperature drop within a previously glaciated world.

Within the North Carolina continental margin, a chronostratigraphic framework consisting of 6 discrete early Miocene depositional sequences was

established via stratigraphic interpretations from over 21,000 km of high-resolution seismic reflection profiles. Each sequence is bound by unconformities which were mapped throughout the continental margin. Biostratigraphic analyses (planktonic foraminifera and nannofossils) of 140 vibracores penetrating these sequences demonstrate that each sequence is a consequence of 4th-order (10^5 years) sea-level cyclicity, similar in duration (100 to 300 ka) and amplitude (100 to 150 m) to the glacioeustatic sea-level fluctuations of the Quaternary Epoch.

Recognition of late Burdigalian high-frequency (4^{th}-order) sea-level cyclicity demonstrates that continental ice sheets were large enough during the early Miocene to drive eustatic sea-level fluctuations with Milankovitch-type periodicities. This further supports Matthews (1984) hypothesis that continental ice caps existed on Antarctica PRIOR to the well documented middle Miocene benthic $\delta^{18}O$ global enrichment event.

1984

A84-1 Origin of dolomites in the Miocene phosphorites of the Pungo River Formation, North Carolina: Allen, M.R., and Baker, P.A., 1984, Geologic Society of America, Abstracts with Programs, v. 16, no. 6, p. 428.

ABSTRACT

The Miocene Pungo River Formation has been divided into four cyclic units in the Aurora Phosphate District of North Carolina. Eighteen similar units have been identified on the continental shelf off North Carolina (Riggs, 1984). Each unit begins with a terrigenous regressive facies which grades upwards into a phosphatic facies and is capped by a marine carbonate transgressive facies. The carbonate consists of barnacle, foraminifera, and other shell fragments, calcite mud, and, in some units, dolosilt and dolomite mud. The dolosilt occurs as clear uniform euhedral rhombs and often dominates the matrix between biogenic fragments, phosphate pellets and intraclasts, and other grains.

Samples from cores in the Aurora District and offshore in Onslow Bay were provided by Stan Riggs. These were analyzed by petrographic XRD, SEM, chemical, and stable isotope techniques. In thin section the dolomite is seen as dispersed rhombs which rarely replace shell material. A few dolomite rhombs are found included in phosphate intraclasts. This suggests that dolomite formation at least sometimes predates phosphatization. X-ray diffraction and elemental analyses identify the dolomite as non-stoichiometric (40 to 50 mole % Mg) and poorly ordered. Dolomites were analyzed for stable oxygen and carbon isotope ratios to determine whether the dolomite formed in fresh, marine, or mixed waters and to assess the importance of microbial sulfate reduction during dolomitization. Measured oxygen isotopic values range from about $\delta^{18}O = +3.5$ to $+5.5\%$ (PDB) and carbon isotopic values range from about $\delta^{13}C = -1.5$ to -4.0% (PDB). The oxygen isotopic values prove an origin in cool shelf waters of wholly marine origin. The slightly negative carbon values result from a minor incorporation of organic carbon into dolomite, perhaps during early stages of sulfate reduction.

A84-2 Cd/Ca and Zn/Ca ratios in sedimentary phosphorites and their relationship to paleonutrient levels in the Miocene phosphorites of North Carolina: Ellington, M.D., Riggs, S.R., and Bray, J.T., 1984, Geologic Society of America, Abstracts with Programs, v. 16, no. 3, p. 136.

ABSTRACT

Present oceanic distributions of cadmium and zinc parallel the major nutrients phosphorus and nitrogen. Recent isotope and trace element geochemistry suggests that increased paleonutrient levels of the deep ocean are reflected by increased Cd/Ca and Zn/Ca ratios in specific fossil planktonic foraminiferal tests (Boyle, 1981; Boyle and Keigwin, 1982; Kester and Boyle, 1982). As phosphate sedimentation reflects changing nutrient levels within the depositional environment, Cd/Ca and Zn/Ca ratios of phosphate grains should reflect changing paleonutrient patterns during phosphate formation.

Pelletal phosphate concentrates were hand-picked from four depositional units of the Pungo River Formation, including a late early Miocene unit from Onslow Embayment and three middle Miocene units from the Aurora Embayment. The elements P, Ca, Cd, and Zn were analyzed by plasma emission spectroscopy. Cd/Ca and Zn/Ca ratios range from 0.083 to 0.919 and 1.90 to 7.29, respectively. Plots of Cd/Ca and Zn/Ca ratios versus P_2O_5 content of the total sediment show positive correlations; Cd/Ca and Zn/Ca ratios increase as the total volume of P_2O_5 increases in the sediments. This correlation may reflect changing nutrient phosphorus levels to the continental shelf and consequent changing rates of phosphate formation and deposition. If this hypothesis is correct, lateral and vertical changes in the ratio profiles could be used to predict sites of optimum phosphogenesis within and between each depositional sequence in a phosphogenic province.

A84-3 Silica authigenesis in calcareous fossils: Neal, D.W., Gray, B.E., and Stewart, T.L., 1984, Geologic Society of America, Abstracts with Programs, v. 16, no. 6, p. 608-609.

ABSTRACT

Types and patterns of silicification in calcareous fossils were examined to determine if variations could be related to changes in age, silica source, and mineralogy and texture of the carbonate host. Silicified material from various geographic locations (Kentucky; West Virginia; Chihuahua, Mexico; North Carolina Continental Shelf) and ages (Mississippian, Cretaceous, Miocene) show little variation which can be attributed to geography or age. Biogenic, volcanic, and diagenetic sources of silica do not appear to influence the type of replacement seen in the fossils. The greatest variation in the type of silica found and the patterns of silicification results from differences in the texture of the original carbonate and/or the solubility of the original carbonate minerals. Fossil skeletal material with a fibrous appearance (brachiopods, bryozoans, pelecypods) are more susceptible to replacement by the development of subhedral to euhedral megaquartz crystals with long axes parallel to the long

axes of the carbonate "fibers". Skeletal material composed of single crystals (echinoderms) or microgranular calcite (foraminifers, ostracodes, barnacles) tend to be replaced most commonly by microcrystalline quartz. Chalcedonic quartz occurrence does not seem to be related to carbonate texture but is related to carbonate mineralogy. Where aragonitic fossil material has been leached and porosity developed, botryoidal accumulations of chalcedony precipitate. This is often associated with the presence of a thin ribbon of microcrystalline quartz which originally may have been opal. Botryoidal chalcedony is also associated with the presence of iron sulfide/oxide grains which often serve as a nucleus on which the silica is precipitated.

A84-4 Paleoceanographic model for Neogene phosphorite sedimentation, southeastern U.S. Continental Margin: Riggs, S.R., 1984, in 1982 Symposium of 5th International Workshop and Seminar on Phosphorite, China National Committee for International Geologic Correlation Program: Geological Publishing House, Beijing, China, v. 2, p. 225-226.

ABSTRACT

Neogene phosphogenic episodes of southeastern U.S. are characterized by:

1. spatial relationships between structure and phosphate deposition;
2. regional distribution patterns of terrigenous, carbonate, and phosphate sediments across the shelf; and
3. cyclical patterns of lithofacies.

These depositional patterns are explained by a paleoceanographic model based upon Neogene glacial events which resulted in:

1. fluctuations of global sea level across the shelf;
2. climatic changes influencing terrigenous influx to the shelf; and
3. modification of the path and dynamics of the Gulf Stream causing different oceanographic water masses to dominate the shelf.

During periods of low sea level, characterized by cooler, more arid climatic conditions and a seaward location of the Gulf Stream, the shelf is dominated by terrigenous sedimentation. As sea level rises, the climate moderates causing a decrease in terrigenous input and migration of the Gulf Stream up against the continental margin. Phosphate sedimentation is initiated in response to first- and second-order structurally-induced Gulf Stream meanders and frontal eddies; this results in the development of cold, deep, nutrient-enriched upwellings onto the outer shelf. The intensity of upwelling and phosphate deposition increases and migrates landward with the transgression. During periods of high sea levels, the affects of the bottom structures in causing upwelling are diminished and warm surface waters of the Gulf Stream dominate the shelf. Warm and humid climatic conditions produce fine-grained terrigenous sediments with subtropical faunas on the inner shelf and grade seaward into carbonate sediments; this sequence caps each transgressive cycle. During the subsequent regression, the carbonates are commonly indurated, shells leached, and sediment by-pass surfaces bored and phosphatized.

A84-5 Patterns of Miocene phosphate sedimentation on the southern United States Continental Margin: Riggs, S.R., 1984, 27th International Geologic Congress, Moscow, U.S.S.R., Abstracts, v. VII, p. 300-301.

ABSTRACT

Extensive drilling and stratigraphic work throughout the southeastern U.S. coastal plain-continental shelf system by many workers have established that the Hawthorn and Pungo River Formations of Miocene age are contemporaneous and contiguous sediment units characterized by abnormally high concentrations of sedimentary phosphate. Neogene sediments are characterized by cyclical depositional patterns which represent several different time scales and distinctive distribution patterns of major lithologic components which represent changing environmental conditions. These cyclical patterns of deposition were direct responses to fluctuations in sea level and associated changes in paleoceanographic and paleoclimatic conditions. A major phosphogenic episode was coincident with the fairly long second-order Miocene transgression. Each sediment unit and sequence of units within the Hawthorn and Pungo River formation, and their associated unconformity surfaces, correlate with fourth-order and established third-order cycles of eustatic sea-level change, respectively.

Changing paleoceanographic conditions interacted with extensive shallow shelf platform environments of first-order structural highs, which projected seaward across the continental margin and delineated regional embayments. The outer nose and adjacent flanks of the first-order structures became sites of major phosphorite sedimentation if the paleoceanographic conditions were right to produce a phosphogenic episode: shoaling and large-scale dynamic upwelling of nutrient-enriched waters in response to deflection of the oceanic boundary current in conjunction with a slowly transgressing sea level. Phosphorite sedimentation generally decreased into the regional first-order embayments as the shelf environments became more remote from the oceanic system. Away from the nose of the first-order structures, second-order structural or topographic highs became more important in controlling the location of phosphate deposition. These highs diverted upwelled waters into adjacent second-order embayments with phosphate forming along the mid-slope environments.

A84-6 Diagenesis associated with cyclic patterns of Miocene sedimentation: Riggs, S.R., Snyder, Scott W., Ellington, M.D., Stewart, T.L., Mallette, P.M., Hine, A.C., and Snyder, Stephen W., 1984, Geological Society of America, Abstracts with Programs, v. 16, no. 3, p. 190.

ABSTRACT

Seismic and lithostratigraphic studies of the Miocene Pungo River Formation in North Carolina indicate that nondepositional/erosional episodes leave a strong diagenetic signature which overprints the complex, cyclic sedimentary pattern of Neogene deposition. Three chronostratigraphic sequences are bound by subaerial unconformities which reflect 3rd-order cycles of sea level change.

These three chronostratigraphic sequences consist of at least 18 discrete depositional units, separated by hiatal surfaces commonly characterized by submarine hardgrounds. Each depositional unit exhibits vertical lithofacies changes, which represent all or part of the typical lithologic cycle (e.g., terrigenous to phosphate to carbonate sediments) formed in response to 4th-order transgressive sea-level cycles. Where the entire lithologic cycle is preserved, a hardground is developed on the hiatal surface capping the carbonate lithofacies. Sediments underlying the hardground exhibit a strong diagenetic profile which decreases downward. Changes include:

1. sedimentary structures associated with hardground formation;
2. differential preservation of microfossils;
3. geochemical modification of syndepositional authigeneic minerals (phosphate, carbonate, clays, etc.); and
4. formation of diagenetic minerals (dolomite, ferroan dolomite, siderite-magnesite, pyrite, clinoptilolite, glauconite, opal-A, opal-CT, carbonate fluorapatite).

Where the depositional unit has been truncated by erosion, only portions of the diagenetic profile are preserved. Understanding these diagenetic processes is critical to interpreting Miocene sedimentation associated with rapidly changing paleoenvironments due to high-frequency sea-level cyclicity and concomitant paleoceanographic processes.

A84-7 Ferruginization and phosphatization of foraminifera in Pleistocene and Holocene sands of the mid-Atlantic Continental Shelf: Riggs, S.R., Snyder, Scott W., and Spruill, R.K., 1984, American Association of Petroleum Geologists, Bulletin, v. 68, no. 4, p. 521.

ABSTRACT

Pleistocene and Holocene sands, up to several meters thick, that contain 5% to 40% phosphate grains occur on the continental shelf of Onslow Bay, North Carolina. Altered foraminiferal specimens, 98% of which belong to the genus Quinqueloculina, exhibit gradational surface discoloration (white to dark yellow-brown) that progresses from late- to early-formed chambers. The percentage of extensively altered specimens varies directly with phosphate concentration in the sand fraction. Microprobe analyses of polished sections from completely discolored specimens indicate that alteration involves a decrease in % CaO and concomitant enrichment in % FeO and % P_2O_5. Degree of alteration diminishes from the outside to the inside of exterior-facing chamber walls (mean values are: 70% to 78% to 82% CaO; 18% to 11% to 7% FeO; 0.8% to 0.5% to 0.4% P_2O_5). Interior chamber walls are less altered (mean values are: 84% CaO, 6% FeO, 0.3% P_2O_5). On a CaO-FeO-P_2O_5 diagram the compositional changes through successive chambers of a single specimen parallel those from unaltered through altered specimens. The chemical compositions of completely discolored specimens fall on a proposed alteration trend between unaltered calcareous specimens and chamber fillings. Chamber fillings contain 0.9% CaO, 49% FeO, 12% MgO, and 1.6% P_2O_5; they are generally black. Relative concentrations of CaO-FeO-MgO plot within the compositional range of siderite and magnesite. Constant MgO values (7.5%) in altered foraminiferal tests demonstrate that initial diagenesis involves conversion to high-Mg calcite. Subsequent alteration is largely

ferruginization and minor phosphatization of the test and the diagenetic materials forming within the chambers.

A84-8 Occurrence of clinoptilolite as moldic fillings of foraminiferal tests in continental margin sediments: Snyder, Scott W., Hale, W.R., Riggs, S.R., Spruill, R.K., and Waters, V.J., 1984, Geological Society of America, Abstracts with Programs, v. 16, no. 6, p. 662.

ABSTRACT

Slightly phosphatic, sandy muds in the lower Miocene Pungo River Formation of southern Onslow Bay (North Carolina continental shelf) contain a diagenetic profile in which dissolution of foraminiferal tests decreases downward from an unconformable contact. The degree of dissolution grades from complete at the top of the unit, where zeolitic internal molds of foraminifera comprise 60% of the sand fraction, to negligible near its base. Foraminifera throughout the unit contain chamber fillings composed of the zeolite mineral clinoptilolite (identified by x-ray powder diffraction, electron microprobe analyses, and crystal morphology based on SEM studies). Many molds are complete enough to permit taxonomic identification, even when the test materials have been completely destroyed.

Clinoptilolite precipitation preceded the dissolution of calcareous tests, as evidenced by the uniformity in test fillings regardless of the extent of dissolution exhibited by the host foraminifera. This occurrence of clinoptilolite is significant because:

1. it demonstrates unequivocally precipitation from pore fluids,
2. precipitation appears to have been restricted to the interior of foraminiferal tests,
3. typical precursors of clinoptilolite (e.g., volcanic glass) have not been recognized in these muds, and
4. siliceous microfossils that might have provided a source of biogenic silica are not found in direct association with the moldic fillings.

Clinoptilolite is linked to the availability of silica, whatever its source, and the smectite present in these Miocene muds may have contributed to silica enrichment of their interstitial fluids.

A84-9 Relationship of benthic foraminiferal biofacies to lithofacies in phosphatic Miocene sediments, mid-Atlantic Continental Shelf: Snyder, Scott W., Waters, V.J., and Riggs, S.R., 1984, American Association of Petroleum Geologists, Bulletin, v. 68, no. 4, p. 529.

ABSTRACT

Changes in benthic foraminiferal assemblages accompany changes in total sediment texture and mineralogy (primarily percent phosphatic grains) throughout the Pungo River Formation in Onslow Bay, North Carolina. Only Burdigalian (late early Miocene) deposits have been cored in southern Onslow Bay. Basal phosphorite sands (30% phosphate) are overlain by phosphatic (8%) muds and

slightly phosphatic (4%) quartz sands. Elongate buliminaceans (Bolivina, Bulimina, Buliminella, Uvigerina) comprise over 50% of the benthic assemblage in phosphorites. They also predominate (43%) in phosphatic muds where Siphogenerina and Florilus become conspicuous faunal elements. Diverse trochospirally coiled forms (mainly Hanzawaia, also Valvulineria and Cibicides) become predominant in quartz sands; buliminaceans decline to 30% of the fauna. Pungo River deposits in northern Onslow Bay are Burdigalian, Langhian (early middle Miocene), and Serravallian (middle Miocene) in age. Burdigalian deposits are non-phosphatic, muddy quartz sands in which Hanzawaia predominates and buliminaceans comprise only 22% of the fauna; Florilus accounts for 5%. Hanzawaia remains the dominant genus in the slightly phosphatic (4%) quartz sands of the Langhian and the phosphatic (10%) sands of the Serravalian; buliminaceans increase to 29% of the fauna, but Florilus nearly disappears. Both vertically and laterally throughout the Miocene of Onslow Bay, nutrient-loving buliminaceans thrive where phosphate content increases. Florilus and Siphogenerina are associated with the influx of fine-grained terrigenous sediments. The Hanzawaia-dominated assemblage thrives in clean, coarser-grained substrates. Regional trends in the distributional patterns of these taxa may aid in locating additional phosphate deposits.

A84-10 Stratigraphic consequences of an erosional transgression: A Holocene model applied to the Quaternary record: Snyder, Stephen W., Hine, A.C., and Belknap, D.F., 1984, Society of Economic Paleontologists and Mineralogists, Abstracts with Programs, v. 1, p. 76.

ABSTRACT

Interpretations of high-resolution seismic profiles and vibracores, supplemented by auger data, C^{14} and amino acid racemization dates from an inner shelf-barrier-lagoon complex in North Carolina, have demonstrated that the landward migrating shoreface has severely truncated and removed almost the entire coastal sedimentary record of the Holocene transgression.

The modern shoreface is actively exhuming a stacked sequence of Quaternary barrier-backbarrier lithosomes. They are:

1. a basal Pleistocene unit;
2. cut by fluvial channels filled with Holocene estuarine sediments;
3. followed by a Holocene lagoonal sequence--heavily dissected by relict tidal inlet channels; and
4. finally capped by a late Holocene regressive shoreface sand.

Shoreface normal profiles demonstrate that none of the Holocene barrier-backbarrier lithosomes, including the relict tidal inlets, extends vertically below the active shoreface profile. Therefore, stratigraphic incision by the migrating shoreface would remove even the deepest record of these environments. The only Holocene lithosomes preserved on the shelf consist of a few estuarine-filled fluvial channels which cut stratigraphically lower into the underlying Pleistocene and Tertiary sequences.

Erosional transgressions occurred throughout the Quaternary, because Tertiary sequences directly crop out on the sea-floor over most of the adjacent continental shelf. The only Quaternary lithosomes identified are estuarine-filled fluvial channels. Furthermore, seismic and aminostratigraphic

investigations of the adjacent coastal plain depict the Pleistocene record as a complex mosaic of fluvial-estuarine sediments which collectively represent several discrete sea-level fluctuations. Thus, the channel-fill lithosomes contain the most complete record for resolving the Quaternary sea-level history of North Carolina.

A84-11 Cyclic Miocene phosphogenic episodes within the North Carolina Continental Margin: a paleoceanographic model: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1984, **Society of Economic Paleontologists and Mineralogists, Abstracts with Programs, v. 1, p. 76.**

ABSTRACT

A paleoceanographic model invoking glacioeustatic sea-level fluctuations and concomitant Gulf Stream (GS) flow dynamics during the Miocene depositional evolution of the North Carolina continental margin is evolving from interpretations of over 14,000 km of high-resolution seismic data, coupled with litho-, bio-, and chemostratigraphic analyses of 140 (9 m) vibracores.

The Miocene section is represented by over 18 depositional sequences. Each sequence is bound by regional unconformities and characterized by highly variable lithologies which are repeated cyclically. The emerging temporal and spatial relationships of the phosphorite sequences suggest that topographic upwelling, resulting from deflection of the GS by local antecedent bathymetric highs, may be the primary mechanism for episodes of increased phosphate formation and accumulation. The apparent episodic nature of the phosphogenic events appears to reflect sealevel-induced paleobathymetric fluctuations of 4th-order cyclicity (10^5 years), with economically significant phosphogenic episodes occurring only when the paleobathymetric conditions forced GS deflection by specific antecedent topographic highs. The sites of phosphorite deposition are controlled by the local paleotopographic framework due to the intricate relationships between GS deflection, antecedent topography, and concomitant zones of topographically-induced upwelling. However, the phosphorite depocenters change position (geographically) in response to changes in the morphology and antecedent bottom topography as the North Carolina continental shelf prograded 100 km eastward. This major depositional episode paralleled the 2nd order Te supercycle, but was dominated by alternating erosional and depositional events associated with 4th-order and/or higher-frequency sea-level cyclicity.

A84-12 Lithostratigraphic response to glacio-eustatic sea-level cyclicity and concomitant Gulf Stream flow dynamics: Miocene stratigraphy, North Carolina Continental Shelf: Snyder, Stephen W., Riggs, S.R., Hine, A.C., and Snyder, Scott W., 1984, **Society of Economic Paleontologists and Mineralogists, Abstracts with Programs, v. 1, p. 77.**

ABSTRACT

A chronostratigraphic framework consisting of at least 18 discrete depositional sequences for the Miocene section of North Carolina was established

via analyses of over 14,000 km of high-resolution seismic data. Our present biostratigraphic control suggests each sequence and its regional bounding unconformities are a consequence of high-frequency (4th-order) sea-level cyclicity similar in duration (100 to 300 ka) and amplitude (≤ 100 m) to Pleistocene glacioeustatic sea-level fluctuations.

Lithostratigraphic analyses of 141 (9 m) vibracores and numerous (50 to 150 m) drill holes have identified discrete cyclic patterns of terrigenous, phosphatic, and carbonate deposition within many of the Miocene sequences. High-concentrations of phosphate occur in either the basal lithofacies or between a basal terrigenoclastic facies and the upper calcarenite facies. Where the complete lithic cycle is preserved, a hardground hiatal surface underlain by a distinct diagenetic profile is commonly found in association with the upper bounding unconformity.

Regional seismic-stratigraphic studies show the Miocene depositional evolution of the North Carolina margin was controlled by an interplay between

1. glacioeustatic sea-level fluctuations, and
2. changes in the position, configuration, and flow dynamics of the Gulf Stream as it
3. responded to sea level-induced bathymetric oscillations and
4. interacted with the antecedent bottom topography.

Paleoceanographic reconstructions (to be presented) demonstrate that the above dynamic interactions provided for a spatially and temporally changing mosaic of paleoenvironments which resulted in the observed, cyclic, vertical succession of disparate depositional regimes (terrigenoclastic versus phosphorites versus subtropical carbonates).

A84-13 Carbonate sediments of the Pungo River Formation, Onslow Bay, North Carolina Continental Shelf: Stewart, T.L. and Riggs, S.R., 1984, Geological Society of America, Abstracts with Programs, v. 16, no. 3, p. 199.

ABSTRACT

Sediments of the Pungo River Formation in Onslow Bay consist of mixed concentrations of carbonate, phosphate, and terrigenous components. Four types of carbonate occur in the Miocene units:

1. fossil shell material including barnacles, echinoids, bivalves, bryozoans, foraminifers, and ostracodes;
2. lime mud;
3. ferroan dolomite rhombs; and
4. calcite cement.

Three Pungo River depositional sequences consisting of at least 18 smaller-scale depositional units crop out in Onslow Bay. In the lower sequence (late Burdigalian age) carbonate occurs as: a) phosphatic biomicrudite overlying phosphorite; b) zeolite-filled foraminifers in phosphatic muddy sand; c) minor dolomite and sparse fossils in quartz sands and muds; and d) foraminifers in muddy quartz sand with local zones of echinoid-foraminiferal biosparudite. Carbonate in the middle sequence (Langhian age) occurs as: a) lime mud with the most diverse fauna in Onslow Bay; b) sparse fossils in quartz sand; and c) bryozoan-barnacle hash. The upper sequence (Serravallian age) consists

dominantly of terrigenous sand and mud with sparse fossil material; the uppermost portion contains abundant dolomite.

Nondepositional and erosional episodes separating the three depositional sequences and 18 depositional units have created subjacent diagenetic profiles of varying character. Individual units exhibit improved fossil preservation and decreased ferroan dolomite content downward within each unit and seaward across the shelf. Some units also contain silicified zones, hardgrounds, or lithified zones formed by the development of syntaxial overgrowths on echinoids and radial rim cements on other fossils.

1983

A83-1 Stratigraphic correlation by trace-element analysis in phosphorite of North Carolina: Dolfi, R.M., and Kimberley, M.M., 1983, Geological Society of America, Abstracts with Programs, v. 15, no. 2, p. 100.

ABSTRACT

The phosphorite-bearing Pungo River Formation has been extensively cored in the area of active mining along the coast of North Carolina. Several authors have noted that the Pungo River Formation is divisible into four beds in the mining district. We have attempted to refine this lithostratigraphy through correlation of trace-element anomalies from bed to bed in adjacent drill cores. Our analytical technique is neutron-activation analysis. Within phosphatic grains of each bed, we can identify two groups of trace elements, i.e. chemically concentrated (marine) elements and physically concentrated (terrigenous) elements. Variation in the ratio of these two groups downward through each core helps distinguish beds which are similar in general appearance. Variation in elemental ratios within each group also helps to define beds. Lateral correlation of trace-element ratios from hole to hole has enhanced our understanding of the depositional sequence in this district.

A83-2 Relationship of phosphate geochemistry to stratigraphic sequences in North Carolina: Ellington, M.D., Riggs, S.R., Hale, W.R., Bray, J.T., and Webb, L.A., 1983, Geological Society of America, Abstracts with Programs, v. 15, no. 2, p. 105.

ABSTRACT

Twenty-three major and trace elements were analyzed by plasma emission spectroscopic techniques on over 130 samples of phosphate pellets, intraclasts, skeletal material, and microsphorite, where occurring in significant concentrations. Samples were from the Aurora Phosphate District on the N.C. coastal plain including the early (?) to early middle Miocene Pungo River Fm. units A and B, the middle Miocene Pungo River unit C, and the Pliocene Yorktown Fm. unit LY, and from the Frying Pan area of Onslow Bay on the N.C. continental shelf including the early Miocene Pungo River Fm. units FPS-1 through FPS-3 and Pleistocene/Holocene unit FPH. Cluster and R-mode factor analyses (SAS) suggest that specific phosphorite units exhibit unique major and trace element

signatures.

1. Unit FPH has the most distinctive major and trace element composition; Fe, Ca, and As are relatively enriched while Mo is depleted. The high Ca is believed to reflect the fairly recent formation of the phosphate while the high Fe reflects ferruginization resulting from subaerial weathering.
2. Units FPS-1, FPS-2, and FPS-3 are very similar in composition, are distinctive from the other units, and probably were deposited during the same phosphogenic episode.
3. Units A and B are compositionally distinct from unit C. Relative to unit C, units A and B are enriched in Fe and Al and depleted in P, Cd, and Zn. This suggests that units A and B were deposited during the same phosphogenic episode which was either different from that of unit C or units A and B were subjected to a period of weathering.
4. Each of the phosphate grain types are compositionally distinct within each stratigraphic unit, reflecting their specific modes of formation.

A83-3 Uranium-phosphorus determinations for selected phosphate grains from the Neogene phosphorites in southeastern Beaufort County, North Carolina: <u>Indorf, M.S., Riggs, S.R., and Bray, J.T., 1983</u>, Geological Society of America, Abstracts with Programs, v. 15, no. 2, p. 105.

ABSTRACT

A total of 154 subsamples were obtained from 19 sediment samples representing units A, B, C, and D/DD of the Miocene Pungo River Fm. and 3 samples from the Pliocene lower Yorktown Fm. Subsamples consisted of 0ϕ, 2ϕ, and 4ϕ size phosphate grains. The 0ϕ and 2ϕ size grains were further separated into intraclast, pellet, skeletal material, and disc grain type groups. Uranium and phosphorus contents were determined by fluorometric and spectrophotometric methods, respectively. Uranium contents ranged from 5 to 286 ppm U with a combined mean of 92 ppm ±27 ppm U. Phosphorus contents ranged from 23.2% to 38.2% P_2O_5 with a combined mean of 30.6% ±0.8% P_2O_5.

An apparent inverse relationship exists between phosphate grain size and mean uranium content. The mean uranium content was 72 ppm U for 0ϕ size grains; 82 ppm U for 2ϕ size grains; and 124 ppm U for 4ϕ size grains. Mean phosphorus and uranium contents of skeletal grains were slightly higher than those of the intraclast, pellet, and disc grains. Phosphate grains from unit D/DD, which is interpreted to be a regressive facies, appear to be depleted in uranium and phosphorus relative to the underlying and overlying transgressive facies. No statistically significant trends were found in the regional distribution of uranium and phosphorus within southeastern Beaufort County.

A83-4 Measurement of early diagenetic oxidation of phosphorite based on U, Th, and REE: Kimberley, M.M., Dolfi, R.M., and Riggs, S.R., 1983, Geological Society of America, Abstracts with Programs, v. 16, no. 6, p. 613.

ABSTRACT

We have conducted a study of trace elements in Miocene phosphorite of coastal North Carolina and in reworked phosphatic grains within Quaternary shelf sand. The elemental composition of reworked Miocene phosphatic grains in Quaternary samples reflects the degree of Quaternary oxidation. Subsurface samples similarly display compositional trends which may be related to Miocene redox facies. Quaternary weathering in Onslow Bay has been related to low stands of sealevel during glaciation. Weathering has progressively altered both the elemental composition and color of phosphatic grains. Dark grains have altered to orange grains which contain ferric and manganic hydrous oxides. These oxides have scavenged metals and preferentially precipitated cerium from seawater. In unweathered drill core of Miocene phosphorite, a similar but subtler alteration is attributed to early diagenetic oxidation during the Miocene. The Aurora mining district was more reducing than adjacent areas of phosphorite accumulation to the east and north. Near Aurora, thorium abundance correlates with the rare-earth elements (REE) whereas uranium correlates better with the REE to the east and north. This uranium precipitated from seawater as did much of the correlative REE, particularly the cerium.

A83-5 Grain-by-grain trace element analysis of phosphorite in North Carolina: Kimberley, M.M., and Riggs, S.R., 1983, Geological Society of America, Abstracts with Programs, v. 15, no. 2, p. 100.

ABSTRACT

We have analyzed individual phosphatic grains, weighing as little as a few milligrams, from the Miocene Pungo River Formation near Aurora, North Carolina, and from core samples collected in Onslow Bay, North Carolina. Phosphatic pellets and intraclasts have proven to be generally similar in trace-element content and appear to have formed in similar geochemical environments. The darkness of grains does not correlate significantly with the content of iron or any other element that we could detect by instrumental neutron-activation analysis. We assume that the proportion of organic matter is a major factor in the darkness of grains. Iron concentrations are more variable than those of cerium; correlation between these two elements is poorer than in manganese nodules. Brachiopod fragments are enriched in uranium and heavy rare-earth elements, indicative of diagenetic mineralization. There is a positive correlation between U and La in grains, indicative of a phosphatic fraction. Positive correlation among Th, Mo, As, and Co is representative of a silicate fraction in the samples.

A83-6 Exploration and potential of offshore phosphate deposits based on depositional models developed from onshore deposits: Riggs, S.R., 1983, American Institute of Mining Engineers, 112th Annual Meeting, p. 93.

ABSTRACT

Exploration models for sedimentary marine phosphorites are based on extensive studies of land-based phosphate deposits ranging from Proterozoic through Neogene age. Phosphate sediments are products of complex interactions of specialized conditions of deposition including:

1. paleoceanographic conditions,
2. geometry and structural setting of the depositional basin, and
3. tectonic framework of the depositional system.

Models of phosphate deposition, high-resolution subbottom seismic systems, and vibracoring techniques successfully demonstrate that offshore exploration is feasible and the resources are very extensive. Numerous phosphate deposits have been proven on the SE US continental margin: similar deposits are probably very extensive in the offshore areas in many parts of the world.

A83-7 Geologic history of the Pleistocene/Holocene phosphorites on the North Carolina Continental Margin: Riggs, S.R., Ellington, M.D., and Burnett, W.C., 1983, Geological Society of America, Abstracts with Programs, v. 15, p. 105.

ABSTRACT

Pleistocene/Holocene sediments in the Frying Pan area of Onslow Bay contain 3 types of phosphate grains. Black phosphate occurs in the basal portion of late Pleistocene carbonates. Orange and brown phosphate occurs in the Holocene sands lying unconformably on the Miocene Pungo River Fm. More than 25 uranium-series age dates, in combination with petrographic and major and trace element analyses of the individual grain types, suggest the following:

1. The black phosphate formed about 100,000 years B.P. and is only preserved where late Pleistocene carbonates have protected it from leaching.
2. The predominant orange grains occur in the absence of carbonate caprocks and have undergone significant leaching and alteration.
3. The brown grains display uranium/thorium isotopic equilibrium and are petrographically and chemically similar to the underlying Pungo River phosphate grains.

The interpreted geologic history is as follows.

1. Late Pleistocene sea-level transgressions initiated dynamic upwelling of cold, nutrient-rich Gulf Stream waters downstream of the Mid-Carolina Platform High forming phosphate on the outer shelf.
2. With continued transgression, warm surface waters of the Gulf Stream dominated the shelf and carbonates were deposited over the phosphates.

3. Subsequent regressions lead to subaerial exposure with extensive fluvial channeling of the carbonate caprock; this exposed much of the Pleistocene phosphate to weathering and development of the orange grains. Where the carbonate caprock remained, the black Pleistocene phosphate was protected from weathering.
4. The Holocene transgression is eroding brown phosphate from the outcropping Pungo River units and incorporating it into the Holocene sands.

A83-8 Diagenetic profiles resulting from cyclic patterns of deposition and nondeposition in Miocene phosphorite sedimentation: Riggs, S.R., Snyder, Scott W., Ellington, M.D., Stewart, T.L., Mallette, P.M., Hine, A.C., and Snyder, Stephen W., 1983, in Lucas, J., and Prevot, L., editors, Proceedings of Sixth International Field Workshop and Seminar on Phosphorites, International Geological Correlation Program 156--Phosphorites, Rabat, Morocco, Resume des Communications, Universite de Louis Pasteur, Strasbourg, France, p. 30.

ABSTRACT

Based on detailed seismic and lithostratigraphic studies, the following depositional model is evolving for the Miocene Pungo River Formation in N.C.

1. Three regional depositional sequences, separated by major unconformity surfaces characterized by subaerial erosional truncation and channeling, formed in response to third-order global sea-level cycles.
2. At least 18 depositional units, separated by hiatal surfaces characterized by nondeposition and development of submarine hardgrounds, formed on the transgression of each fourth-order sea-level cycle.
3. Each depositional unit is characterized by vertical lithologic changes of terrigenous, phosphate, and carbonate sediment components, which represent all or some portion of the typical lithologic cycle.
4. High concentrations of phosphate (2% to 75%) occur either in the basal facies or in a transitional zone between the basal terrigenous facies and the upper carbonate facies.
5. Periods of nondeposition and erosion associated with subsequent sea-level regression, produced complex patterns of preservation and diagenetic alteration within each depositional unit.
6. Where the entire depositional unit is locally preserved, it is characterized by a hardground developed on the hiatal surface on top of the carbonate facies during submarine exposure and nondeposition.
7. The mineralogy, chemistry, and foraminiferal preservation within the sediments underlying the hardground have a strong diagenetic signature which decreases downward from each hiatal surface. This diagenetic overprint includes:
   a) sediment structures associated with hardground formation,
   b) a geochemical modification sequence of authigenic mineral components such as the phosphate and carbonate grains and clay minerals, and

c) formation of new minerals such as dolomite, ferroan dolomite, siderite-magnesite, clinoptilolite, glauconite, pyrite, opal-A and opal-CT, and carbonate fluorapatite.

8. Understanding the diagenetic alterations of the mineralogically and chemically simple foraminiferal tests (recrystallization, mineralization, and dissolution) is beginning to provide a base for distinguishing between authigenic mineral formation and diagenetic alteration associated with more complex sediment components.
9. The upper portion of many depositional units, including the carbonate facies and associated hardgrounds, have often been truncated by erosion leaving only the diagenetic profile as evidence of cyclic deposition and the presence of a hiatus.

Thus, sediment studies suggest that the mineralogy and major and trace element chemistry of numerous sediment components are sensitive indicators of diagenetic history associated with nondepositional and erosional episodes which have severely complicated both the depositional patterns and authigenic sediment components. These diagenetic events are particularly critical in understanding and interpreting Miocene sedimentation due to the extreme cyclicity of paleoceanographic processes resulting from Neogene glaciation and deglaciation.

A83-9 Selected benthic foraminifera as indicators of primary vs. secondary phosphate formation: Snyder, Scott W., 1983, in Lucas, J., and Prevot, L., editors, Proceedings of Sixth International Field Workshop and Seminar on Phosphorites, International Geological Correlation Program 156--Phosphorites, Rabat, Morocco, Resume des Communications, Universite de Louis Pasteur, Strasbourg, France, p. 34.

ABSTRACT

Phosphate deposits of the United States middle Atlantic coastal plain and continental shelf occur in the early/middle Miocene Pungo River Formation, the Pliocene Yorktown Formation and in the Pleistocene/Holocene surface sands on the outer continental shelf. Phosphatic sediments (up to 75% of the sand fraction) occur in at least four depositional units of the Pungo River, while the lower Yorktown Formation contains up to 40% phosphate in the sand fraction. A strong positive correlation exists between phosphate concentration and the relative numerical abundance of certain elongate benthic foraminiferal species belonging to several genera within Superfamily Buliminacea. As phosphate content increases or decreases, there are concomitant and proportional changes in the collective abundance of these forms. This relationship exists vertically through the stratigraphic section and laterally within individual phosphate units. Both temporally and spatially, the genera Bolivina, Bulimina and Buliminella are associated with phosphate occurrence. Specimens are typically unaltered or only slightly recrystallized. Modern representatives of these same forms thrive in nutrient-rich, oxygen-poor conditions that often characterize zones of upwelling. Their association with ancient phosphorites may reflect the paleoenvironmental conditions conducive to primary phosphate formation.

Conversely, those few middle Atlantic phosphate-rich deposits in which these taxa are not abundant may represent accumulations of transported phosphates

(e.g., the uppermost phosphorite unit in the Aurora Area) or secondarily reprecipitated deposits. Of particular interest here is the Pleistocene/Holocene sand on the modern continental shelf (phosphate concentrations of 5 to 40%) that contains a markedly different benthic foraminiferal fauna. The lack of buliminaceans commonly associated with primary phosphogenesis and the fact that those foraminifers present (predominantly miliolids) have been diagenetically altered suggests that this phosphate may be of secondary origin. Phosphate grains were either mechanically reworked or geochemically dissolved from underlying Pungo River deposits and redeposited or reprecipitated in the surficial sands. Similarities between the distributional patterns of these younger phosphates and the phosphate-rich units of the underlying Pungo River Formation support this hypothesis.

A83-10 Comparison of Pungo River Formation foraminiferal assemblages and associated phosphatic sediments from the N.C. Continental Shelf and Coastal Plain: Snyder, Scott W., Waters, V.J., and Riggs, S.R., 1983, Geological Society of America, Abstracts with Programs, v. 15, no. 2, p. 59-60

ABSTRACT

Benthic and planktonic foraminiferal assemblages from the Pungo River Formation of the North Carolina continental shelf (Southern Onslow Bay) are richer and more diverse than those from the coastal plain (Aurora Embayment). Predominant benthic species (Bolivina lowmani, B. paula) and some species of secondary importance (Siphogenerina spp., Uvigerina spp., Lenticulina americana) from Onslow Bay are generally less abundant or insignificant in the Aurora area. Marked vertical changes in benthic faunal predominance and diversity characterize the Aurora area and contrast with the uniform faunal composition through the Onslow Bay sequence. The most striking change in the latter section is an abrupt increase in the abundance of planktonic foraminifers (P/B ratio increasing upward from 1:4 to nearly 2:1). A similar trend occurs at Aurora but planktonic specimens are much less abundant. The species composition and faunal diversity values of Onslow Bay benthic assemblages more closely resemble those from upper Aurora units, but planktonic foraminiferal age assignments suggest biostratigraphic equivalence with the lower part of that section. Faunal differences in age-equivalent strata are paralleled by sedimentological changes. Onslow Bay phosphorites are very fine grained and dominantly pelletal; Aurora phosphorites are fine grained and dominantly intraclastic. Faunal and lithologic dissimilarities reflect variations in depositional environment between the two areas; Onslow Bay phosphorites accumulated in more open water, possibly farther offshore. Each embayment evolved somewhat independently as the product of complex interaction among changing eustatic sea level, structural features of varying magnitude, and resultant paleoceanic circulation patterns.

A83-11 3-D stratigraphic modeling from high-resolution seismic reflection data: an example from North Carolina Continental Shelf: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1983, **American Association of Petroleum Geologists, Bulletin, v. 67, no. 3, p. 549-550.**

ABSTRACT

Over 2,000 km (1,240 mi) of high-resolution seismic reflection data were "rapidly" reduced to stratigraphic line drawings with a predetermined vertical exaggeration of 100:1 using a graphics digitizing tablet and desk-top computer. These data form the basis of a three-dimensional stratigraphic model for the upper southeastern North Carolina continental margin.

Correlations between the seismic data and drill, core, quarry, and outcrop data from the adjacent emerged coastal plain, supplemented by lithostratigraphic and biostratigraphic analyses of over 200 (9 m) vibracores collected along the seismic lines depicts an internally-consistent chronostratigraphic framework ranging in age from middle Eocene to late Pliocene. Seismic sequence analysis delineates five mid-late Paleogene depositional sequences, each bound by basin-wide unconformities. The distribution of these sequences is regionally controlled by the Mid-Carolina Platform High of the Cape Fear Arch and locally influenced by Gulf Stream erosional events.

The Neogene section is an extremely complex, highly variable lithic package consisting of at least ten depositional sequences bound by regional unconformities and associated channels. Preliminary biostratigraphic analyses (both nannoflora and planktonic foraminifera) of vibracores penetrating these sequences suggest they represent high-frequency (4th- and possibly 5th-order) sea-level cyclicity. The seismic data indicate that these short pulse sea-level episodes were primarily low amplitude (< 50 m) events. The general distribution for each Neogene sequence, as well as the temporal and spatial relationships of lithofacies changes, seems to be a consequence of a constant interplay between high-frequency sea-level cyclicity and concomitant Gulf Stream dynamics.

The evolving depositional model for the upper southeastern North Carolina margin consists of a few low-frequency (3rd-order), high-amplitude, mid-late Paleogene sea-level events. During their maximum transgression, the western boundary current bypassed the Charleston Bump to the south and impinged on the North Carolina shelf 35 to 40 km southeast of Cape Fear. These Gulf Stream erosion events deeply scoured the shelf, extending the Blake Plateau to the north. Conversely, the Neogene was dominated by high-frequency, low-amplitude sea level cyclicity. Maximum transgression was relatively lower, forcing the Gulf Stream to be deflected by the Charleston Bump to the south. Consequently, the Neogene sequences comprise a major depositional episode in which the shelf prograded east to the present location of the Florida-Hatteras slope.

1982

A82-1 Paleoceanographic model for Neogene sediment deposition--Carolina Continental Margin: Riggs, S.R., 1982, Geological Society of America, Abstracts with Programs, v. 14, p. 599.

ABSTRACT

The Neogene sediment sequence on the Carolina continental margin is a sensitive record of changing and episodic oceanographic conditions. The sediments are characterized by:

1. regional distribution patterns of terrigenous, carbonate, and phosphate sediments across the shelf;
2. cyclical patterns of deposition of each lithofacies; and
3. strong spatial relationships between first- and second-order structures and phosphate deposition.

These depositional patterns are explained by a paleoceanographic model based upon Neogene glacial events which resulted in:

4. fluctuations of global sea level across the shelf;
5. climatic changes influencing terrigenous influx to the shelf; and
6. modification of the path and dynamics of the Gulf Stream, causing different oceanographic water masses to dominate the shelf.

During periods of low sea level, characterized by cooler, more arid climatic conditions and a seaward location of the Gulf Stream, the shelf is dominated by terrigenous sedimentation. As sea level rises, the climate moderates causing a decrease in terrigenous input and migration of the Gulf Stream against the continental margin. Phosphate sedimentation is initiated in response to first- and second-order structurally-induced Gulf Stream meanders and frontal eddies; this results in the development of cold, deep, nutrient-enriched upwellings onto the outer shelf. The intensity of upwelling and phosphate deposition increases and migrates landward with the transgression. During periods of high sea levels, the affects of the bottom structures in causing upwelling are diminished and warm surface waters of the Gulf Stream dominate the shelf. Warm and humid climatic conditions produce fine-grained terrigenous sediments with subtropical faunas on the inner shelf and grade seaward into carbonate sediments; this sequence caps each transgressive cycle. During the subsequent regression, the carbonates are commonly indurated, shells leached, and the sediment by-pass surfaces bored and phosphatized.

A82-2 Phosphatic bacteria in the Neogene phosphorites of the Atlantic Coastal Plain--Continental Shelf system: Riggs, S.R., 1982, Geological Society of America, Abstracts with Programs, v. 14, p.77.

ABSTRACT

Petrographic studies and microanalyses utilizing an SEM equipped with an x-ray spectrographic analyzer suggest that the phosphate in allochemical grains occurs dominantly in two forms.

1. Phosphate occurs as very uniform 0.5 to 2.0μ diameter spheres, which occur independently or form chains and massed colonies that display various stages of cell division, and are interpreted to be fossil bacterial cells.
2. These spherical structures are embedded in a cryptograined matrix of phosphate that is finer than 0.1μ.

Leaching of the intraclastic allochemical grains, both in nature and in the lab, dissolves the grains from the surface inward. The cryptograined matrix is more readily dissolved causing the disseminated spheres to be exposed on the allochemical grain surfaces and in solution pits. The spheres appear to be encased in a slightly less soluble sheath which temporarily protects them from dissolution; once the sheath is dissolved, the remainder of the sphere rapidly dissolves. Leaching of the pelletal allochems progresses similarly, except there is preferential dissolution of the grain interior. This leads to a temporary stage characterized by a thin exterior "eggshell" composed of a dense mass of coalesced bacterial cells. This "eggshell" layer is interpreted to reflect a mucilaginous grain coating produced by most organisms in the process of fecal excretion and subsequent bacterial processes. When phosphorus is abundantly available from either the surrounding waters or the decomposition of organic matter, bacteria mobilize and fix excess phosphorus as inorganic material within internal volutin granules. It is hypothesized that the phosphorus-rich cell is then transformed during post-mortem alteration to a cell outline of phosphate with smooth surface textures. With geologic time, the cell is recrystallized into a radiating aggregate of carbonate fluorapatite crystals which produce a "raspberry" surface texture on the modified bacterial cell.

A82-3 Pleistocene/Holocene phosphorite formation--North Carolina Continental Margin: Riggs, S.R., Snyder, Scott W., Ellington, M.D., Burnett, W.C., and Beers, M., 1982, Geological Society of America, Abstracts with Programs, v. 14, nos. 1 and 2, p. 77.

ABSTRACT

In a 310 km^2 portion of Onslow Bay, N.C., the Pleistocene/Holocene sand sheet contains greater than 3% P_2O_5 with local samples up to 18% P_2O_5. The sand sheet varies from 0 to 3 m thick and lies upon Miocene sediments which dip off the southeast flank of the mid-Carolina Platform High. A minor portion of the phosphate is petrologically and chemically similar to the phosphates in the underlying Pungo River Formation and probably has been reworked. However, the dominant phosphate component has no counterpart within the older sediments. Three independent lines of evidence suggest that the latter phosphate grains are of Pleistocene/Holocene age.

1. More than thirteen uranium-series age dates suggest the presence of a component within the samples that could be younger than 150,000 years B.P.
2. Foraminifera that are Pleistocene to Recent in age occur in various stages of phosphatization (including internal fillings, surface encrustations, and replacement of calcareous tests).
3. Petrographic and chemical analyses demonstrate all degrees of phosphate development, ranging from the initial phase to a dominantly phosphate

phase; grains of the latter phase have lower % P_2O_5 and higher CaO/P_2O_5 ratios than the Miocene phosphate grains.

Two plausible sources of phosphorous may explain this Pleistocene/ Holocene phosphogenic episode.

1. The coincident distribution of high phosphate concentrations in the Pleistocene/Holocene sediments with the Pungo River phosphorite outcrop belt suggests a possible derivation by chemical dissolution of the older sediments and reprecipitation within the younger sediments.
2. Major sea level transgressions and the associated shifts in the Gulf Stream result in upwelling and encroachment of nutrient-rich waters onto the continental shelf across the topographic high of Frying Pan Shoals.

A82-4 Seismic stratigraphy, lithostratigraphy, and amino acid racemization of the Diamond City Formation: reinterpretation of a reported "mid-Wisconsin high" sea-level indicator from the North Carolina Coastal Plain: Snyder, Stephen W., Belknap, D.F., Hine, A.C., and Steele, G.A., 1982, Geological Society of America, Abstracts with Programs, v. 14, p. 84.

ABSTRACT

The Diamond City Fm. is a poorly-sorted, fossiliferous, sandy-silt to silty-clay sequence intercalated with coarser shell beds, clay laminae, and discrete organic-rich horizons which unconformably underlies the Holocene barrier and back-barrier sediments of the Cape Lookout cuspate foreland. Twenty five radiocarbon analyses yield apparent ages of 12.5 to >45 ka with most clustering between 22 to 30 ka. These data have influenced others to interpret the Diamond City Fm. as a back-barrier sequence developed during a "mid-Wisconsin" high sea stand. However, a mid-Wisconsin interglacial sea stand within 10 m of present is in conflict with sea-level interpretations based on pollen, oxygen isotopes, and U-series dated coral reef terraces worldwide.

Interpretations of high-resolution seismic reflection data depict several depositional sequences within the Diamond City Fm., each abruptly truncated by an erosional surface and associated channels. Chronostratigraphic correlations to vibracore, auger and core hole data indicate the Diamond City Fm. is a complex mosaic of several mid to late Pleistocene coastal lithosomes which resulted from high-frequency (4th- and 5th-order) glacioeustatic sea-level fluctuations. This interpretation has been augmented by amino acid racemization analyses, which yield ages of approximately 700 and 500 ka (isotopic stages 17 to 21 and 11 to 13) for the lower sequences of the Diamond City Fm. The apparent "live" radiocarbon dates can be explained by 1 to 10% contamination of "dead" materials. Other C^{14}- supported "mid-Wisconsin high" sequences are now being re-examined.

A82-5 Tertiary structural framework and resulting depositional patterns of the southeastern North Carolina Continental Margin: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1982, Geological Society of America, Abstracts with Programs, v. 14, p. 84.

ABSTRACT

Interpretations of high-resolution seismic reflection profiles, supplemented by litho- and bio-stratigraphic analyses of 9 m vibracores, have delineated the Tertiary structural framework and resulting depositional patterns of Onslow Bay, NC. The Paleogene section is a NE-SW striking band of successively-younger onlapping sequences which closely parallels the Mid-Carolina Platform High of the Cape Fear Arch. The Neogene depositional patterns, however, are dominated by several local structures which were active during the Miocene epoch. In NE Onslow Bay, the Miocene sequences thicken abruptly across, and change strike to parallel the north-south oriented White Oak Lineament. In SW Onslow Bay, these sequences again change strike and thicken along the Cape Fear Monocline. Several shallow Miocene outliers, which are the surficial expression of subbottom "flexures", were also identified. Most of these structures are coincident with mapped magnetic and/or Bouguer gravity anomalies, suggesting they are the surficial expression of differential movement along older basement structures within the Carolina Platform. The timing of deformation associated with these structures as well as others along the SE U.S. Continental Margin indicates a regional tectonic event, perhaps casually related to the rapid sea-floor spreading event which was responsible for the Miocene transgression as calculated by Pitman (1978) (2nd-order Te supercycle).

North of Onslow Bay, the Miocene sequences thin across the Cape Lookout High, a pre-Miocene topographic high produced by differential erosion during the prolonged period of subaerial exposure between the TM1.1 and TM1.4 3rd-order, sea-level high stands. Other significant erosional events were found to be important in developing small depositional basins within this trailing-edge continental margin.

A82-6 Planktonic foraminiferal biostratigraphy and cyclicity of phosphate sequences, southern Onslow Bay, mid-Atlantic Continental Shelf: Waters, V.J., Snyder, Scott W., and Riggs, S.R., 1982, Geological Society of America, Abstracts with Programs, v. 14, no. 7, p. 643.

ABSTRACT

The Carolina Phosphogenic Province includes three distinct depositional embayments (Aurora, Northeast Onslow, Frying Pan) located off the east flank of the Carolina Platform and separated from one another by east-west oriented second-order structures. Vibracores from the Frying Pan Embayment penetrate three depositional supersequences bounded by major interregional unconformities (Vail et al., 1977):

1. a thin Pleistocene/Holocene shelly sand sheet,

2. the phosphatic Miocene Pungo River Formation, and
3. lower Miocene/upper Oligocene calcareous quartz sand (Zone N4).

The Pungo River Formation includes phosphatic depositional sequences corresponding with lithostratigraphic units FP-1 to FP-5. Phosphorite sands (FP1-FP3) and phosphatic muddy sands (FP4) lie within the Catapsydrax stainforthi Zone (N6) based on the co-occurrence of Globorotalia fohsi peripheroronda, Globigerinoides quadrilobatus altlapertura, and G. ruber (forma subquadratus). Muddy quartz sands (FP5) contain a planktonic assemblage assigned to the lower part of the Globigerinatella insueta Zone (N7) based on the appearance of Globorotalia acrostoma and forms that are morphologically transitional between Globigerinoides quadrilobatus triloba and G. sicanus.

If the cyclic depositional patterns within the Pungo River Formation are compared to global eustatic sea level changes, individual depositional units correspond to fourth- or higher-order cycles within the third-order Miocene transgression TM 1.4 of the second-order Te supercycle. Phosphorites of the Frying Pan Embayment are slightly older than those currently being mined in the Aurora Embayment, but the significance of inter-embayment age relationships is not yet fully understood.

1981

A81-1 Relation of Miocene phosphorite sedimentation to structure in the Atlantic Continental Margin, southeastern United States: Riggs, S.R., 1981, American Association of Petroleum Geologists, Bulletin, v. 65, p. 1669.

ABSTRACT

Regional sedimentologic and stratigraphic studies of Miocene phosphorites on the continental margin of the southeastern United States demonstrate a strong structural control over the formation and deposition of major concentrations of phosphorite in the Hawthorn and Pungo River Formations. The first-order structures controlled the regional limits of the phosphogenic system and provided the necessary depositional environments. Major phosphate sedimentation was concentrated along the nose and flanks of the Ocala arch and Carolina platform and decreased to a minimum into the intervening Southeast Georgia and Hatteras Embayments. Recent discoveries of Miocene phosphorite on the North Carolina continental shelf, in combination with the extensive lag deposits of phosphate on the Blake Plateau, represent a major phosphogenic system which occupies a position relative to the Carolina platform that is analogous to that of the major central and south Florida phosphogenic province relative to the Ocala arch.

Superimposed upon the regional structural framework is a series of second- and third-order structural highs and adjacent basins. Each structural high producing a platform or shoaling environment with the necessary associated accumulation basins, may contain one or more phosphate deposits. The specific location, size, and geometry of the resulting deposit is dictated by the folding or faulting, subaerial or submarine erosion, primary depositional processes, groundwater solution and collapse, etc. The location of the second- and third-order structures and the first-order structural highs dictates the

subsequent depositional-erosional history. The latter determines the ultimate preservation and degree of secondary alteration of each phosphate deposit.

A81-2 Continental shelf hardgrounds, Onslow Bay, N.C.: Riggs, S.R., Hine, A.C., and Snyder, Stephen W., 1981, Summary of Results of Reefs and Hardgrounds Workshop, U.S. Bureau of Land Management, Charleston, S.C., p. 34-35.

ABSTRACT

Onslow Bay, North Carolina is characterized by extensive hardgrounds that extend from the base of the lower forebeach (and locally within the beach face), seaward to the outer edge of the continental margin. The Tertiary stratigraphic units dip easterly off the east flank of the Cape Fear Arch, a Cenozoic structure on top of the basement Carolina Platform. This has resulted in a general north-south outcrop pattern of Tertiary units across Onslow Bay between Cape Fear and Cape Lookout. Due to the very thin and sporadic distribution of the Holocene sand sheet, the bottom morphology of most of the Bay is determined by the lithologies of the outcropping Tertiary units and the superimposed Pleistocene carbonates. The outcropping units in Onlsow Bay and their general lithologies are as follows:

1. Holocene Sand Sheet	Entire Shelf
a. Thin & Irregular Sands & Gravelly Sands	
2. Pleistocene	
a. Beach Rock	Cape Shoals & Coastal Zone
b. Terrigenous Fluvial/Coastal Channel-Fill Sequence	Inner Shelf
c. Carbonate Channel-Fill Sequence	Mid & Outer Shelf
d. Bedded Carbonate Sequence	Outer Shelf & Eastern Onslow Bay
3. Pliocene Yorktown Fm.	
a. Clayey & Shelly Sands	Northeast Onslow Bay
4. Miocene Pungo River Fm.	Central Onslow Bay
a. Interbedded Dolosilts, Biorudites, Phosphatic Clays, & Phosphorite Sands	
5. Lower Miocene Silverdale Fm.	Western Onslow Bay
a. Calcareous & Quartz Sands	
6. Oligocene Belgrade Fm.	Western Onslow Bay
a. Moldic Limestones	

Each unit produces different types of hardgrounds dependent upon the lithologies and their interbedded nature, geometry and origin of the beds, and the erosional history. The resulting hardgrounds include a) very flat and smooth surfaces which grade into highly dissected plateau topography with up to 10 m scarps; b) linear scarp ridges with up to 5 m relief produced by the dip slopes of interbedded lithologies or by differential cementation of such deposits as beachrock and channel-fills; and c) broad zones of irregular and undulating topographies occurring along outcrop belts of tight to slightly indurated Tertiary lithologies.

The hardgrounds are actively being modified by a complex interaction of biological and physical processes supplying "new" sediments to the sporadic

Holocene sand sheet. The specific benthic community, their populations and the associated bioerosion processes are dictated by a) location within the Onslow Bay system, b) the lithology and degree of induration, and c) the relief and geometry of the hardground surfaces.

A81-3 Depositional patterns of Neogene sediments around Carolina Platform on mid-Atlantic Continental Shelf: Riggs, S.R., Lewis, D.W., Hine, A.C., Snyder, Stephen W., Snyder, Scott W., and Waters, V.J., 1981, American Association of Petroleum Geologists, Bulletin, v. 65, no. 9, p. 1669.

ABSTRACT

An extensive network of high-resolution Uniboom subbottom seismic profiles in combination with 9-m vibracores were obtained across the North Carolina continental shelf in Onslow Bay. Resulting data delineate an extremely complex depositional pattern of the Neogene sediments around the east and southeast flank of the Carolina Platform. This major broad platform structure trends southeast across the mid-Atlantic shelf and consists of Paleogene and Cretaceous sediments. The Neogene section, dominated by the Miocene Pungo River Formation, forms a complex clinoform sediment package which dips and thickens eastward and southeastward from the platform margin. This sediment package consists of numerous depositional sequences which are abruptly truncated by erosional surfaces and associated channels. Each channeling system was subsequently filled during the following depositional regime. The depositional sequences, which may reflect third- and fourth-order cyclical events, are characterized by interbedded lithologies consisting of phosphorite sands, phosphatic foraminiferal muds, dolosilts, and calcareous quartz sands. Deposition of the Pungo River Formation reflects deposition on a major second-order transgressive cycle. Thus, the upper part was deposited over the edge of the Carolina Platform filling numerous erosional channels in the underlying sedimentary units. Postdepositional folding followed by subsequent erosional cycles severely truncated the sediments again. This resulted in a series of flexure basins and channels, filled with Pungo River sediments, lying on top of the Carolina Platform as isolated outliers. The complex depositional-erosional patterns of the Pungo River sediments reflect several orders of cyclical sedimentation taking place on the continental shelf during the Miocene.

A81-4 Miocene phosphorite sedimentation on the Atlantic Continental Shelf, Onslow Bay, North Carolina: Riggs, S.R., Lewis, D.W., Hine, A.C., and Snyder, Stephen W., 1981, American Association of Petroleum Geologists, Bulletin, v. 65, p. 979.

ABSTRACT

An extensive sequence of phosphorites outcropping on the Atlantic continental shelf of Onslow Bay, North Carolina, has been delineated by utilizing a series of vibracores and high resolution subbottom profiles (3.5 kHz, uniboom, and sparker). This broad outcrop belt extends 100 km from western Bogue Banks,

southwestward across the shelf toward the outer part of Frying Pan Shoals off Cape Fear, North Carolina. Along the outcrop zone the Tertiary phosphorites have been and are presently being eroded, supplying reworked phosphate grains in diluted concentrations to the associated thin Pleistocene to recent sediment and rock blanket. The Tertiary phosphorites are primarily an interbedded sequence of muddy, quartzose phosphorite sands; phosphatic dolosilts; and fossiliferous, dolomitic, phosphatic, quartz sands. The sediment sequence closely resembles that found in the Pungo River Formation in the Aurora area on the North Carolina coastal plain, a major mining district, and is presently considered to be equivalent to the Pungo River Formation of middle Miocene age. These phosphorites unconformably overlie the slightly glauconitic, calcareous, fine quartz sands, calcarenites, and sandy, moldic limestones of lower Miocene and/or Oligocene age. Small parts of the updip outcrop belt of the Tertiary phosphorites, as well as the downdip section to the southeast, are covered by a thickening sequence of fossiliferous, clayey, quartz sands of the Yorktown Formation (Pliocene). The distribution of the Tertiary phosphorites is primarily related to the Cape Fear arch, a major coastal plain structural element, and is locally controlled within Onslow Bay by several second-order structural features and associated entrapment basins.

A81-5 Cyclic deposition of upper Tertiary phosphorites of the North Carolina Coastal Plain and their relation to global sea-level curves: Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Snyder, Scott W., 1981, American Association of Petroleum Geologists, Bulletin, v. 65, no. 5, p. 979.

ABSTRACT

The upper Tertiary phosphorites in the Aurora area occur within the Miocene Pungo River Formation (units A, B, C, and D) and the Pliocene Yorktown Formation (lower and upper units). These units are characterized by the following patterns of sedimentation.

1. Three major erosional unconformities and five diastemic surfaces mark the boundaries between consecutive units and the under- and overlying formations.
2. Indurated carbonate sediments, which usually contain either a weathered fossil assemblage or are completely moldic, cap each unit. The carbonate surfaces locally contain a rock-boring infauna and are often phosphatized.
3. Phosphate sedimentation began in unit A and increased to a maximum through unit C, was negligible in unit D, was reinitiated in the lower Yorktown, and was non-existent in the upper Yorktown.
4. Phosphate concentration generally increases upward within each unit until carbonate sediments become important, then the phosphate decreases.
5. The dominant carbonate within each unit is as follows: unit A and B, dolosilt; unit C, calcitic micrite; unit D, dolosilt with abundant calcite shell material; and both Yorktown units, calcitic micrite with abundant calcite shells.

This sequence of upper Tertiary sediment units suggests a cyclical pattern

controlled by global eustatic sea level fluctuations. Each depositional unit, its carbonate cap, and the associated diastemic surfaces, correlate with established third-order sea level cycles. Units A, B, and C appear to represent the maximum transgressive portion of the second-order Miocene supercycle. Phosphate sedimentation was coincident with the transgression; the maximum deposition occurred during the highest level of the sea. Unit D was deposited only over the eastern portion of the area as a regressive facies of the supercycle. The Pliocene Yorktown sediments were deposited during the next supercycle. The lower Yorktown phosphorites coincided with the maximum transgression while the non-phosphatic upper Yorktown was deposited during the subsequent regressive phase.

1980

A80-1 Buried channels within the inner continental shelf: origin, geometry, and seismic facies: Hine, A.C., Snyder, Stephen W., and Riggs, S.R., 1980, Geological Society of America, Abstracts with Programs, v. 12, p. 447.

ABSTRACT

High resolution seismic profiling (750 km) off the North Carolina coast has revealed a number of buried channels lying within the inner continental shelf. Both paleo-fluvial and paleo-tidal inlet channels are present. These channels are significant in understanding coastal response to a marine transgression because they trap sediments indicative of changing environments and have high preservation potential. Channel geometry (plane view), across-shelf continuity, cross-section size/shape, and infilling structures seen in seismic profile provide clues to the paleo-hydraulic behavior of the former streams or inlets.

Buried fluvial channels can be distinguished from former tidal inlets by their across-shelf continuity. We have traced two fluvial systems approximately 23 km from the back-barrier lagoon out to mid-shelf depths (22 m) via closely spaced seismic profiles. Where profiles are sparse, correlations are made by recognizing similarities in seismic infilling facies. The paleo-fluvial channels are also the largest channels having subsurface widths of 4.6 km and relief up to 24 m.

Buried tidal-inlet channels can be distinguished by their close physical association with historically known inlets. Former tidal-inlet channels cannot be traced extensively either in a landward or seaward direction. The pattern of smaller, shallower lagoonal channels radiating abruptly away from the deep, main inlet throat is also diagnostic.

Nine categories of seismic infilling facies have been defined, each indicative of paleo-hydraulics and mode of channel infilling. Once channel origin is confirmed, seismic infilling structures aid significantly in interpreting channel history.

A80-2 **Foraminifera of the Pungo River Formation, central Coastal Plain of North Carolina: Katrosh, M.R., and Snyder, Scott W., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of Southeastern U.S., Abstracts, p. 9.**

ABSTRACT

Benthic foraminiferal assemblages of the Pungo River Formation (middle Miocene) from the central North Carolina coastal plain indicate deposition in nearshore inner continental shelf to middle shelf environments.

In Beaufort and Pamlico Counties, part of the Aurora Embayment, faunas from the lower part of the formation (units A and B) are dominated by Buliminella elegantissima, Caucasina gracilis, and Elphidium excavatum. Florilus pizzarensis, Cibicides lobatulus, Elphidium limatulum, Nonionella miocenica, Hanzawaia concentrica, and H. nipponica occur sporadically and are of secondary importance when present. High faunal dominance (averaging 50% or greater), low diversity values (Shannon-Wiener Information Function averaging 1.4), and the rarity of planktic foraminifera suggest that these units were deposited in nearshore, shallow water environments. With the exception of E. limatulum, dominant species from the upper part of the Formation (units C, D, and DD) are those that are of secondary importance in the lower units. Faunal dominance averages 33%, diversity values are moderate (averaging 2.3), and planktic specimens are more abundant. These units were deposited in more open water marine environments.

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

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

A80-3 **Preliminary report on the Pungo River Formation in Onslow Bay, North Carolina Continental Shelf: Lewis, D.W., Riggs, S.R., Snyder, Scott W., and Waters, V.J., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of Southeastern U.S., Abstracts, p. 10.**

ABSTRACT

The distribution of an extensive sequence of Tertiary phosphorites has been delineated in the shallow subsurface across the continental shelf of Onslow Bay, N.C. Extensive vibracoring and high-resolution subbottom profiling (3.5 kHz, Uniboom, and sparker) have outlined a broad belt of phosphatic sediments

that extent southwestward for 100 km from western Bogue Banks, across the shelf, to the outer portion of Frying Pan Shoals off Cape Fear, N.C. Locally along this zone, the Tertiary phosphorites have been and continue to be eroded, supplying reworked phosphate grains to the Pleistocene and Holocene sediments in concentrations averaging a few percent, with local areas containing 20% and occasionally reaching 80%. This reworked phosphate is dominantly fine-grained, well rounded, and has a caramel color.

The Tertiary section in Onslow Bay consists primarily of Oligocene or lower Miocene units unconformably overlain by sediments of middle Miocene age which are, in turn, unconformably overlain by either Pliocene or Pleistocene sediments. The Oligocene and lower Miocene units are predominantly moldic, sandy limestones and fine quartz sands. The middle Miocene consists of four major sediment groups with facies variation within each group. These include:

1. barnacle hash, muddy dolomitic barnacle hack, and barnacle-rich dolosilt;
2. interbedded clay, quartz sand, and chert bearing dolosilt;
3. muddy calcarenites and calcarenic quartz sands; and
4. muddy, fossiliferous phosphatic sands and phosphoritic sands.

The sediment sequence closely resembles that found in the Pungo River Formation in the mining district near Aurora, N.C. The phosphorite units of the Pungo River Formation in Onslow Bay contain dominant dark brown pelletal grains which range from 20% to 40% and occasionally constitute 50% to 65% of the sediment. The overlying Pliocene Yorktown Formation consists of two units. The lower Yorktown sediments consist of phosphatic quartz sands, dark green mud and muddy sands, and dolomitic mud and fine sand. The upper Yorktown is composed of slightly fossiliferous silty clay to clayey silt. The phosphatic portion of the lower Yorktown Formation averages 10% to 15% phosphate grains that are dominantly the brown intraclastic type.

A80-4 Structural control of phosphorite sedimentation during the Miocene in the southeastern United States: Riggs, S.R., 1980, 26th International Geological Congress, Paris, France, Resumes, v. II, p. 536.

ABSTRACT

Sedimentologic and stratigraphic studies demonstrate that three scales of structures have controlled the formation and subsequent deposition of the Miocene Hawthorn and Pungo River phosphorites in SE United States. The first-order structures, the Ocala Arch--SE Georgia Embayment--Cape Fear Arch--Hatteras Embayment, define the regional limits of the phosphogenic system and provide the extensive coastal and shelfal depositional environments. Major phosphate sedimentation was concentrated along the nose and flanks of the two major arch structures, decreasing into the embayments. Superimposed on the regional framework is a series of second-order structural highs and adjacent basins. Each major structural shoaling system, essential for the formation of the phosphate, and the necessary accumulation basins, has the possibility of containing one or more phosphate districts depending upon the size and geometry of the system and the subsequent geologic history. The third-order structures represent the

detailed topography of the second-order structures. The specific location, size, and geometry of the entrapment basins where the phosphates accumulate, is dictated by the genesis of the topographic features (i.e. structural deformation, primary depositional processes, subaerial or submarine erosion, or groundwater solution and collapse associated either with the prephosphate units or contemporaneous with phosphate deposition). Individual or groups of mines occur within this level of structural control.

A80-5 Cyclic deposition of Upper Tertiary phosphorites of the Aurora area, North Carolina, and its relationship to global sea-level curves: Riggs, S.R., Lewis, D.W., Scarborough, A.K., and Snyder, Scott W., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of southeastern U.S., Abstracts, p. 12.

ABSTRACT

The Upper Tertiary phosphorites in the Aurora area occur within the Miocene Pungo River Formation (units A, B, C, and D) and the Pliocene Yorktown Formation (lower and upper units). These units are characterized by the following patterns of sedimentation.

1. Three major erosional unconformities and five diastemic surfaces mark the boundaries between consecutive units and the under and overlying formations.
2. Indurated carbonate sediments, which usually contain either a weathered fossil assemblage or are completely moldic, cap each unit. The carbonate surfaces locally contain a rock-boring infauna and are often phosphatized.
3. Phosphate sedimentation began in unit A and increased to a maximum through unit C, was negligible in unit D, was re-initiated in the lower Yorktown, and was non-existent in the upper Yorktown.
4. Phosphate concentration generally increases upward within each unit until carbonate sediments become important, then phosphate decreases.
5. The dominant carbonate within each unit is as follows: units A and B, dolosilt; unit C, calcitic micrite; unit D, dolosilt with abundant calcite shell material; and both Yorktown units, calcitic micrite with abundant calcite shells.

This sequence of Upper Tertiary sediment units suggests a cylcical pattern controlled by global eustatic sea-level fluctuations. Each depositional unit, its carbonate cap, and the associated diastemic surfaces correlate with established third-order sea-level cycles. Units A, B, and C appear to represent the maximum transgressive portion of the second-order Miocene supercycle. Phosphate sedimentation was coincident with transgression. Unit D was deposited only over the eastern portion of the area as a regressive facies of the supercycle. The Pliocene Yorktown sediments were deposited during the next supercycle. The lower Yorktown phosphorites coincided with the maximum transgression while the non-phosphatic upper Yorktown was deposited during the subsequent regressive phase.

A80-6 **Stratigraphy and petrology of the Pungo River Formation, central Coastal Plain, North Carolina: Scarborough, A.K., Riggs, S.R., and Snyder, Scott W., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of Southeastern U.S., Abstracts, p. 12.**

ABSTRACT

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

The Pungo River Formation consists of the four major sediment packages (units A, B, C, and D) described by Riggs et al. (this volume), and three lateral facies (units BB, CC, and DD). Phosphorite sedimentation was concentrated in units A, B, and C which are laterally correlative throughout most of the study area. However, the muddy, phosphorite, quartz sands of unit B and possibly the phosphorite, quartz sands and carbonate sediments of unit C grade downdip to the southeast into an 11 m thick diatomaceous facies (unit BB). Units A, B, and C grade into a slightly phosphatic, calcareous, quartz sand facies to the south, 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 Aurora Embayment grades laterally into 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 fine to very 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 south result in decreased phosphate content within the Formation.

The depositional pattern of the regionally persistent and cyclical lithologies of the Pungo River Formation suggests that units A through C were deposited during a major transgression. The overlying unit D was deposited during the subsequent regressive phase. Within the Aurora area, each of the sediment units is separated from the overlying unit by a period of increased carbonate and decreased phosphate deposition. Truncation of the units by erosion took place prior to the deposition of the Pliocene Yorktown Formation. The extensive erosion produced an apparent offlap geometrical configuration within the Pungo River units that actually represent a transgressive or onlap sediment sequence.

A80-7 Synthesis of phosphatic sediment-faunal relationships within the Pungo River Formation: paleoenvironmental implications: Snyder, Scott W., Riggs, S.R., Katrosh, M.R., Lewis, D.W., and Scarborough, A.K., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of Southeastern U.S., Abstracts, p. 9-10.

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 sparse foraminiferal assemblages. Planktic specimens are rare to absent in these units. Similar assemblages persist as the units thicken to the east. The sporadic occurrence of open shelf species in units A and B suggests that the depositional embayment was not restricted; but conditions were clearly not generally suitable for open shelf species. The frequent dominance 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 that are dominated by middle shelf species. Planktic 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. This 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*.

A80-8 Miocene seismic stratigraphy, structural framework and sea level cyclicity: North Carolina Continental Shelf: Snyder, Stephen W., Hine, A.C., and Riggs, S.R., 1980, Southeastern Geological Society and Florida Bureau of Geology, Symposium on Miocene of Southeastern U.S., Abstracts, p. 13.

ABSTRACT

Stratigraphic interpretation of over 1000 km of high-resolution seismic reflection data has delineated the stratigraphic and structural framework for several Miocene depositional sequences within the Carolina Platform of Onslow Bay, North Carolina. Comparison of the observed stratigraphy with published seismic, magnetic, gravity and core hole data indicates that the distribution, thickness and depositional pattern of each sequence has been controlled by:

1. the regional tectonic framework;
2. several local, second-order structural features; and
3. global eustatic sea level fluctuations.

A broad zone of phosphatic, middle Miocene sediments and rocks crop out at mid-shelf across the northern segment of the Carolina Platform. This outcrop belt trends northeast to southwest, and extends from Frying Pan Shoals off Cape Fear Arch, a mid-platform structural high. South of Bogue Banks, the middle Miocene sequences abruptly change strike and run parallel to a north-south oriented structural lineament, herein designated the White Oak Fault Zone. North of Bogue Banks, the Miocene depositional sequences thin over the Cape Lookout High, which is presently thought to be a pre-middle Miocene topographic high. Several shallow basins, which are the surficial expression of subbottom "flextures," were identified within the Miocene outcrop belt of Onslow Bay. These flexures probably reflect differential subsidence within the Carolina Platform.

The interpreted Miocene transgressive and regressive history is compatible to synchronous events in the continental margins and cratonic basins of the world. Each of the major depositional sequences and associated unconformities correspond to established second- and third-order global eustatic sea-level cycles. The Silverdale Formation, a lower Miocene sequence, corresponds to a third-order global cycle. The middle Miocene Pungo River Formation represents a second-order supercycle. Several major unconformities identified within the Pungo River Formation via high-resolution seismic profiling allow us to subdivide this unit into four discrete depositional sequences, each tentatively assigned to a separate third-order global cycle. Similarly, the Pliocene Yorktown Formation can be separated into two distinct depositional sequences, each corresponding to an individual third-order global cycle.

A80-9 High-resolution seismic stratigraphy and global eustatic sea-level fluctuations: Cape Lookout, North Carolina: Snyder, Stephen W., Hine, A.C., Riggs, S.R., and Lewis, D.W., 1980, Geological Society of America, Abstracts with Programs, v. 12, p. 526.

ABSTRACT

Stratigraphic interpretation of over 500 km of high-resolution seismic reflection data has allowed us to redefine the geochronologic, stratigraphic and structural framework for a portion of the eastern North Carolina continental margin. The observed transgressive and regressive history is compatible to synchronous events in the continental margins of the world. Each of the major depositional sequences and associated unconformities identified correspond to the second- and third-order global eustatic sea-level cycles of Vail and others (1977). In addition, discrete sediment packages produced by higher frequency sea-level cycles were identified, and are attributed to glacioeustatic and/or local tectonic events.

The two oldest depositional sequences encountered, the Belgrade Fm. (late Oligocene) and the Silverdale Fm. (lower Miocene), correspond to two distinct third-order cycles. A major phosphogenic middle Miocene sequence, the Pungo River Fm., can be subdivided into four discrete depositional sequences, each

representing a separate third-order global cycle. Similarly, a Pliocene sequence, the Yorktown Fm., can be separated into two distinct depositional sequences, each corresponding to an individual third-order global cycle.

The distribution, thickness and depositional pattern of each of these depositional sequences has been controlled by two major structures: (1) the Cape Lookout High and (2) the White Oak Lineament.

1979

A79-1 Environments of deposition of the southeastern United States Continental Shelf phosphorites: Riggs, S.R., 1979, in Marine Phosphatic Sediments, editors, Burnett, W.C., and Sheldon, R.P., East-West Resource Systems Institute, Honolulu, Hawaii, p. 11-12.

ABSTRACT

The well-known Miocene phosphorites of the SE United States Coastal Plain, extend seaward onto the Atlantic Continental Shelf. On the shelf the phosphorites occur both in the Miocene beds in the subsurface and in the surface sediments south of Cape Hatteras, N.C. The surface sediments generally contain between 1 to 4% phosphate grains. However, in Onslow Bay, N.C., where the Miocene phosphorites crop out on the shelf, there is a broad zone where the phosphate grains occur in excess of 4% and locally reach 40% of the sediment. It is presently felt that the phosphorite in the surface sediments is not modern but rather is being eroded from the Miocene and reworked into the surface sediments. Various work during the past ten years has established that the Miocene phosphorites do occur in the subsurface on the shelf off Jacksonville, Fla., Savannah, Ga., and Onslow Bay, N.C. Even though these subsurface deposits are only very poorly known, it is believed that these shelf deposits are much more extensive than previously supposed.

Since the continental shelf phosphorites are part of the same extensive Miocene sediment system which produced the phosphorites in the region between Florida and North Carolina, the environments of deposition are also much the same. Phosphorite sedimentation was primarily controlled by regional structural highs such as the Ocala Arch and the Sanford High in Florida, the Beaufort Arch in South Carolina, and the Cape Fear Arch in North Carolina. The coastal marine and nearshore shelf environments around these structural highs were the primary sites of phosphorite formation and deposition. In the shallower coastal environments, the phosphorite formed primarily as microsphorite mud and intraclastic grains. The sand and gravel intraclasts were highly fragmented and abraided during subsequent transport. These grains were diluted primarily by terrigenous sands and clays with some authigenic dolomite as they were deposited in the associated entrapment basins. Downslope, in the nearshore shelf environments, silt and fine sand-sized pelletal phosphorites were the dominant phosphate component formed. These regular pelletal phosphorites accumulated in the entrapment basins adjacent to the structural highs where they were diluted primarily by authigenic dolomite, terrigenous quartz sand, and some clay minerals.

BIBLIOGRAPHY OF ABSTRACTS

P. Pertinent Selected Articles by Other Authors (41)

P. PERTINENT SELECTED ARTICLES BY OTHER AUTHORS

P1 Biostratigraphy and paleoecology of a diatomaceous clay unit in the Miocene Pungo River Formation of Beaufort County, North Carolina: Abbott, W.H., and Ernissee, J.J., 1983, in Ray, C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 287-354.

ABSTRACT

The diatomaceous clay unit from two cores from the Pungo River Formation of Beaufort County, North Carolina, contains two diatom assemblages and essentially one silicoflagellate assemblage. Based on the diatom ranges, an age equivalent to Blow's (1969) zones N8-N9 was obtained for the older diatom assemblage and an age equivalent to zone N11 for the younger assemblage. The age range of the silicoflagellate assemblage is inclusive of the diatom assemblages. The diatomaceous clay was deposited in a marine near-shore environment with reducing bottom conditions and nutrient-rich surficial water. The water may have been cooler or upwelling greater during the deposition of the younger assemblage.

P2 Geology of the continental shelf, Onslow Bay, North Carolina, as revealed by submarine outcrops: Blackwelder, B.W., MacIntyre, I.G., and Pilkey, O.H., 1982, American Association of Petroleum Geologists Bulletin, v. 66, p. 44-56.

ABSTRACT

Lithologic and stratigraphic data from rocks dredged from the continental shelf off Onslow Bay, North Carolina, provide surface control for seismic studies of the southeastern United States continental margin and help to explain the distribution of potentially economic phosphate-rich sediments on this shelf. Outcropping Miocene rocks in this area indicate that the region has long been a positive geologic feature and has received relatively little Pliocene and Pleistocene sedimentation. Leached, molluscan-moldic calcareous quartz sandstones of late Oligocene to early Miocene age (Belgrade Formation) and middle to late Miocene age (Pungo River Formation) crop out in southwestern and northeastern Onslow Bay, respectively. These two areas border a band of highly phosphatic surficial sediments probably derived from unlithified, phosphatic units of the Pungo River Formation. Lower Pleistocene calcarenites that correlate with the Waccamaw Formation crop out on the sea floor near Cape Fear, which bounds Onslow Bay on the south. A core on Frying Pan Shoals off Cape Fear, after passing through Pleistocene coquina, calcareous quartz sandstone, and oolitic sand, penetrated upper Pliocene calcarenites of the Bear Bluff Formation and middle Miocene phosphatic argillaceous sandstones of the Pungo River

Formation. Samples from this core hole show that phosphate increases toward the top of the unindurated Pungo River Formation section, indicating that this formation is probably the source of the high phosphate concentrations in the surficial sediments near Cape Fear, where the Bear Bluff calcarenites also crop out. Upper Pleistocene units include oolitic limestones adjacent to the outer shelf, calcareous quartz sandstones around Cape Fear, and molluscan coquinas near Cape Lookout which bounds Onslow Bay on the north. The outer shelf is blanketed by submarine lithified algal limestones and sandstones of Holocene age.

P3 The relation of phosphorites to ground water in Beaufort County, North Carolina: Brown, P.M., 1958, Economic Geology, v. 53, p. 85-101.

ABSTRACT

Recent ground-water studies undertaken by the U.S. Geological Survey in cooperation with the North Carolina Division of Mineral Resources have delineated phosphorite deposits, tentatively regarded as being of middle Miocene age, in Beaufort County. These deposits lie unconformably on limestone of Eocene age and are unconformably overlain by late Miocene marl. The phosphorites, buried beneath strata ranging in thickness from 45 to 250 feet, underlie an area approximating 450 square miles. The total thickness of the phosphorite column throughout the area ranges from several feet to nearly 90 feet.

The phosphorite column consists of phosphatic sands and intercalated shell limestones. The sands, composed of pellets of brown sand-size collophane (probably carbonate-fluorapatite) and sand-size, flat-sided angular quartz with some silt, clay, and organic material, have a median diameter between 0.50 and 0.25 mm. Chemical analyses of representative samples of the raw sand show a variation in P_2O_5 content from 8 to 31 percent. The P_2O_5 content is apparently proportionate to the collophane content throughout the area.

Reconstruction of the geologic history suggests that the phosphorites were deposited as chemical precipitates and as in situ replacements in a restricted marine basin where the pH of the water acted as the primary depositional control.

Reconstruction of the hydrologic history of the phosphorites indicates that the deposits were preserved under artesian conditions; they were never subjected to alteration under water-table conditions. The absence of postdepositional alteration makes this area a potentially classic one for studies of phosphorite genesis.

Chemical analyses of artesian waters from the phosphorites and from limestones overlain by phosphorites reveal significantly greater concentrations of iodide and bromide in solution than are present in water from overlying sediments or from underlying limestones not overlain by phosphorites. Such anomalies if present in other similar terranes, may indicate the presence of buried phosphorites.

The depth and size distribution of the material suggest a recovery method utilizing wells constructed to "pump sand."

P4 Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: Brown, P.M., Miller, J.A., and Swain, F.M., 1972, **U.S. Geological Survey Professional Paper 796, 79 p.**

ABSTRACT

This report describes and interprets the results of a detailed subsurface mapping program undertaken in that part of the Atlantic Coastal Plain which extends from the South Carolina and North Carolina border through Long Island, N.Y. Data obtained from more than 2,200 wells are analyzed. Seventeen chronostratigraphic units are mapped in the subsurface. They range in age from Jurassic(?) to post-Miocene. The purpose of the mapping program was to determine the external and internal geometry of mappable chronostratigraphic units and to derive and construct a permeability-distribution network for each unit based upon contrasts in the textures and compositions of its contained sediments.

The report contains a structure map and a combined isopach, lithofacies, and permeability-distribution map for each of the chronostratigraphic units delineated in the subsurface. In addition, it contains a map of the top of the basement surface. These maps, together with 36 stratigraphic cross sections, present a three-dimensional view of the regional subsurface hydrogeology. They provide focal points of reference for a discussion of regional tectonics, structure, stratigraphy, and permeability distribution. Taken together and in chronologic sequence, the maps constitute a detailed sedimentary model, the first such model to be constructed for the middle Atlantic Coastal Plain.

The chronostratigraphic units mapped record a structural history dominated by lateral and vertical movement along a system of intersecting hinge zones. Taphrogeny, related to transcurrent faulting, is the dominant type of deformation that controlled the geometry of the sedimentary model.

Twelve of the seventeen chronostratigraphic units mapped have depositional alinements and thickening trends that are independent of the present-day configuration of the underlying basement surface. These 12 units, classified as genetically unrooted units, are assigned to a first-order tectonic stage. A structural model is proposed whose alinements of positive and negative structural features are accordant with the depositional geometry of the chronostratigraphic units assigned to this tectonic stage. The dominant features of the structural model are northeast-plunging half grabens arranged en echelon and bordered by northeast-plunging fault-block anticlines. Tension-type hinge zones that strike north lie athwart the half grabens.

Five of the seventeen chronostratigraphic units mapped have depositional alinements and thickening trends that are accordant with the present-day configuration of the underlying basement surface. These five units, classified as genetically rooted units, are assigned to a second-order tectonic stage. A structural model is proposed whose alinements of positive and negative features are accordant with the depositional geometry of the chronostratigraphic units assigned to this tectonic stage. The dominant feature of this model is a graben that stands tangential to southeast-plunging asymmetrical anticlines. Tension-type hinge zones that strike northeast lie athwart the graben.

To account for the semiperiodic realinement of structural features that has characterized the history of the region and as a working hypothesis, we

propose that the dominant tectonic element, which is present in the area between north Florida and Long Island, N.Y., is a unit-structural block, a "basement" block, bounded by wrench-fault zones. We propose that forces derived principally from the rotation and precession of the earth act on the unit-structural block and deform it. Two tectonic models are proposed. One model is compatible with the structural and sedimentary geometries that are associated with chronostratigraphic units assigned to a first-order tectonic stage. It features tension-type hinge zones that strike north and shear-type hinge zones that strike northeast. The other model is compatible with the structural and sedimentary geometries associated with chronostratigraphic units assigned to a second-order tectonic stage. It features tension-type hinge zones that strike northeast and shear-type hinge zones that strike north.

Using a working concept of a fixed system of intersecting hinge zones, we conclude that the geometry of the regional structural-sedimentary system is associated predominantly with the action of lateral compressive forces, and that vertical forces operative in the region are chiefly the resultants of compressional stress. A geographic distribution of sedimentary troughs in the region studied is discussed, together with the nature of their boundaries and cross structures during each of the two tectonic stages.

The correlation framework established in this report utilizes both formally designated stratigraphic units and informally designated working units. The latter are identified by letter symbols (A-I). For each chronostratigraphic unit mapped, we include lithologic and biostratigraphic descriptions. Paleontologic data, chiefly the occurrence and distribution of Ostracoda recovered from well cuttings and cores, were used in the subsurface mapping. Ostracoda and Foraminifera that are characteristic of the units mapped in the subsurface are listed in the text and are identified on the stratigraphic cross sections. Type reference sections in the subsurface are designated for each of the chronostratigraphic units mapped.

The measured combined thickness for beds of sand, shale, and carbonate are computed as percentages of the total thickness of the chronostratigraphic interval in which they occur. Using these data, seven lithologic percentage categories (lithofacies), based upon textural and chemical composition, are established. These categories encompass the observed percentage variability in the vertical occurrence of sand, shale, and carbonate in the sediment mass within the report area. The delineation of the different categories by means of boundary lines and patterns drawn on an isopach map is used to construct a lithofacies map for each of the 17 chronostratigraphic units mapped.

Each lithofacies is assigned a number, ranging from 1 to 7, indicative of its comparative position on a scale of relative intrinsic-permeability lithology. The number 1 is assigned to a very high intrinsic-permeability lithology, whereas the number 7 is assigned to a very low intrinsic- permeability lithology. The numbers, together with the areal distribution of a lithofacies to which each number is assigned, constitute a permeability- distribution map for each of the 17 chronostratigraphic units mapped.

The series of combined isopach, lithofacies, and permeability-distribution maps, together with the series of structure-contour maps, illustrate the distribution of intrinsic permeability in that part of the Atlantic Coastal Plain which extends from the South Carolina and North Carolina border through Long Island. N.Y.

P5 Phosphate in the Atlantic and Gulf Coastal Plains: Cathcart, J.B., 1968, in Brown, L.F., editor, Proceedings 4th Forum of Geology of Industrial Minerals: University of Texas Press, Austin, Texas, p. 23-24.

ABSTRACT

Phosphate pellets are widespread in marine sedimentary rocks of Cretaceous to Holocene age on the Coastal Plains of the Eastern and Southern United States. Economic deposits of phosphorite are confined to the Atlantic Coastal Plain, and are known only in rocks of middle Miocene age or in younger rocks that derived much or all of their phosphate from middle Miocene rocks.

In the Atlantic Coastal Plain, phosphate pellets are particularly widespread from North Carolina to the southern tip of Florida in rocks of middle Miocene age, although some pellets are found in rocks of Cretaceous to Holocene age. In the Gulf Coastal Plain, phosphate is widespread only in rocks of Cretaceous and Paleocene age. Younger rocks contain phosphate pellets only at a few localities where they were probably reworked from older rocks.

Economic phosphorite deposits are in part structurally controlled. All are in basins on the flanks of positive areas that were rising at the time of phosphate deposition; all are on the north or east sides of the positive areas, except for those of the land-pebble district of south Florida; all are in positions that suggest that phosphorus could have been supplied by cool, southward-moving near-shore ocean currents. Phosphate was precipitated in the basins when cool water, diverted by the positive areas, was turbulently mixed with warm waters of the Florida Current and the Gulf Stream. The scarcity of phosphate in Tertiary rocks of the Gulf Coast is probably due to the position of the Floridian Plateau, which diverted currents away from the Caribbean and the Gulf Coast.

Economic deposits of North Carolina, South Carolina, South Georgia--North Florida, and the central peninsula of Florida are similar in gross features. They are weakly consolidated, sedimentary rocks consisting of quartz and phosphate sand, clay, and in minor amounts, limestone and dolomite. The primary phosphate mineral in all of the deposits is a carbonate fluorapatite. Differences in the economic deposits include variation in chemical composition, size distribution of phosphate particles, clay mineralogy, the amount and intensity of leaching, and the formation of aluminum phosphate minerals. Differences seem to vary systematically from north to south.

Reserves are measured in billions of tons of recoverable phosphate particles containing a minimum of 30 percent P_2O_5. Resources of phosphate not minable under present conditions (particularly in the phosphatic limestone of the Hawthorn Formation) have not been measured, but they are likely to amount to scores of billions of tons.

P6 Sedimentation in Onslow Bay: Cleary, W.J., and Pilkey, O.H., 1968, in Guidebook for Field Excursions, Geological Society of America, Southeastern Section: Southeastern Geology, Special Publication 1, Durham, N.C., p. 1-17.

ABSTRACT

The most important factor in the history of sedimentation on the Onslow Bay continental shelf has been a low rate of sedimentation. The low rate of sedimentation is due to the fact that no important rivers drain into the embayment and that sediment exchange from adjacent Long and Raleigh Bays is limited. The elongate shoals at Capes Fear and Lookout are responsible for the lack of exchange from adjacent bays. Sediment cover in Onslow Bay is thin and outcrops of underlying consolidated Tertiary sediments are frequent. The sediments are primarily relict or residual and the nearshore Recent sediment band that is well developed elsewhere on the Southern U. S. Atlantic shelf is essentially absent here. The areal distribution of sediment textural and mineralogical characteristics is quite patchy.

Outer shelf sediments are highly calcareous and commonly contain a large proportion of algal fragments. Central and inner shelf sediments tend to be less calcareous but usually contain significant amounts of largely fragmental mollusc shells. A relict nearshore fauna is present over much of the central shelf. Black shells and abundant aragonitic oolites offer further evidence of the relict nature of much of the sediment. Heavy mineral analysis indicates that most of the non-carbonate sand-size fraction is ultimately derived from the Piedmont Province and not the Coastal Plain. The distribution of fine sand-size mica indicates that deposition of fine materials is restricted primarily to a few miles wide nearshore band and beyond the shelf break.

P7 Nearshore rock exposures and their relationship to modern shelf sedimentation: Crowson, R.A., and Riggs, S.R., 1976, Geological Society of America, Abstracts with Programs, v. 8, no. 2, p. 156-157.

ABSTRACT

The nearshore marine bottom (less than 15 meters in depth) in west Onslow Bay, North Carolina presents a complex relationship between the carbonate rock exposures and surrounding modern sediments. A pelecypod mold and cast limestone, probably the Castle Hayne Formation of Eocene age, with extensive interbeds of fossil oyster bioherms (Crassostrea gigantissima) are exposed on approximately 50% of the sea floor around New River Inlet. Two major sets of processes are presently acting upon this ancient rock surface to produce the modern topography, sediments, and carbonate rocks. The dominant constructive processes are controlled by biologic agents which include vermitid reefs, encrusting algae, sediment trapping bryozoa and corals. The dominant destructive processes are controlled by the mechanical agents of waves and currents and the biologic agents of boring pelecypods and polychates and burrowing crustaceans. The results of the processes are: 1) highly irregular rock surfaces with steep landward facing scarps (up to 5 meters in relief) subparallel to the beach with large boulders

at their base; 2) a series of vermitid reefs growing along the crest of the scarps in the vicinity of New River Inlet; and 3) the production of a thin blanket of loose sediment varying in texture from boulders to clay sized particles composed dominantly of limestone rock fragments, quartz sand, micrite mud, and a mixed assemblage of modern and fossil shell material. Thus, the modern processes operating on the rock surface result in distinct morphologic features and the production of sediments which have a strong internal heritage.

P8 The economic feasibility of mining phosphorite deposits of the continental shelf adjacent to North Carolina: Development Planning and Research Associates, Inc. (DPRA), 1987, Manhattan, KS., Unpublished company report no. 3707.000 for the U.S. Department of Interior, Minerals Management Service, 166 p.

EXECUTIVE SUMMARY

The purpose of this study is to evaluate the economic feasibility of mining phosphorite deposits of the outer continental shelf adjacent to the state of North Carolina, more specifically in Onslow Bay. The study results are expected to aid the U.S. Department of Interior and the State of North Carolina in making a decision regarding whether or not to proceed with other research tasks necessary for the possible exploration of the resource.

Physical Resource Description

The existence of Miocene phosphorite sediments on the outer continental shelf of the southeastern United States has been known since the early 1960s. Geologic investigations of the Carolina Coastal Plain during the late 1960s through the early 1980s collectively established the geologic picture of phosphate occurring in Onslow Bay. While numerous data sources were consulted in preparation of this report, the greatest concentration of data was obtained from studies supported by the National Science Foundation and the University of North Carolina Sea Grant program. The results of these studies are contained in unpublished theses and research files held by the Department of Geology at East Carolina University and the Department of Marine Sciences at the University of South Florida.

These data include approximately 14,000 kilometers of seismic sections, 144 vibracore logs, hundreds of surface samples, and hundreds of kilometers of side-scan sonar logs. In addition, thousands of chemical analyses of various litho-stratigraphic and individual lithologic components have been conducted. While the data base is extensive, none of the Onslow Bay phosphate can be classified as "demonstrated reserve," but rather should be classified between a hypothetical and inferred resource. Additional sampling and deep drilling are needed to further delineate the phosphate resource. However, a preliminary resource assessment was completed for this study, providing a best estimate of the quantity and quality of the phosphate deposits.

The analysis of the available data indicated that several geologic units contain phosphate ores that have the potential to be developed into a commercial mining operation. One of these geologic units, designated as Frying Pan Sequence-1 (FPS-1), is the most well-known because it has been explored extensively. The phosphate-bearing sediments vary in thickness from zero to 11 meters in the outcrop area to a maximum thickness of approximately 20 meters. The samples analyzed indicate that P_2O_5 content varies considerably, from approximately 2 to 23 percent, with an average of 9.5 percent in FPS-1.

Other principal geologic units, including Bogue Bank Sequence-1 (BBS-1), BBS-2 and BBS-8 are less well-known. These deposits vary in thickness from zero to 50 meters. Based on limited samples taken from outcrop areas, they appear to have a lower average P_2O_5 content than FPS-1. However, knowledge of landside deposits and how the phosphate deposits are formed indicate the P_2O_5 content very likely increases down dip, as is the case in North Carolina and Florida deposits. Estimates of P_2O_5 content presented below, however, are based solely on the results of samples taken at shallower depths, generally less than 10 meters.

GEOLOGIC UNIT	SURFACE AREA (square meters)	ORE QUANTITY (tonnes)	INPLACE CONCENTRATE (tonnes)	AVERAGE P_2O_5 CONTENT (percent)
FPS-1 (Outcrop area)	185.5	902.3	419.9	13.9
FPS-1 (Subsurface area)	2,350.1	35,150.9	10,094.7	9.3
BBS-1 (Outcrop area)	812.1	6,305.4	893.3	4.3
BBS-1 (Subsurface area)	1,240.4	36,784.4	5,211.1	4.3
BBS-2 (Outcrop area)	238.7	1,892.4	441.6	7.1
BBS-2 (Subsurface area)	629.5	15,600.4	3,302.3	7.3
BBS-8 (Outcrop area)	70.0	326.7	58.9	5.5
BBS-8 (Subsurface area)	201.9	1,951.6	330.7	5.1
TOTALS	5,728.1	98,914.3	20,752.5	7.3

The phosphatic material in the FPS-1 unit has properties similar to the phosphate deposits currently being mined by Texasgulf near Aurora, North Carolina. This unit outcrops on the ocean floor, and, as such has very little overburden. While the P_2O_5 content of this geologic unit is variable, a site has been identified which is believed capable of yielding an average P_2O_5 content of approximately 14.2 percent. Because other units, though less well known, appear to be less attractive for exploration because of overburden and/or low P_2O_5 content, the FPS-1 unit is the focus of this study.

P9 Structure and development of the Southeast Georgia Embayment and northern Blake Plateau; preliminary analysis: Dillon, W.P., Paull, C.K., Buffler, R.T., and Fail, J.P., 1979, in Watkins, J.S., Montadert, L., Dickerson, P.W., editors, Geologic and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 27-46.

ABSTRACT

Multichannel seismic reflection profiles from the Southeast Georgia Embayment and northern Blake Plateau show reflectors that have been correlated tentatively with horizons of known age. The top of the Cretaceous extends

smoothly seaward beneath the continental shelf and Blake Plateau, unaffected at the present shelf edge. A reflector inferred to correspond approximately to the top of the Jurassic section onlaps and pinches out against rocks below. A widespread smooth reflector probably represents a volcanic layer of early Jurassic age that underlies only the northwestern part of the research area. A major unconformity beneath the inferred volcanic layer is probably of Late Triassic or Early Jurassic age. This unconformity dips rather smoothly seaward beneath the northern Blake Plateau, but south of a geological boundary near 31° N, it has subsided much more rapidly, and reaches depths of more than 12 km. Development of the continental margin north of the boundary began with rifting and subsidence of continental basement in the Triassic. An episode of volcanism may have been due to stresses associated with a spreading center jump at about 175 million years ago. Jurassic and Cretaceous deposits form an onlapping wedge above the inferred early Jurassic volcanics and Triassic sedimentary rocks. During Cenozoic times, development of Gulf Stream flow caused a radical decrease in sedimentation rates so that a shelf that was much narrower than the Mesozoic shelf was formed by progradation against the inner edge of the stream. South of the 31° N geological boundary, the basement probably is semi-oceanic and reef growth, unlike that in the area to the north, has been very active at the outer edge of the plateau.

P10 Stratigraphy and paleoenvironment of the phosphatic Miocene strata of North Carolina: Gibson, T.C., 1967, Geological Society of America Bulletin, v. 78, p. 631-650.

ABSTRACT

Foraminifera and Mollusca collected from the phosphatic Pungo River Formation and the overlying Yorktown Formation in eastern North Carolina were analyzed and interpreted for stratigraphic and environmental significance in order to determine optimum depositional sites for primary phosphorite.

The Mollusca and benthonic foraminifera of the Pungo River Formation correlate with those of the Calvert Formation of Maryland, and the planktonic foraminifera in both of these formations correlate with the Globigerinatella insueta zone of Trinidad, postulated as late Aquitanian age. The paleoenvironment of the phosphorite deposition, interpreted primarily from the benthonic foraminifera, was of cool-temperate waters, ranging in depth from 100 to 200 m in the phosphatic beds to less than 70 m in the upper calcareous beds where phosphate is scarce. Phosphorite deposition occurred in an oceanic embayment located south of the Fort Monroe high in southern Virginia and north of a positive feature whose axis lies in the vicinity of New Bern, North Carolina. Cool-temperate waters in this area during Pungo River time indicate that circulation patterns of ocean currents and the resultant faunal provinces were not the same as those at present and later in the Miocene. In the Pungo River and its time equivalents of the Atlantic Coastal Plain, the presence of thick diatomaceous clay units, volcanic ash beds, shards, attapulgite clays, and other minerals probably derived from volcanic rocks, suggests a volcanic source somewhere off the coast during the Miocene.

The Yorktown unconformably overlies the Pungo River Formation. The unconformity is marked by channels into the Pungo River, filled with phosphatic

pebbles, vertebrate bones, and lower Yorktown molluscs and microfauna. The coarse-grained phosphatic material is derived from the underlying fine-grained primary phosphorite in the Pungo River and is abundant only in the lower part of the Yorktown Formation. Deposition of the lower part of the Yorktown occurred in waters about 100 m deep. The waters gradually became more shallow as deposition of the formation continued until depths of less than 15 m, and probable brackish conditions were reached as the uppermost part of the formation was deposited. Temperature of the waters, cool- temperate during lower Yorktown deposition, became warm-temperate to subtropical in later Yorktown time. The faunal patterns suggest that circulation patterns reached their present state during late Yorktown time.

P11 Stratigraphy of Miocene through Lower Pleistocene strata of the U.S. central-Atlantic Coastal Plain: Gibson, T.C., 1983, in Ray C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 35-80.

ABSTRACT

Miocene, Pliocene, and Pleistocene strata were deposited in two embayments in the central Atlantic Coastal Plain, the Salisbury to the north and Albemarle to the south. Both embayments underwent local tectonics, and no single area within either has a continuous section.

Deposition in both embayments began in early Miocene time. In the Salisbury embayment, the early deposits were largely biogenic (Fairhaven Member of the Calvert Formation), and the center of deposition was located in Maryland. Relatively continuous clastic deposition commenced in the late early Miocene and continued through the middle Miocene (Plum Point Marl Member of the Calvert Formation and the Choptank and St. Marys formations). Deltaic deposition began in the northern part of the embayment, as seen in the Calvert and Kirkwood formations and influenced environments west of the delta lobe. The center of deposition in the Salisbury embayment shifted southward into Virginia during late Miocene time ("Virginia St. Marys" beds) and continued there through the early and middle(?) Pliocene (Yorktown Formation); only the southeastern part of the embayment received sediments in the late Pliocene and early Pleistocene (uppermost part of the "Yorktown" Formation). Environments throughout this time were largely inner shelf (less than 60-m depths), and some marginal-marine to nonmarine intervals.

The Albemarle embayment in North Carolina received largely biogenic and biochemical deposition during the early and early middle Miocene (Pungo River Formation). This was followed by uplift in the middle and late Miocene. Clastic sedimentation started near the Miocene-Pliocene boundary and continued with minor hiatuses throughout much of the Pliocene and into the early Pleistocene (Yorktown, uppermost part of the "Yorktown", Duplin, Croatan, and Waccamaw formations). Some Pungo River strata formed in middle-shelf environments as deep as 100 m; most younger strata were deposited in inner-shelf environments (less than 60-m depth), but some in marginal-marine intervals.

P12 Key foraminifera from Upper Oligocene to Lower Pleistocene strata of the central Atlantic Coastal Plain: Gibson, T.C., 1983, in Ray, C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 355-453.

ABSTRACT

Biostratigraphically important planktonic and benthic foraminiferal species from strata of late Oligocene to early Pleistocene age in the central Atlantic Coastal Plain are described and illustrated. Thirty planktonic species are used, in conjunction with a few radiometric ages, to date the strata. The ages derived are: "Silverdale" beds of latest Oligocene age; Pungo River and Calvert formations of late early to early middle Miocene age; Choptank Formation of middle middle Miocene age; St. Marys Formation of late middle to early late Miocene age; "Virginia St. Marys" beds of late Miocene age; Yorktown Formation of early to late(?) Pliocene age; and uppermost "Yorktown", Croatan, and Waccamaw formations of late Pliocene and early Pleistocene age.

Thirty-seven species and subspecies of benthic Foraminifera important for regional correlation are described, and ranges are given for this area. New species described are Bolivina pungoensis, Bolivinopsis fairhavenensis, Epistominella pungoensis, Cibicides cravenensis, C. croatanensis, C. pungoensis, Svratkina croatanensis, Nonion calvertensis, Florilus chesapeakensis, and Elphidium neocrespinae. New subspecies described are Nonion advenum pustulosum and Elphidium latispatium pontium.

P13 Age and correlation of the Yorktown (Pliocene) and Croatan (Pliocene and Pleistocene) Formations at the Lee Creek Mine: Hazel, J.E., 1983, in Ray, C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 81-200.

ABSTRACT

The fossiliferous beds above the Pungo River Formation (middle Miocene) in the Lee Creek open pit mine in Beaufort County, North Carolina, are approximately 70 feet (21.3 m) thick. This thickness includes 46 feet (14 m) that is correlative with the Yorktown Formation of the type area and is referred to that unit, and, above the Yorktown, a fossiliferous section 23 feet (7 m) thick that is assigned to the Croatan Formation.

The 149 species or subspecies of ostracodes identified were from 16 samples from the Yorktown and Croatan. Coefficients of faunal similarity were calculated for all samples, and the resulting matrix was subjected to unweighted pair-group cluster analysis. Three major faunal groupings were delineated. The principal faunal discontinuity occurs at the Yorktown-Croatan contact about 46 feet (14 m) above the base of the Yorktown. The beds below this level belong to the Pterygocythereis inexpectata and Orionina vaughani ostracode assemblage zones. Correlation with other Coastal Plain deposits containing planktonic foraminifers indicates that the Orionina vaughani assemblage zone is planktonic foraminifer

zones N19 and N20 in age and that the Pterygocythereis inexpectata assemblage zone may approximate the lowest part of planktonic zone N19 in age. Thus, the Yorktown in the Lee Creek Mine is of early Pliocene age. This is seemingly corroborated by a K/Ar date of 4.4 ± 0.2 my on the Orionina vaughani assemblage zone in Virginia.

A third major faunal assemblage is found in the beds of the Croatan Formation, which are referable to the Puriana mesacostalis ostracode assemblage zone. The upper part of the Croatan can be correlated with rocks in Florida and North Carolina that have been radiometrically dated by the He/U method at about 1.8 to 1.9 my. A tentative He/U radiometric date of 2.4 my was obtained for the lower part of the Croatan at the mine. If a date of about 2.0 my is used for the Pliocene-Pleistocene boundary, the Croatan as used in the mine spans the Pliocene-Pleistocene boundary .

P14 Ocean bottom survey of the U.S. South Atlantic OCS region: Final Report to The U.S. Geological Survey: Henry, V.J., 1983, U.S. Geological Survey, Office of Marine Geology, Woods Hole, Massachusetts, 99 p. plus Appendices.

INTRODUCTION, OBJECTIVES, AND WORK PLAN

The area surveyed included the U.S. South Atlantic continental shelf between Jacksonville, Florida and Cape Hatteras, North Carolina from the three mile inner shelf boundary seaward to the 50 m isobath (Fig. 1).

The survey was carried out under contract with the U.S. Geological Survey, Office of Marine Geology, Woods Hole, MA (contract #14-08-0001-06266) to determine the occurrence and distribution of biological and geological hazards on the ocean bottom and shallow subbottom relative to potential hydrocarbon development and subsequent environmental impact in the U.S. South Atlantic OCS region. Specific objectives were to:

1. map biologically sensitive features such as livebottoms and reefs;
2. map potential geological hazards and constraints such as hardgrounds, sink holes, buried channels, mobile bedforms, scour and faults;
3. relate the above features to shallow, geologic structure and stratigraphy;
4. map smaller bedforms, biota, texture and other indicators of bottom conditions;
5. evaluate remote sensing system capability in terms of accomplishing project objectives; and
6. prepare geologic atlases for the shelf areas included in the Jacksonville (NH17-5) and Brunswick (NH17-2) 2-degree topobathy sheets.

Reports discussing the results of earlier portions of the survey have been published as parts of USGS Open File Reports (see Henry and Giles, 1980 and Henry et al. 1981). Tracklines along which data were collected are shown in Figure 2. The University of Georgia (UGA) data were obtained using the R/V Bluefin operated by the Skidaway Institute of Oceanography. Eleven cruises were made during the period July 1978 through February 1982. These cruises were designated, sequentially, as GS1 through 9, TT-1 and GS-A. Cruises GS1 through 4, GS-7, TT-1 and GS-A were conducted off Georgia, GS5 and GS6 off South Carolina and GS-8 and GS-9 off North Carolina.

Approximately 6,000 km of trackline were surveyed. Bottom conditions and features were observed and/or recorded using an O.R.E. 3.5 kHz tuned transducer, an EG&G Mark IB sidescan sonar and a sled-mounted Jay-Mar Ocean Eye 1000 b/w television. Shallow subbottom features were mapped using the O.R.E. transducer, a Bolt PAR 1 cu. inch air gun and an EG&G model 225 UNIBOOM system. Position along the tracklines was maintained using a Northstar 6000 LORAN C receiver. Cruise reports and a data acquisition inventory list are presented in Appendix I and II, respectively. The total trackline data acquired using each system is given in Table 1.

Table 1. Total Trackline Data Acquisition

3.5 kHz System	5,662 km
UNIBOOM/Air Gun System	5,734 km
Sidescan Sonar System	5,871 km
Underwater Television System	874 km

Significant information also was obtained from 22 dives of the R/V *Diaphus* made during August 15-18, 1978. The primary purpose of the submersible surveys was to examine shelf edge features and to groundtruth 3.5 kHz and sidescan sonar data interpretation. Dive locations are shown in Figure 3.

In addition to the text, a series of trackline maps on a 2-degree topobathy base are presented under separate cover in Appendix IV, graphically depicting bottom and subbottom conditions and features encountered along the tracklines. Data map Series A through D, respectively, present data on bedforms/textures, hardbottoms/livebottoms, shallow subbottom geology and TV observations/biota. These data are summarized in Figures 4-7. Figures 8-30 are located at end of report.

Atlases, submitted under separate cover as Appendix V, were prepared summarizing the geological, physical and chemical characteristics of the portion of the continental shelf included on the Jacksonville (NH 17-5) and Brunswick (NH17-2) 2-degree topobathy maps. Data sources included the results of this survey, published literature and reports from other BLM studies. The purpose of the atlases is to provide a graphic overview of selected topics relating to bottom and shallow subbottom shelf conditions in the form of maps, plates, figures and bibliography. Supplementary reports that resulted from the Ocean Bottom Survey are bound separately as Appendix III A-D. Information from these reports is incorporated into the text.

Data acquisition relative to instrument systems used varied in terms of coverage along tracklines (Table 1). Almost 98% trackline coverage was attained with the 3.5 kHz and sidescan sonar systems. UNIBOOM/airgun coverage amounted to approximately 90% of the tracklines run. Television observations were made along 15% of the tracklines. However, towing was carried out only during daylight hours and as weather permitted. Nighttime towing was not feasible due to poor picture quality caused by backscatter from plankton and other particulate matter in the water column. The results presented, therefore, are biased to the extent that total acquisition by the several instrument systems varied according to weather, downtime and, relative to television observations, ambient light conditions. The area in which the least data were obtained was in Long Bay where cruise GS-8 encountered severe weather conditions. Sparker and 3.5 kHz data from USGS R/V *Fay* cruises were used to supplement GS-8 data.

P15 Deep structure and evolution of the Carolina Trough: Hutchinson, D.R., Grow, J.A., Klitgord, K.D., and Swift, B.A., 1982, in, Watkins, J.S., and Drake, C.L., editors, Studies in Continental Margin Geology: American Association of Petroleum Geologists Memoir 34, p. 129-152.

ABSTRACT

Multichannel seismic-reflection data together with two-dimensional gravity and magnetic models suggest that the crustal structure off North Carolina consists of normal continental crust landward of the Brunswick magnetic anomaly (BMA), rift-stage crust in the 80 km-wide zone between the BMA and the East Coast magnetic anomaly (ECMA), and normal oceanic crust seaward of the ECMA.

P16 The Pungo River Formation, a new name for middle Miocene phosphorites in Beaufort County, North Carolina: Kimrey, J.O., 1964, Southeastern Geology, v. 5, p. 195-205.

ABSTRACT

This paper proposes the designation, Pungo River Formation, for a previously unnamed phosphorite unit of middle Miocene age that underlies more than 700 square miles of Beaufort County, North Carolina.

The Pungo River Formation is composed of interbedded phosphatic sands, silts and clays, diatomaceous clays, and phosphatic and non-phosphatic limestones. The formation dips gently to the east in Beaufort County; its thickness ranges from a featheredge, a few miles east of the City of Washington, to more than 110 feet in the southeastern part of the county.

P17 Description of the Pungo River Formation in Beaufort County, North Carolina: Kimrey, J.O., 1965, North Carolina Department of Conservation and Development, Division of Mineral Resources, Bulletin 79, 132 p.

ABSTRACT

This report describes the lithology and stratigraphy of the Pungo River Formation that underlies part of Beaufort County, North Carolina. The formation contains potentially economic beds of phosphatic sand. It is composed of interbedded phosphatic clays, diatomaceous clays, phosphatic limestones, silty claystones, coquinas, calcareous clays, and phosphatic sands. The P_2O_5 content of the phosphatic sands ranges up to a known maximum of about 21 percent of the raw core sample. The above materials usually occur in definite zones, or horizons, in the formation that may be traced laterally across the county.

The depth and thickness of the Pungo River Formation and the delineation of lithologic zones within the formation were determined by gamma-ray logs of existing water wells and gamma-ray and resistivity logs of core holes that penetrated the unit. Additional core holes were then drilled and the P_2O_5,

content of material from the core holes was determined. It was determined that there is a generally direct relationship between the gamma-ray emission intensity of the phosphatic sands in the formation and their P_2O_5 content. This relationship was used to estimate P_2O_5 contents where core-hole and analytical data was not available.

Beaufort County is in the east-central part of the North Carolina Coastal Plain. Its economy is geared primarily to production of agricultural and timber products.

The Pungo River Formation was apparently deposited in a northeast-southwest trending basin whose axis lies southeast of Beaufort County. Subsequent downwarping to the southeast has resulted in erosional beveling of the top of the formation. The formation underlies more than 700 square miles of the eastern part of Beaufort County. Its thickness ranges from a featheredge, a few miles east of the city of Washington, to more than 120 feet near the south shore of the Pamlico River in eastern Beaufort County. Its depth below mean sea level ranges from a minimum of about 40 feet near its western limits to more than 230 feet in the northeastern part of the county.

A fence diagram of the formation, lithologic logs, P_2O_5 analyses, beneficiation data, and selected gamma-ray and resistivity logs are included in this report.

P18 Basin structure of the United States Atlantic Continental Margin: <u>Klitgord, K.D., and Behrendt, J.C., 1979</u>, in Watkins, J.S., Montadert, L., Dickerson, P.W., editors, Geologic and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 85-112.

ABSTRACT

A detailed magnetic study of the U.S. Atlantic continental margin north of Cape Hatteras delineates the pattern of basins and platforms that form the basement structure. A 185,000 km, high-sensitivity aeromagnetic survey acquired in 1975 over the entire U.S. Atlantic continental margin forms the basis of this study. Magnetic depth-to-source estimates were calculated for the entire survey using a Werner "deconvolution" type method. These depth-to- basement estimates are integrated with multichannel seismic reflection profiles to interpolate basement structures between seismic profiles.

The deep sediment-filled basins along the margin are bounded on their landward sides by blockfaulted continental crust; their seaward sides are marked by the East Coast magnetic anomaly. The trends of the landward sides of these basins vary from 030° in the south to 040° in the north, consistent with a common pole of opening for all of the basins. The ends of these basins are controlled by sharp offsets in the continental crust that underlie the various platforms. These offsets are the result of the initial breakup of North America and Africa and are preserved as fracture zones under the continental rise.

The regions west of the various basins are comprised of platforms of Paleozoic and older crust and embayments of Triassic-Jurassic age. The Long Island platform is a series of ridges and troughs. These troughs are oriented northeastward, parallel with the Baltimore Canyon trough and the Georges Bank trough. The Connecticut Valley Triassic basin has a broad magnetic low associated with it that can be traced across Long Island. A similar magnetic

signature is associated with the trough between Martha's Vineyard and Nantucket Island, suggesting that it also may be a Triassic basin. The Salsbury Embayment with its Triassic-Jurassic age sediments lies just west of the Baltimore Canyon trough while the Carolina platform, which has a few smaller Triassic basins within predominantly Paleozoic and older crust, lies landward of the Carolina trough. The area around Charleston is another major embayment of Triassic-Jurassic age, and west of the Blake Plateau is the Florida platform with Paleozoic and older crust.

A magnetic basement high associated with the East Coast magnetic anomaly separates oceanic crust from the deep sediment-filled troughs. The minimum depth of this high ranges from 6 to 8 km and the susceptibility contrast suggests that it is more likely an uptilted block of oceanic crust than a massive intrusive body. The magnetic anomaly probably is produced by a combination of a basement high and an "edge effect," where the edge is between the uptilted block and flat-lying, nonmagnetic sediments to the west.

P19 Phosphorite grains: their application to the interpretation of North Carolina shelf sedimentation: Luternauer, J.L., and Pilkey, O.H., 1967, Marine Geology, v. 5, p. 315-320.

SUMMARY

Study of phosphorite grains in North Carolina continental shelf, beach, sound, and river sediments reveals that: (1) the shelf is an important source of beach sediment, and (2) North Carolina shelf cuspate embayments are essentially independent entities, in terms of sediment content and transport.

P20 Tropical reef corals: tolerance of low temperatures on the North Carolina continental shelf: MacIntyre, I.G., and Pilkey, O.H., 1969, Science, v. 166, p. 374-375.

ABSTRACT

Individual heads of two species of reef or hermatypic coral, Solenastrea hyades (Dana) and Siderastrea siderea (Ellis and Solander), occur on rock outcrops on the inner continental shelf off North Carolina in waters where winter bottom temperatures are as low as 10.6° C. These temperatures are significantly lower than previously assumed minimum temperatures for the survival of tropical reef corals in their natural environment.

P21 **Physiographic features on the outer shelf and upper slope, Atlantic Continental Margin, southeastern United States: MacIntyre, I.G., and Milliman, J.D., 1970, Geological Society of America Bulletin, v. 81, p. 2577-2598.**

ABSTRACT

Both erosional and constructional processes appear to have formed physiographic features near the shelf break along the southeastern United States, as indicated by extensive echo-sounder profiles, rock-dredge material, and bottom photographs. Between Cape Hatteras, North Carolina, and Fort Lauderdale, Florida four distinct physiographic areas are delineated each having characteristic morphologies and lithologies.

The ridges and well-defined troughs on the outer shelf and upper slope (depths of about 50 to 150 m) between Cape Hatteras and Cape Fear may be related largely to earlier Gulf Stream erosion, and the rocks (algal limestones and sandstones) and sediments dredged from these features probably are mainly Holocene, relict shallow-water deposits forming a thin veneer over this erosional surface of the sea floor. Relatively rapid accumulation of pre-Holocene sediments may account for the general absence of pronounced physiographic features on the outer shelf and upper slope from Cape Fear to Cape Kennedy. Ledges, small terraces, and rises (depths of 50 to 110 m) in this area are probably Holocene features eroded into, or constructed on the pre-Holocene sediments, which are covered by transgressive Holocene algal limestones and sandstones similar to those collected to the north. The lithology, together with radiocarbon dates of rock material, indicate that well-defined ridges in depths of 70 to 90 m between Cape Kennedy and Palm Beach are relict oölitic ridges or "dunes" formed during the Holocene transgression; these features are now covered by modern *Oculina* sp. coral debris. From Palm Beach to Fort Lauderdale, where the continental shelf is narrow and shallow, a small ridge present at the shelf break (15 to 30 m) is thought to be an "inactive" coral reef.

P22 **Phosphate mining at the Lee Creek Mine: McLellan, J.H., 1983, in Ray, C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina, Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 25-34.**

ABSTRACT

Although phosphate has been sought in North Carolina for approximately a century, prospecting leading to production began only in the 1950s and culminated in 1966 with the first shipment of concentrate from Texasgulf's Lee Creek Mine, on the south bank of the Pamlico River, near Aurora, Beaufort County, North Carolina. The mining and processing operations are described, insofar as they are relevant to the study of the geology and paleontology. The ore occurs in the Pungo River Formation, from which it is obtained by removal of 90-100 feet (27-30 m) of overburden, using dredge and dragline in an open pit mine. Access to strata in place is very limited. Most fossils are collected by prospecting

the spoil piles (mostly Yorktown and overlying formations), but some are obtained from ore residue and from coarse rejects at the mill (mostly Pungo River Formation).

P23 Reconnaissance geology of the inner continental shelf, Cape Fear region, North Carolina: Meisburger, E.P., 1979, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Ft. Belvoir, Virginia, Technical Report TP79-3, 135 p.

ABSTRACT

The Inner Continental Shelf off the North Carolina coast between the South Carolina border and Cape Lookout, North Carolina, was surveyed to obtain information on bottom and subbottom sediment deposits and structures. The location and the extent of deposits of sand suitable for restoration and nourishment of nearby beaches were investigated. Primary survey coverage consisted of 824 kilometers (445 nautical miles) of seismic reflection survey and 139 cores ranging in length from 0.6 to 6.1 meters (2 to 20 feet).

More than half of the area surveyed is underlain by two thick sections of Coastal Plain sediments characterized by seaward-dipping, progradational internal beds which generate a characteristic acoustic pattern on seismic reflection records. These beds are exposed on the shelf floor in places and elsewhere are covered by a thin sediment blanket. Samples of these extensive units indicate that one is of Cretaceous age and the other of Oligocene age. Both units consist predominantly of fine quartz sand.

Other sediment units closely underlying the shelf floor consist of planar- to complex-bedded sheet and channel-fill deposits of predominantly quartz sand or biogenic calcium carbonate. These deposits range in age from Eocene to Holocene.

Modern sediment accretion on the inner shelf appears to be largely restricted to the shoal fields off Cape Lookout and Cape Fear, and to inlet shoals along the coast. Elsewhere on the inner shelf floor, modern sediments are thin and discontinuous, and modern shelf processes appear to be largely confined to reworking, winnowing, and redepositing older deposits.

P24 Sediments of the continental margin off the eastern United States: Milliman, J.D., Pilkey, O.H., and Ross, D.A., 1972, Geological Society of America Bulletin, v. 83, no. 5, p. 1315-1333.

ABSTRACT

The character and distribution of surficial sediments on the continental shelf and slope between northern Maine and southern Florida have been defined on the basis of more than 6,000 bottom samples. Most shelf sediments were deposited in shallow water (probably littoral depths) during the last lower stand of sea level. Modern sediments are accumulating only in estuaries, in certain nearshore areas and on the continental slope.

A large portion of the shelf sediment north of latitude 41° N was deposited

by Pleistocene glaciers that covered the area. Sediments on the middle Atlantic shelf consist of predominantly arkosic to subarkosic fluvial sands. The inner shelf off the southeastern United States is covered by suborthoquartzitic fluvial sands, derived mostly from Piedmont rivers; carbonate rich sands occur over much of the outer shelf and upper slope. Residual detritus, reworked from underlying mid-Tertiary formations, is an important sedimentary component on Georges Bank and Nantucket Shoals, Onslow Bay, the Florida-Hatteras slope, and the Blake Plateau.

Although most sediments are not in compositional equilibrium with the present-day shelf environment, there is considerable evidence to suggest that many may be in at least partial textural equilibrium. Holocene reworking has removed most fine-grained sediment, leaving only coarse to medium sand. Some fine-grained fluvial sediment escapes the estuaries and nearshore during floods and storms, but this influx is not sufficient to offset the effect of winnowing by currents and waves. A significant portion of the modern nearshore sediment, in fact, may be derived from landward transport of fine-grained sediment from the central and outer shelf. Despite the evidence of active sediment movement on the shelf, however, the net lateral transport of sand and gravel appears to be limited.

Because of the lack of present-day terrigenous sedimentation, a primary source of modern shelf sediment is calcareous skeletal material. If the present-day surface were preserved in the geologic record, much of it probably would be a carbonate rich layer, containing altered and reworked skeletal material representing a variety of depositional environments.

P25 Stratigraphic and structural setting of the middle Miocene Pungo River Formation of North Carolina: Miller, J.A., 1971, PhD Dissertation, University of North Carolina, Chapel Hill, N.C., 82 p.

ABSTRACT

Borehole data from the subsurface middle Miocene section of North Carolina show that these rocks can all be assigned to the Pungo River Formation of Calvert age. The top of the formation is revised in the type core and surrounding area to conform with lithologic and paleontologic criteria used to define the unit elsewhere.

Structural, isopach, and lithofacies maps of the formation establish north-trending flexure zones and northeast-trending noses and troughs which have had a dominant effect on sediment distribution and thickness in the unit. These structural features were a major influence in determining the site of precipitation and concentration of phosphate in the formation.

Benthonic foraminifera which are regionally characteristic of the unit are listed. These foraminifera indicate that most of the formation was deposited in an open marine, normal salinity, shallow shelf environment. Abundant diatom remains indicate waters rich in silica and in nutrients, provided by upwelling waters enriched in these constituents.

The rock suite, which includes commercial phosphorite, and the structural setting of the Pungo River Formation are shown to be similar to those associated with numerous other primary phosphorite occurrences. Deposition of such phosphorites appears to be influenced primarily by physical (structural)

conditions on the sea floor, and secondarily by biologic influences. Volcanic activity does not appear necessary to account for the formation of phosphate. The replacement of carbonates by phosphate is of minor importance in Pungo River sediments.

P26 Stratigraphy, structure, and phosphate deposits of the Pungo River Formation of North Carolina: Miller, J.A., 1982, North Carolina Department of Natural Resources and Community Development, Geological Survey Bulletin 87, 32 p.

ABSTRACT

Borehole data from subsurface early and middle Miocene rocks of North Carolina show that the phosphatic sand, clay, and limestone comprising this part of the section can all be assigned to the Pungo River Formation. The definition of the top of the formation is revised in the type core and the surrounding area to conform with lithologic and paleontologic criteria used to define the unit elsewhere.

Structural, isopach, and lithofacies maps of the formation show that north-trending flexure zones (hinge lines) and northeast-trending noses and troughs have greatly affected sediment distribution and thickness in the Pungo River. These structural features, particularly the hinge lines, were a major influence in determining where primary phosphate was formed and concentrated.

Foraminifera recovered from the formation are in part time-diagnostic and in part facies-controlled, and they indicate that most of the formation was deposited in a slightly restricted, shallow shelf environment of normal salinity. Abundant diatom remains indicate that Pungo River seawater was rich in silica and in nutrients, thought to have been provided by upwelling deep ocean waters.

The rock suite, which includes high concentrations of phosphate, and the structural setting of the Pungo River Formation are similar to those associated with numerous other primary phosphorite occurrences. Deposition of such phosphorites appears to be influenced primarily by physical (structural) conditions on the sea floor, and secondarily by biologic activity and current distribution.

P27 Reconnaissance geology of the submerged and emerged coastal plain province, Cape Lookout area, North Carolina: Mixon, R.B., and Pilkey, O.H., 1976, U.S. Geological Survey Professional Paper 859, 45 p.

ABSTRACT

Surficial deposits of the submerged and emerged parts of the Coastal Plain province in the Cape Lookout area, North Carolina, consist mainly of terrigenous sand, silt, and clay of Quaternary age which almost completely mantle more consolidated Pliocene strata of the Yorktown Formation. Calcareous deposits composed largely of skeletal calcirudites and calcarenites and oolitic calcarenites, probably late Pleistocene to Holocene in age, are present on the shelf southwest of Cape Lookout. A narrow band of algal limestone and calcareous quartz sandstone is exposed along the shelf break. Abundant ooliths and a

displaced fossil faunal assemblage, which includes intertidal, inlet, and inner-shelf species, indicate that the Quaternary Continental Shelf sediments are of shallow-water origin. Sediments underlying the emerged Coastal Plain were deposited mainly in barrier, backbarrier, and very nearshore marine environments.

Trends of sand ridges on the Onslow and Raleigh Bay shelf segments suggest that these ridges are constructional features formed subaqueously on the shelf floor during the latter part of the Holocene transgression by storm-generated waves and currents. The ridges are almost certainly being modified today. Shelf-edge features such as the terrace and the paired ridge and trough in the southeastern part of the map area were probably formed by a combination of erosion and biohermal accumulation during a lower stand of the sea. The most prominent landforms on the mainland are Pleistocene barriers (with associated relict beach ridges and Carolina Bays) and backbarrier flats.

The down-to-the-coast steplike topography of the subaerial barriers and backbarrier flats in the Cape Lookout area represents partially preserved depositional surfaces and indicates an episodic progradation of the coast toward the south, east, and northeast. The trends of late Pleistocene shorelines in this area and in the Pamlico Sound region to the north suggest that the ancestral Cape Lookout, formed by the seaward-projecting Newport and Arapahoe barriers, extended farther southeast across the Continental Shelf at that time than did contemporary capes to the north or south. The outermost Continental Shelf and upper Continental Slope in this area have formed by a process of upbuilding and outbuilding throughout the late Tertiary and Quaternary, as evidenced by beds of fairly uniform thickness deposited essentially parallel to the present sea floor. Sparker profiles indicate that Cape Lookout and its associated shoals are not related to structural arching of the underlying beds.

A contour map on the base of the Quaternary deposits shows a shallow linear depression in the youngest Tertiary strata which diverges from the present course of the Neuse River near Flanner Beach and trends south-southeast between the Pleistocene Newport and Arapahoe barriers toward the present-day Cape Lookout. The filled depression appears to be a Pleistocene course of the Neuse River; the association of the ancestral Neuse River with an ancestral Cape Lookout supports Hoyt and Henry's hypothesis that capes along the southeastern coast of the United States coincide with river mouths and result from the reworking, by transgressing seas, of deltas deposited on the shallow inner shelf during low stands of the sea.

P28 Relationship of surface sediments on the lower forebeach and nearshore shelf to beach nourishment at Wrightsville Beach, North Carolina: <u>Pearson, D.R., and Riggs, S.R., 1981</u>, Shore and Beach Journal, v. 49, p. 26-31.

INTRODUCTION

Wrightsville Beach occupies one of the coastal islands which form the continuous chain of sand barriers along the coast of North Carolina. Field information collected from the forebeach and the nearshore shelf off Wrightsville Beach indicates that man's activities have had a profound effect on the surface sediments of this offshore area. As part of a larger research project, surface sediment samples and vibracores up to seven feet in length, were collected from six sample stations off Wrightsville Beach. The six stations, which were located along a traverse oriented perpendicular to the shore, extended from 0.25 to 3.05 nautical miles offshore. In addition, 18 miles of high resolution seismic subbottom profiles were run through this inner three nautical mile area.

Several beach nourishment projects have been undertaken in the recent past to check erosion along Wrightsville Beach. These projects have involved the construction and periodic replenishment of artificial berms and dunes with predominantly estuarine derived sediments. Erosion, which has kept pace with the renourishment projects, resulted in the net removal of large volumes of sediments from the beach. Analyses of surface sediment samples from the lower forebeach and the nearshore shelf indicate that these sediments were probably derived from the renourishment fill lost from Wrightsville Beach. Estimates of the total volume of nourishment sediment which has been eroded from the beach, is volumetrically adequate to have supplied the lower forebeach and nearshore shelf area with a thin veneer of sediments.

P29 Upwelling processes associated with Western Boundary Currents: Pietrafesa, L.J., 1990, in Burnett, W.C., and Riggs, S.R., editors, Neogene to Modern Phosphorites: Cambridge University Press, Cambridge, England, Phosphate Deposits of the World, Volume III, chapter 1, p. 3-26.

ABSTRACT

Upwelling processes associated with Western Boundary Currents (WBCs) include not only classical wind driven coastal upwelling but also mechanisms due to buoyancy flux, topography and boundary current frontal instabilities. Sharp breaks in cross-shelf bottom topography can create localized transient pockets of uplifted isopycnals during occasions of wind-forced upwelling events. Longshore variations in bathymetry interacting with a WBC can have the effect of torquing the sheared jet across isobaths and kinematically inducing upwelling, creating regions of persistent or quasi-permanent upwelling. Isolated topographic ridges or bumps, such as the Charleston Bump, a topographic rise sitting atop the continental slope directly in the path of the Gulf Stream can cause WBCs to deflect offshore creating a downstream wave trough which, via bottom Ekman suction, can support a continental slope region of persistent upwelling. WBCs are characterized by frontal instabilities which manifest themselves as shelf-break hugging, downstream-propagating frontal meanders and filaments. These features are found to be responsible for creating shelf-break upwelling domes and ridges. These events can act occasionally in concert with wind and buoyancy stress-forcing to create shelf-wide upwelling. All of the above WBC related upwelling processes are shown to be important to the supply of high concentrations of phosphate to local continental margin and shelf regions. Relatively high values of phosphate are shown to exist where the upwelling processes described above are present in WBC systems, such as the Gulf Stream.

P30 Physical oceanographic processes in the Carolina Capes: Pietrafesa, L.J., Janowitz, G.S., and Wittman, P.A., 1985, in Atkinson, L.P., Menzel, D.W., and Bush, K.A., editors, Oceanography of the Southeastern U.S. Continental Shelf: American Geophysical Union, Coastal and Estuarine Sciences No. 2, p. 23-32.

ABSTRACT

Oceanographic processes in the Carolina Capes region of the South Atlantic Bight are influenced by the cuspate shore line and prominent shoals that extend to the shelf break. Meteorological, hydrographic, and moored current data indicate that synoptic scale wind and Gulf Stream events are the primary driving forces in the region. Topographically enhanced upwelling may be important at the shelf break.

P31 A North Carolina shelf phosphate deposit of possible commercial interest: Pilkey, O.H., and Luternauer, J.L., 1967, Southeastern Geology, v. 8, p. 33-51.

ABSTRACT

An elongate, surficial deposit of phosphatic sand has been located adjacent to and east of Frying Pan Shoals off Cape Fear, North Carolina. The area of highest phosphate concentration is about 10 miles long and three to four miles wide and is in water depths between 20 to 30 meters. The richest sample obtained contained 40% phosphorite grains by count and 7.78% P_2O_5. Since the observed material is surficial, the P_2O_5 values may have been decreased by dilution with quartz and shell material and increased by winnowing of nonphosphatic fines. Bottom photos and continuous bottom soundings indicate that rock outcrops are present. Dredged rocks from the area are friable, obviously weathering, slightly phosphatic limestones. It is tentatively concluded that the phosphatic sand is derived as a weathering concentrate from the outcropping limestone. It is suggested that the thickness of the deposit will depend on sub bottom topography and the length of time during which weathering of the limestone has occurred. Further prospecting of the area is definitely warranted. Suggested procedures for further investigation are given.

P32 Cenozoic depositional and structural history of the North Carolina Margin from seismic-stratigraphic analyses: Popenoe, P., 1985, in Poag, C.W., editor, Geologic Evolution of the United States Atlantic Margin: Van Nostrand Reinhold Co., New York, New York, p. 125-188.

ABSTRACT

The Cenozoic history of the U.S. continental shelf, slope, and rise off North Carolina has been reconstructed from stratigraphic analyses of

high-resolution seismic-reflection profiles tied to offshore and onshore wells. The sedimentary history is intimately tied to sea-level variations that shift erosional and depositional forces laterally with eustatic change, resulting in complex depositional packages and unconformities. The Cenozoic strata consist of eleven major depositional packages reflecting large eustatic sea-level cycles. Smaller eustatic cycles within these depositional packages have not been defined, but the most evident ones are discussed.

The effects of sea-level variations on the North Carolina margin are amplified because of the geometry of the continental edge and its effect on Gulf Stream flow. The North Carolina area lies leeward of a major bathymetric ramp that overlies the corner of the Carolina platform (Cape Fear arch) on the northern Blake Plateau. This ramp has affected the Gulf Stream flow throughout its history. During low eustatic sea level, the Gulf Stream was deflected offshore by the ramp, and both subaerial erosion and concurrent sedimentation occurred across the shelf and the northern Blake Plateau off North Carolina. During higher eustatic level, the Gulf Stream overrode the bathymetric ramp and eroded tracks across the northern plateau that presently are preserved beneath the Florida-Hatteras Shelf. During the highest eustatic levels, the Gulf Stream flowed through the Suwannee Straits, a structural depression across northern Florida and southern Georgia.

The eustatic changes in sea level have caused major shifts in depocenters and unconformities that span the marine-coastal plain boundary. These shifts in depocenters and major unconformities have been traditionally interpreted as tectonic in origin; however, the present data demonstrate that they are chiefly caused by oceanographic and subaerial processes on a gradually subsiding continental edge.

In the Late Cretaceous and Paleocene, Gulf Stream flow was through the Suwannee Straits, and sedimentation off North Carolina was chiefly controlled by upbuilding of the shelf accompanying margin subsidence. These conditions changed in the early Eocene, when a sea-level drop caused the Gulf Stream to flow through the Straits of Florida. The flow off North Carolina during the Eocene was diagonal to the crustal structure (Cape Fear arch) and differentially eroded the area of Cape Fear and built a shallow-water shelf into the Carolina trough at Cape Hatteras. These high eustatic conditions were repeated in the middle Oligocene when the Gulf Stream eroded a deep track off Cape Fear.

In the late Oligocene regression, a delta was prograded into the erosional cut in the area of Cape Fear, building this area out relative to northern Onslow Bay. Along with subaerial exposure and erosion of the shelf, this event created the outer Onslow Bay basin southeast of Cape Lookout. A second major depositional-erosional hole north of Cape Hatteras--the Aurora basin and subsequent Aurora embayment--was also partly created at this time. This basin was separated from the outer Onslow Bay basin by the Cape Lookout high, the erosional remnant of a large, spitlike feature that underlies Cape Hatteras.

Following a brief sea-level high in the early Miocene, when the distal end of the Oligocene delta was eroded by Gulf Stream currents, sea level again regressed, exposing the shelf to near the present edge of the northern Blake Plateau. During this time the Aurora and outer Onslow Bay basins were deepened by fluvial cutting and subaerial exposure.

In the early Miocene transgression, a shallow-water reef grew at the edge of the northern Blake Plateau. The reef was bordered by a landward lagoon, and sedimentation onlapped inland into the Aurora and outer Onslow Bay embayments. As water deepened in the middle Miocene and deposition proceeded landward, the reef, whose growth could not keep pace with the transgression, was overridden by Gulf Stream currents. The middle Miocene is characterized by a rugged unconformity cut by the Gulf Stream on the northern Blake Plateau, by an outbuilding of the Florida-Hatteras Shelf that filled the outer Onslow Bay basin, and by marginal filling of the Aurora embayment by long-shelf currents.

The upper Miocene, Pliocene, and Pleistocene sediments record additional eustatic shifts; however, by this time the Florida Hatteras Shelf was well developed and the Gulf Stream was not able to erode into it significantly. During the transgressive events, southward-flowing shelf currents north of Cape Hatteras filled the Aurora embayment with southward-prograding shelf sands.

The seismic data indicate a major episode of slope erosion from the southward-flowing Western Boundary Undercurrent (WBUC) during eustatic highs, suggesting a linking of the position of the undercurrent to eustatic change. The slope sediments eroded during these high stands helped form the Blake Outer Ridge.

P33 Geology and paleontology of the Lee Creek Mine, North Carolina, Part II: Ray, C.E., editor, 1987, Smithsonian Contributions to Paleobiology, no. 61, 283 pp.

ABSTRACT

Volume I of this projected series of three volumes included the prologue to the series, a biography of Remington Kellogg, and 13 papers on geology and paleontology other than Mollusca and Vertebrata (except otoliths). It was published in 1983 as Smithsonian Contributions to Paleobiology number 53. The present volume consists of a foreword and five chapters devoted to molluscan paleontology. The foreword recounts the earliest scientific publication of New World fossils, all mollusks, and reproduces Martin Lister's illustrations of them. William M. Furnish and Brian F. Glenister record the nautilid genus *Aturia* from the Pungo River Formation and discuss its occurrence elsewhere. Druid Wilson describes a new pycnodont oyster from the Pungo River Formation and lists the Cenozoic pycnodonts from the Atlantic and Gulf Coastal Plain; he also summarizes the stratigraphic and geographic occurrences of the subgenera of *Ecphora*, *Ecphora* and *Stenomphalus*, naming a new species of each from the Pungo River Formation, and a new species of the former from the St. Marys Formation of Maryland. Thomas G. Gibson clarifies the relationships and stratigraphic utility of 17 taxa (including one new species from the Pungo River Formation) of pectinid bivalves on the basis of biometric study of large samples from lower Miocene to lower Pleistocene beds in and near the mine. Lauck W. Ward and Blake W. Blackwelder describe a molluscan fauna of 194 species, including 30 new species and 3 new subspecies, from the Chowan River (upper Pliocene) and James City (lower Pleistocene) formations, and conclude that the fauna reflects a subtropical thermal regime and that it was deposited under open marine conditions at depths not exceeding 25 meters.

P34 Geology and paleontology of the Lee Creek Mine, North Carolina, Part I: Ray, C.E., editor, 1983, Smithsonian Contributions to Paleobiology, no. 53, 529 pp.

ABSTRACT

This volume of papers on the geology and paleontology of the Lee Creek Mine is the first of three to be dedicated to the late Remington Kellogg, who initiated Smithsonian studies of the mine. It includes the first 14 papers, as well as a biography of Remington Kellogg by Frank C. Whitmore, Jr., and a prologue by Clayton E. Ray. This study places the Lee Creek Mine in the larger context of the history of Neogene geology and paleontology of the middle Atlantic Coastal Plain. Jack H. McLellan outlines the development and operation of Texasgulf's phosphate mine and manufacturing plant at Lee Creek, particularly as they relate to geological and paleontological studies. Thomas G. Gibson describes the regional patterns of Miocene-Pleistocene deposition in the Salisbury and Albemarle embayments of the central Atlantic Coastal Plain. On the basis of cluster analysis of 16 samples, including 149 taxa of ostracodes from fossiliferous beds above the Pungo River Formation, Joseph E. Hazel determines that the Yorktown Formation at the Lee Creek Mine is early Pliocene in age and the Croatan Formation spans the Plio-Pleistocene boundary. Among the ostracodes, 2 genera, 31 species, and one subspecies, are diagnosed as new. Walter H. Wheeler, Raymond B. Daniels, and Erling E. Gamble survey the post-Yorktown development in the region of the Neuse-Tar-Pamlico rivers. Primarily on the basis of auger holes, they begin with the Aurora paleoscarp marking the top of the Yorktown Formation, on which the organic-rich shell sequence (Croatan or James City Formation) was deposited, followed unconformably by the Pamlico morphostratigraphic unit; the inner edge of the Pamlico msu is associated with the Minnesott Ridge. H. Allen Curran and Patricia L. Parker divide the "Upper Shell" unit at the mine into three bivalve assemblage zones, probably formed through mass mortality in a series of local catastrophic events. Edward S. Belt, Robert W. Frey, and John S. Welch interpret Pleistocene deposition at the mine on the basis of biogenic and physical sedimentary structures, enabling them to recognize five major unconformities and four depositional sequences, indicative of a progradational shoreline under tectonically stable conditions. Their fourth depositional cycle includes a freshwater peat member thought to be of Sangamon interglacial age, on the basis of Donald R. Whitehead's pollen analysis. This analysis reveals high percentages of sedge and grass pollens, an absence of boreal indicators, tree pollen frequencies similar to those of interglacial deposits to the north and south, and general similarity of the fossil pollen spectrum to modern pollen assemblages of eastern North Carolina. Francis M. Hueber identifies the gymnospermous genera Pinus, Juniperus, and Taxodium, and tentatively the angiospermous genus Gleditsia among the quartz-permineralized woods from the lower part of the Yorktown Formation at the mine; he also discusses the resin-like specimens, which are of unknown biological source and for which the stratigraphic source (Yorktown Formation, above the source of the woods) is known for only one specimen. William H. Abbott and John J. Ernissee report one silicoflagellate and two diatom assemblages (equivalent to Blow's zones N9 and N11) in a diatomaceous clay of the Pungo River Formation from two cores in Beaufort County; one new species of

diatom is described. On the basis of 30 species of planktonic Foraminifera and a few radiometric dates, Thomas G. Gibson assigns ages from latest Oligocene through early Pleistocene to 10 stratigraphic units in the central Atlantic Coastal Plain; he describes 37 species and subspecies of benthic Foraminifera, of which 10 species and 2 subspecies are new. Scott W. Snyder, Lucy L. Mauger, and W.H. Akers assign an age of late-early to early-late Pliocene for a 15-meter section of the Yorktown Formation at the mine, based on 29 taxa of planktonic Foraminifera. Druid Wilson describes as a new genus and species of barnacle a puzzling fossil from inside the shell of the bivalve Mercenaria from the Croatan Formation. Porter M. Kier reports one species of echinoid from the Pungo River Formation, three from the Yorktown Formation, of which one is new, and two from the Croatan Formation. John E. Fitch and Robert J. Lavenberg record 45 taxa of teleost otoliths from the Yorktown Formation, representing 27 genera, of which 22 are new to the Pliocene of North America, and 6 are first fossil records.

P35 Mineralogic nature and origin of phosphorite, Beaufort County, North Carolina: Rooney, T.P., and Kerr, P.F., 1967, Geological Society of America Bulletin, v. 78, p. 731-748.

ABSTRACT

A large Miocene phosphorite deposit on the Atlantic Coastal Plain in Beaufort County, North Carolina, contains estimated reserves of 10 billion tons. The phosphorite zone, where examined, is 60 feet thick, and the P_2O_5 content of the untreated ore is about 18 percent. The sediment consists of phosphate pellets, sand-sized quartz grains, and clay, with thin beds of indurated coquina and phosphatic dolomite.

The phosphate pellets contain quartz grains, glauconite, carbonaceous matter, and organic remains. Although most of the pellets are structureless, some show concentric layering around a nucleus.

Chemical, X-ray-diffraction, infrared-spectral, and other data demonstrate that the phosphorite mineral is francolite, and that CO_2 is an integral part of the apatite structure.

The clay fraction of the phosphorite includes montmorillonite, illite and clinoptilolite. The clay minerals and zeolite probably originated through alteration of volcanic detritus from an undetermined source.

Studies indicate origin of the phosphorite to have been in a shallow marine basin characterized by a reducing environment, phosphate replacement of calcareous sediments, local reworking and alteration of certain of the pellets, and coincidence of phosphorite deposition with pyroclastic activity.

P36 An evaluation of methods for mapping hard bottoms in the South Atlantic Bight: Ross, S.W., Barber, E.K., Searles, R.B., and Riggs, S.R., 1987, Atlantic States Marine Fisheries Commission, Special Report Nos. 8 and 9, 122 p. plus Appendices and 13 p., respectively.

INTRODUCTION

The Southeast Area Monitoring and Assessment Program-South Atlantic (SEAMAP-SA) is responsible for providing a unifying framework for management and research agencies operating in the marine waters of the South Atlantic Bight (SAB). This program potentially inherits a huge volume of historical data from throughout the area, much of which has not been extensively analyzed. These data, from federal and state cruises, university projects, and individual research efforts, date back at least to the 1950's. With some extensive filtering and manipulations a wealth of knowledge on animal and habitat distributions and abundances could be extracted. SEAMAP, therefore, initiated this project to evaluate data on the area's hard bottom resources and to determine who would be interested in these data. Also of importance to SEAMAP, in addition to feasibility of historical data analysis, is the development of guidelines for data handling that will be compatible with future sampling. A consensus is needed from the many area-wide agencies having an influence on the habitat and its biota as to the data requirements dictated by their management or research goals.

Quantity of habitat is often underemphasized in biology. Ecologists are routinely concerned with animal or plant relationships to abiotic factors and their roles in determining community structure. Type of habitat is, thus, an important ecological characteristic. For biota like primary reef fishes that are tied to certain habitats (i.e. substrates), the amount of habitat is also very important and can often be equated with the biomass or numbers of the biota. Data on the placement, size, and type of reef (hard bottom) habitat can indirectly provide much information about the inhabiting biota because data exist on species composition, distribution, and abundance for numerous types of reefs. In fact, if given the depth, season, latitude, and profile of a SAB or northern Gulf of Mexico hard bottom, a reasonably accurate list of associated algae, invertebrates, and fishes, including relative abundances, could be provided.

Basic knowledge of the hard bottom, non-coral habitats of the temperate SAB and northern Gulf of Mexico has lagged behind that for tropical coral reefs. Significant progress in data analysis over the last decade has shown that South Atlantic Bight hard bottoms are an important offshore habitat (e.g. Smith, 1976; Grimes et al., 1982; Wenner, 1983; Parker and Ross, 1986), perhaps even the most productive offshore habitat. In attempting to manage, utilize, or study the biological resources of such areas it is necessary to know how extensive the habitat is as well as what it contains. There have been several large-scale efforts to quantify or describe SAB hard bottom locations (Huntsman and MacIntyre, 1971; Parker et al., 1983; Henry et al., 1983; Barans and Henry, 1984), the most recent of which (Mearns, 1986) was incorporated into this study. As pointed out by Mearns (1986) the terms reef, live bottom, hard ground, rock outcrop, and hard bottom are often used incorrectly and interchangeably. We generally used the term "hard bottom" to describe the SAB emergent and productive continental shelf lithified structures; ecologically, however, reef, live bottom, and outcrop may be synonymous in the way biota respond to complex habitats.

Ultimately, we believe it will be possible to accurately classify the benthic habitats of the SAB and estimate their areas. Such information would be useful in developing habitat specific fishery management plans, determining fishery yields for habitat specific organisms, predicting impacts from energy or mining explorations, and planning future research. The ultimate product is a long-term goal. This report represents a first attempt at addressing some problems relevant to quantifying one major continental shelf habitat (hard bottom) in a section of the SAB.

The objectives of this project were to: 1) conduct a survey of SAB agencies having management responsibilities in the area to determine their involvement with hard bottom habitats, the type and detail of data they need, and how they view management of such data, and 2) evaluate the adequacy of representative data sources from a test area in Onslow Bay, NC for their adequacy to meet the needs identified by the survey and their ability to delineate hard bottom resources. The latter objective involved characterizing the type and format of data, variables included, and ease of data manipulation. In addition, data were evaluated for their ability to delineate hard bottom resources. We emphasize that our findings are most relevant to the North Carolina test area. Our evaluation of methods and problems may be widely applicable, but because our data were from a restricted area, attempts to use our analyses outside the test area or especially outside North Carolina may yield variable and inaccurate results.

P37 Structure of the continental slope off the eastern United States: Schlee, J.S., Dillon, W.P., and Grow, J.A., 1979, in Doyle, L.J., and Pilkey, O.H., editors, Geology of Continental Slopes: Society of Economic Paleontologists and Mineralogists, Special Paper 27, p. 95-118.

ABSTRACT

The continental slope off eastern United States is built across a zone of deeply buried (6-12 km) fault blocks that formed during the rifting of continents. Associated with these blocks are intrusives, salt diapirs, and reef complexes; all are underlain by a zone of thinned continental, transitional, and oceanic crust beneath the shelf slope, and upper continental rise. Four basic sedimentary units appear to underlie much of the slope: (1) a probable terrigenous clastic-evaporite-volcanic sequence associated with fault blocks; (2) a carbonate platform reef sequence, which probably formed along the ancestral shelf-slope break; (3) a marine and non-marine sequence built over the carbonate rocks north of the Blake Plateau as the shelf in some areas prograded seaward during the Cretaceous; and (4) a thick rise prism of sediments of Tertiary and younger age that laps up on the base of the slope north of the Blake Spur. Much of the present slope is an erosional surface, cut into lower Tertiary and Upper Cretaceous strata during Cenozoic marine regressions as sediment moved downslope to build the rise prism; the shelf-slope break has retreated 5-30 km from the break that existed during the Late Cretaceous. Over the Blake Plateau, periodic scour by currents associated with the ancestral Gulf Stream caused a 300-km landward jump of the shelf break at about the end of Paleocene as the plateau continued to subside.

Laterally, the slope varies in the distance that it retreated (maximum to

the south) and in the degree to which reeflike masses are developed. Continuous well-developed carbonate banks or reefs controlled location of the shelf edge of the southern Blake Plateau; they were terminated both there and to the north near the end of the Early Cretaceous, although reef formation may have shifted to locations beneath the present continental shelf.

Local progradation of the outer shelf and slope occurred during parts of the Jurassic and Cretaceous, depending on the sediment supply and the effects of transgression and regression of sea level. During the Tertiary, however, erosion and retreat of the shelf edge was dominant.

P38 Planktonic foraminifera and biostratigraphy of the Yorktown Formation, Lee Creek Mine: Snyder, Scott W., Mauger, L.L., and Akers, W.H., 1983, in Ray, C.E., editor, Geology and Paleontology of the Lee Creek Mine, North Carolina Part I: Smithsonian Contributions to Paleobiology, no. 53, p. 455-482.

ABSTRACT

The open-pit phosphate mine of Texasgulf Inc. at Lee Creek provides the most nearly complete section of the Yorktown Formation in North Carolina. The Yorktown exposure at this locality has yielded a rich and diverse vertebrate fauna. However, the biostratigraphic position of this important exposure has been difficult to determine because previous studies of planktonic foraminifera have yielded too few species to provide a basis for precise interpretation. During this study 29 species and subspecies of planktonic foraminifera were identified from 42 samples taken at vertical intervals of 35 cm through a 15 m section of the Yorktown Formation. Concurrent portions of the range zones of eight taxa indicate an age of late early to early late Pliocene (from just below the base of Blow's zone N19 to the middle of his zone N20).

P39 Stratigraphy and depositional history of Bogue Banks, North Carolina: Steel, G.A., 1980, M.S. Thesis, Duke University, Durham, N.C., 201 p.

ABSTRACT

Forty-one auger holes were drilled along the 40 km (26 mi) length of Bogue Banks, N.C., and two on the adjacent mainland. Sediments found beneath the island are of Tertiary, Pleistocene, and Holocene age. Tertiary units found were the lower Miocene Haywood Landing Member of the Belgrade Formation, the middle Miocene Pungo River Formation, and the Plio-Miocene Yorktown Formation. The contact of the Tertiary Formation with the overlying Quaternary sediment is an angular unconformity with a general dip of the older beds to the east and south. The late Pleistocene Diamond City Clay, known to occur to the east beneath Shackleford and Core Banks, thins and pinches out beneath the western half of Bogue Banks.

Carbon-14 dating indicates that Holocene deposition began beneath Bogue a minimum of 9300 years B.P. Transgressive and regressive sequences dominate the Holocene section. Three depositional environments are represented within the

transgressional sequences. These are back barrier, dune and overwash, and inlet (including flood tidal delta). Inlet sediments representing a minimum of 11 relict inlets were found. All of the regressional sediments were deposited in the nearshore marine environment. The rate of rise of sea level apparently played an important role in controlling the depositional history of the island. An area near the east end of Bogue may have served as a hinge zone during regressional sedimentation. East of the hinge zone transgressional sedimentation continued without interruption and the eastern section swung landward. West of the hinge zone regressional sedimentation took place and the western section swung seaward.

P40 Holocene evolution of the shelf surface, central and southern Atlantic Shelf of North America: Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P., and Sears, P., 1972, in Swift, D.J.P., Duane, D.P., and Pilkey, O.H., editors, Shelf Sediment Transport Process and Pattern: Dowden, Hutchinson, and Ross Inc., Stroudsburg, Pennsylvania, p. 499-514.

ABSTRACT

The floor of the central and southern Atlantic shelf is a palimpsest or multiple imprint surface. An initial pattern is an erosional one consisting of major transverse shelf valleys and plateau-like interfluves. The dominant pattern is that of constructional topography formed at the foot of the shoreface. This constructional pattern is undergoing modification toward a third pattern in response to the modern hydraulic regime; therefore, the term "relict" does not seem an adequate descriptor. A unifying concept for the interpretation of Holocene shelf history is that of Bruun coastal retreat. This variant of the equilibrium profile hypothesis states that a rise in sea level over an unconsolidated coast results in shore-face erosion, equivalent to parallel slope retreat, and a concomitant aggradation of the adjacent sea floor. The resulting discontinuous debris mantle, the Holocene transgressive sand sheet, is only partly autochthonous with respect to the Holocene sedimentary cycle, since it incorporates Holocene fluvial deposits.

The surface of this sand sheet has been molded into a variety of morphologic elements. Where the sheet has been generated directly from the retreating shoreface, a ridge-and-swale topography has been empressed upon it. Off cuspate forelands, the convergence of littoral drift has resulted in cape-associated shoals. Off estuary mouths the intersection of littoral drift with the reversing estuary tide has created inlet-associated shoals. Seaward of each of these shoal types, earlier generations of the same shoals commonly occur. The resulting shelf-transverse sand bodies, formed by the progressive landward displacement of shoreline depositional centers, are shoal-retreat massifs.

The ridge-and-swale topography is impressed on shoal-retreat massifs, as well as on other sectors of the shelf floor and appears to be a stable end-configuration toward which a variety of depositional and erosional topographies tend to converge. The asymmetry of large-scale morphological elements and also of small-scale bedforms suggests that southward sediment transport in the Middle Atlantic bight intensifies toward shore and toward the

south. The southward asymmetry of ridges and shoal complexes is seen as far south as Florida.

P41 Outline of Tertiary stratigraphy and depositional history of the U.S. Atlantic Coastal Plain: Ward, L.W., and Strickland, G.L., 1985, in Poag, C.W., editor, Geologic Evolution of the United States Atlantic Margin: Van Nostrand Reinhold Co., New York, New York, p. 87-124.

ABSTRACT

On the Atlantic Coastal Plain, sediments representing most of the Tertiary stages provide a record of the intermittent local downwarping of a trailing-edge coast as well as widespread deposition during marine high stands. Principal depocenters along the Atlantic Coastal Plain were the Salisbury, Albemarle, and Southeast Georgia embayments. Sedimentation occurred principally in these basins but occasionally overlapped the arches that separate them. This overlapping may have been due to local downwarping of an arch, such as occurred on the Cape Fear arch during the Pleistocene, or to extremely high sea-level stands as occurred in the middle Eocene and late Pliocene.

This series of intermittently active basins has produced a complex sequence of lithic units that, in some ways, differ greatly from their Gulf Coastal Plain equivalents and, in other ways, are remarkably similar. Strikingly different, however, were the sedimentation rates in the two areas. Although several thousand meters of sediment were deposited in the Gulf area during a particular time interval, the Atlantic received only a few hundred meters. The Gulf sequence, in many cases, is composed principally of deltaic sediments, whereas, along the Atlantic coast, sedimentation was almost entirely marine. The Atlantic region, therefore, may be a better area to study global sea-level fluctuations than the more structurally active Gulf area.

An excellent area to study the onlap-offlap record of sea-level pulses is in the Salisbury embayment, specifically along the Pamunkey River in the central Virginia Coastal Plain. Within a short distance on that river, a richly fossiliferous series of beds ranging in age from the middle Paleocene to the late Pliocene crop out. The units are readily recognizable and easily traced, and their boundaries or contacts well defined. A very detailed record of submergence, emergence, and structural movement has been documented by use of mollusks, ostracodes, dinoflagellates, and calcareous nannofossils.

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