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Abstract

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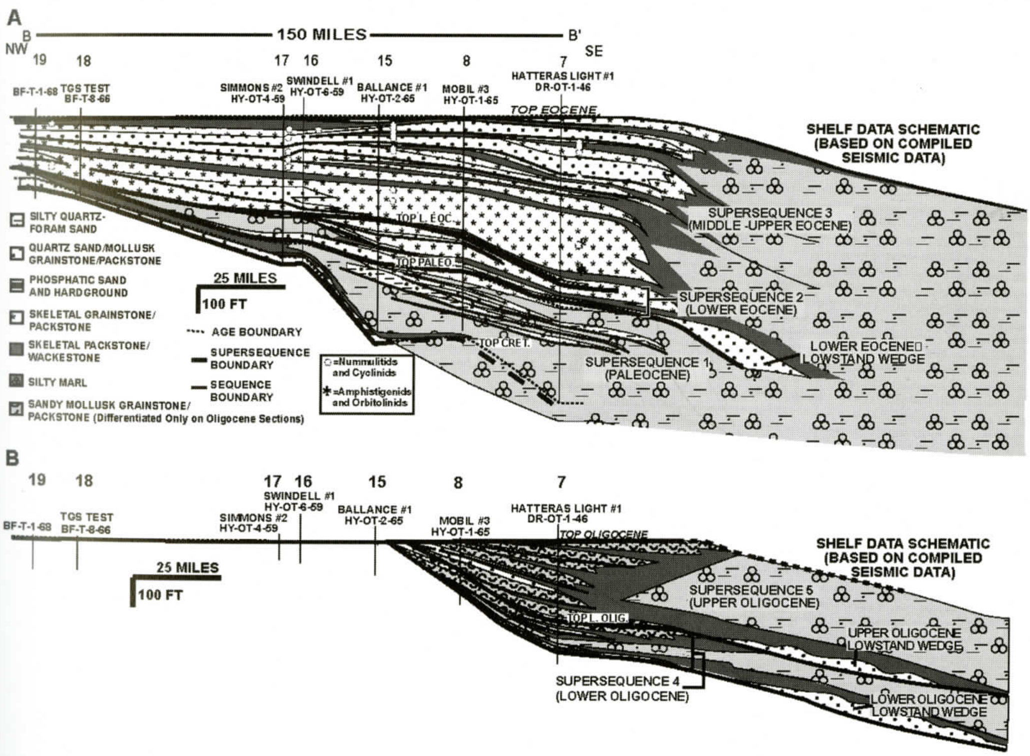
Theme Issue: The Cape Fear Arch, Transition between the Northern and Southern Atlantic Coastal Plain



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2) Cite references and prepare bibliographic lists in accordance with the method found within the pages of this journal.
3) Submit line drawings and complex tables reduced to final publication size (no bigger than 8 x 5 3/8 inches).
4) Make certain that all photographs are sharp, clear, and of good contrast.
5) Stratigraphic terminology should abide by the North American Stratigraphic Code (American Association Petroleum Geologists Bulletin, v. 67, p. 841-875).
6) Email Acrobat (pdf) submissions are encouraged.

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SOUTHEASTERN GEOLOGY

The Cape Fear Arch, Transition between the Northern and Southern Atlantic Coastal Plain

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ABOUT THE GUEST EDITOR

W. Burleigh Harris (Bill) became interested in geology through the inspired teaching of Ed Howard in the 60's. After completing undergraduate and graduate degrees, he worked as an exploration geologist in the petroleum industry for several years and later as a mineral resources geologist for the Virginia Division of Mineral Resources. In the early 70's he entered the University of North Carolina at Chapel Hill to pursue a doctorate in geology. At UNC-CH he developed an interest in carbonate geology working under Dan Textoris. Through his efforts and those of Walter Wheeler he focused on Mesozoic carbonates and stratigraphy in the coastal plain. During a conversation on a field trip with Mike Bottino he developed an interest in radiometric dating of glauconite and bentonite, and has continued this area of research with his colleague at UNC-CH, Paul Fullagar. Upon completing his PhD (1975) he joined the Department of Earth Sciences at the University of North Carolina at Wilmington, but returned to industry for a couple of years in the early 80's working for Exxon Production Research in Houston, Texas. At EPRCo Bill worked in the seismic stratigraphy group on projects in Australia, the Middle East and Europe. He was helping establish a European school for Exxon geologists and geophysicists that integrated field observations and seismic interpretation of depositional sequences using Paleogene stratotypes when he returned to academe in 1984.

At UNCW Bill has served as the department chair of earth sciences and also as the associate dean of the graduate school, but in the summer of 2002 he returned to the department full-time. He is a licensed geologist in the State of North Carolina and currently serves as chair of the N.C. Coastal Plains Earth Sciences Consortium, which includes state, federal and university scientists, who are studying the geology and hydrostratigraphy of the coastal plain. Bill has been on the organizing committee of all Bald Head Island Conferences. He continues to work on Cretaceous, Paleogene and Neogene stratigraphy, and in recent years his interests have included enhancing scientific literacy in K-12 schools. He is currently the PI on a National Science Foundation grant that places science graduate students in middle school classrooms in New Hanover County. Bill has published more than 100 papers, abstracts and guidebooks on geology, and enjoys working on research projects with former professors and former students turned colleagues.

PREFACE

Papers in this volume represent presentations given at the Fourth Bald Head Island Conference on Coastal Plains Geology, held November 16-19, 2002, at Ft. Fisher, N.C. The Fourth Conference focused on the Cape Fear Arch as the Transition between the Northern and Southern Coastal Plain with 75 geologists participating from 12 states.

The Bald Head Island Conferences were established through the auspices of The University of North Carolina at Wilmington in 1986 to promote dialogue among coastal plains geologists in an informal and relaxed setting. The conferences provided a forum for the sharing of knowledge and the development of cooperative ventures among researchers.

The First Conference was held on Bald Head Island, N.C., in fall 1986 and was funded by The University of North Carolina at Wilmington and Bald Head Island Management, Inc. Twenty-three invited coastal plains geologists from 11 states participated. The First Conference had a general theme, with sessions on the Cretaceous, Paleogene and Neogene of the Gulf and Atlantic Coastal Plains and continental shelves.

The Second Conference was held on Hilton Head Island, S.C., in fall 1990 and was funded by the U.S. Department of Energy, Savannah River Operations Office, the Westinghouse Savannah River Company, and The University of North Carolina at Wilmington. Thirty invited coastal plains geologists from seven states participated. The theme of the Second Conference dealt with the Savannah River Region: Transition between the Gulf and Atlantic Coastal Plains.

The Third Conference was held in fall 1992, also at Hilton Head Island, S.C., and was funded by The University of North Carolina at Wilmington and the Florida Geological Survey. Sixteen invited participants from five states attended. The Third Conference focused on the Florida Neogene.

Sadly, of the 47 geologists who participated in one of the first three conferences, Rolf Aadland (not pictured), Don Colquhoun, Wally Fallaw, Jim Owens, Juergen Reinhardt, Norm Sohl and Vic Zullo are now deceased. It is to these fine geologists and friends that this volume is dedicated.

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V. 42, No. 4, May 2004, p. 191-216

SUPERGROUP STRATIGRAPHY OF THE ATLANTIC AND GULF COASTAL PLAINS (MIDDLE? JURASSIC THROUGH HOLOCENE, EASTERN NORTH AMERICA)

ROBERT E. WEEMS

JEAN M. SELF-TRAIL

LUCY E. EDWARDS

926A National Center, U.S. Geological Survey, Reston, VA 20192

ABSTRACT

An inclusive supergroup stratigraphic framework for the Atlantic and Gulf Coastal Plains is proposed herein. This framework consists of five supergroups that 1) are regionally inclusive and regionally applicable, 2) meaningfully reflect the overall stratigraphic and structural history of the Coastal Plains geologic province of the southeastern United States, and 3) create stratigraphic units that are readily mappable and useful at a regional level. Only the Marquesas Supergroup (Lower Cretaceous to lowest Upper Cretaceous) has been previously established. The Trent Supergroup (middle middle Eocene to basal lower Miocene) is an existing name here raised to supergroup rank. The Minden Supergroup (Middle? through Upper Jurassic), the Ancora Supergroup (Upper Cretaceous to lower middle Eocene), and the Nomini Supergroup (lower Miocene to Recent) are new stratigraphic concepts proposed herein. In order to bring existing groups and formations into accord with the supergroups described here, the following stratigraphic revisions are made. 1) The base of the Shark River Formation (Trent Supergroup) is moved upward. 2) The Old Church Formation is removed from the Chesapeake Group (Nomini Supergroup) and moved to the Trent Supergroup without group placement. 3) The Tiger Leap and Penney Farms formations are removed from the Hawthorn Group (Nomini Supergroup) and moved to the Trent Supergroup without group placement. 4) The Piney Point and Chickahominy formations are removed from the Pamunkey Group (Ancora Supergroup) and moved to the Trent Supergroup without group placement. 5) the Tallahatta Formation is removed from the Claiborne Group (Trent Supergroup) and placed within the Ancora Supergroup without group placement.

INTRODUCTION

The Atlantic and Gulf Coastal Plains were recognized early as a discrete geologic terrain (Godon, 1809; Maclure, 1809), but elucidation of their detailed stratigraphy and structure was long hampered by the paucity of good outcrops within these regions. River bluff outcrops are the only natural exposures throughout most of the region, and early studies relied heavily on these outcrops and occasional "marl pits" to reveal something of the characteristics of the sediments that lay beneath the surface (for example, Ruffin, 1832, 1843; Rogers, 1836; Tuomey, 1848, 1858; Wailes, 1854). Commonly, correlation among these widely spaced outcrops was uncertain and controversial. As the population grew, stimulating economic development, quarrying and drilling for mineral resources began in earnest. From these activities, the number of places where Coastal Plains sediments could be studied greatly expanded. In addition to pits and quarries dug to exploit near-surface materials, the search for oil, gas, and large reservoirs of ground water provided an expanding resource of samples and data from the deeper stratigraphic horizons that previously had been unattainable (for example, Shearer, 1938; Spangler, 1950; Winston, 1971; Meyerhoff and Hatten, 1974; Forgotson and Forgotson, 1976).

Early stratigraphic studies throughout this region were initiated either by individual state geological surveys (particularly New Jersey, Maryland, South Carolina, Alabama, Mississippi, and Texas) or by the United States Geological Survey. In the latter case, the impetus for stratigraphic studies usually derived either from analysis of the economic potential of specific resources found in subregional areas, such as sand and gravel, greensand, ceramic clays, glass sand, etc. (Dall and Harris, 1892; Smith and Johnson, 1887) or from interest in the national capital region (McGee, 1886; Darton, 1894). With the notable exception of the stratigraphic synthesis attempted by Dall (1898), all of these studies looked at the stratigraphic framework of only a part of the Coastal Plains region. As a result, the stratigraphic framework that emerged was erected to satisfy only local needs and was useful only at a subregional scale. Even at the group and supergroup level of stratigraphy, the existing frameworks were never intended to be inclusive of all strata present in each region. Thus, even though some forty-four groups and one supergroup have been established within the Gulf and Atlantic Coastal Plains (Figures 1A-1C), fully half of all the strata present in the region are not part of any of these higher stratigraphic rankings.

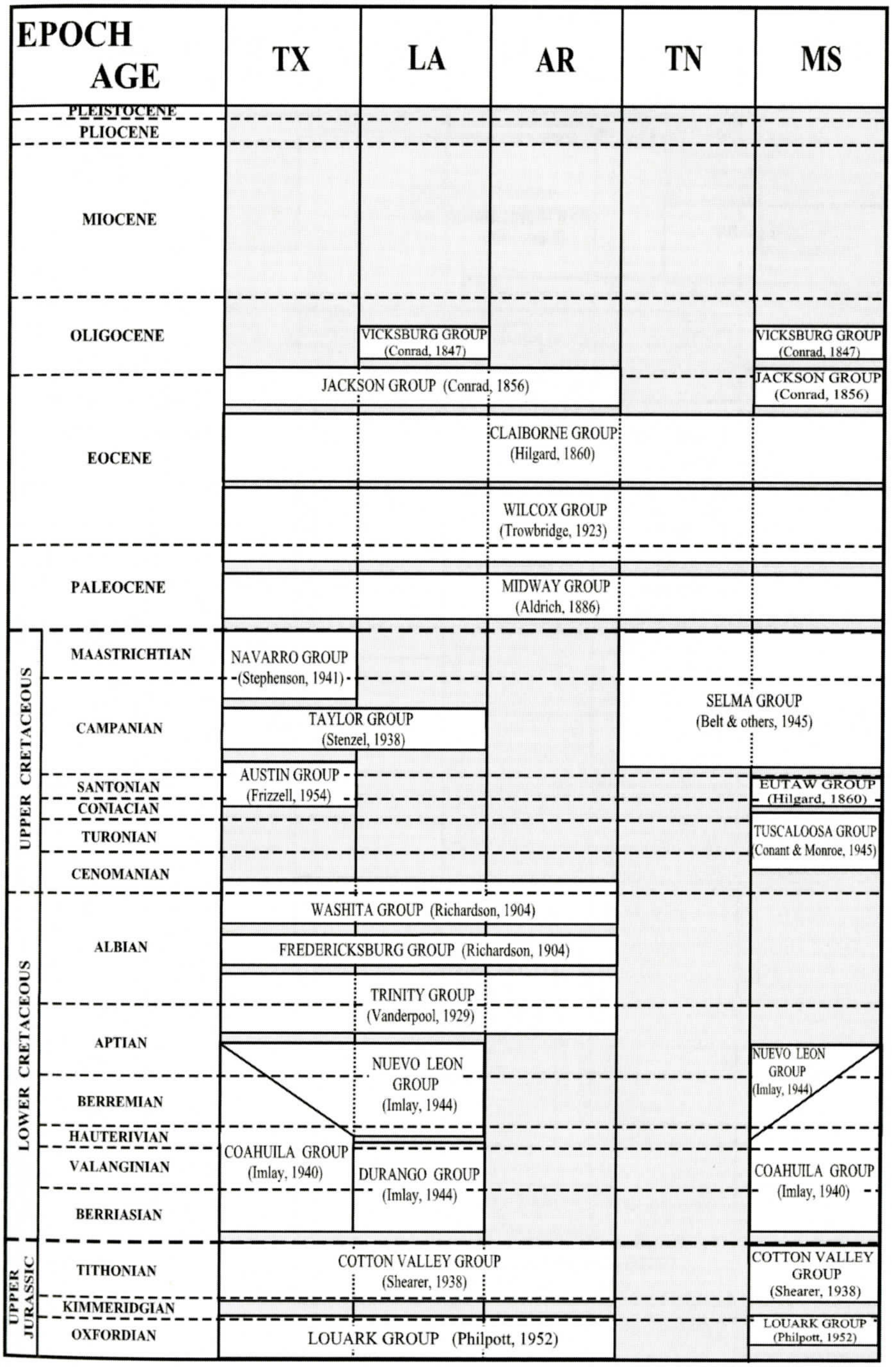
This hodge-podge approach to stratigraphy is not in violation of the North American stratigraphic code (North American Commission on Stratigraphic Nomenclature [NACSN], 1983), and it probably was inevitable that our understanding of the stratigraphy of this vast but poorly exposed region would have evolved in the manner that it did. At the same time, however, the group and supergroup nomenclature that evolved is a framework that is neither easily accessible nor user-friendly. In addition, it discourages many from trying to understand or embrace the entirety of the stratigraphic framework of the Coastal Plains, and obscures the structural history and tectonic evolution of the region. For these reasons, we believe that it is time to take a truly regional view of the stratigraphic framework of the Atlantic and Gulf Coastal Plains and begin to erect a group and supergroup stratigraphic framework that 1) is truly applicable on a regional basis, 2) is inclusive of all strata within the province, and 3) reflects the major stages of structural, tectonic, and climatic evolution that the province has experienced. Such a synthesis is greatly aided by modern strategies for basin analysis that can be applied to data from numerous deep coreholes and geophysical logs.

Much controversy exists concerning the proper group-level stratigraphic framework that should be applied within most of the Atlantic and Gulf Coastal Plains. For now, we defer most of this important work and, with only a few necessary or uncontroversial exceptions, confine ourselves herein to establishing an inclusive supergroup stratigraphic framework. Within this framework, the controversies concerning group level stratigraphy can be debated and resolved at a future date.

SUPERGROUP STRATIGRAPHIC FRAMEWORK

The supergroup stratigraphic framework for the Atlantic and Gulf Coastal Plains should include the recognition of large-scale, regionally recognizable tectonic, climatic, and depositional events that can serve as a basis for subdividing the strata preserved within this region. Therefore, we choose to establish supergroups that are readily recognizable sequences of strata with 1) similarities in mineralogies, 2) similar or interrelated environments of accumulation, and 3) similar depositional fabrics. Boundaries between supergroups are placed at regionally significant unconformities, because these boundaries provide both litho-spatial and temporal boundaries for each package. Temporal boundaries are not part of the definition of lithostratigraphic units. However, in a depositional setting such as the Atlantic and Gulf Coastal Plains, the presence of numerous, regionally extensive unconformities allows us to arrive at a definition of each stratigraphic package that includes temporal cohesiveness. Thus, our supergroup units embrace both lithostratigraphic and allostratigraphic mapping concepts.

The definition here of inclusive supergroups is partially constrained by the existence of two previously defined Mesozoic supergroups in



Figures 1A (next two pages for 1B and 1C). Summary diagram showing the time-spans and geographic areas of stratigraphic groups currently used in the Atlantic and Gulf Coastal Plains. The reference listed for each group is the oldest found that refers to each unit specifically as a group. Many of these units were described earlier with some other term of designation, such as "beds," "formation," or "division." Groups defined in New Jersey are not in current use in that state. Many of the blank intervals between designated groups contain stratigraphic horizons not currently included within any established group.

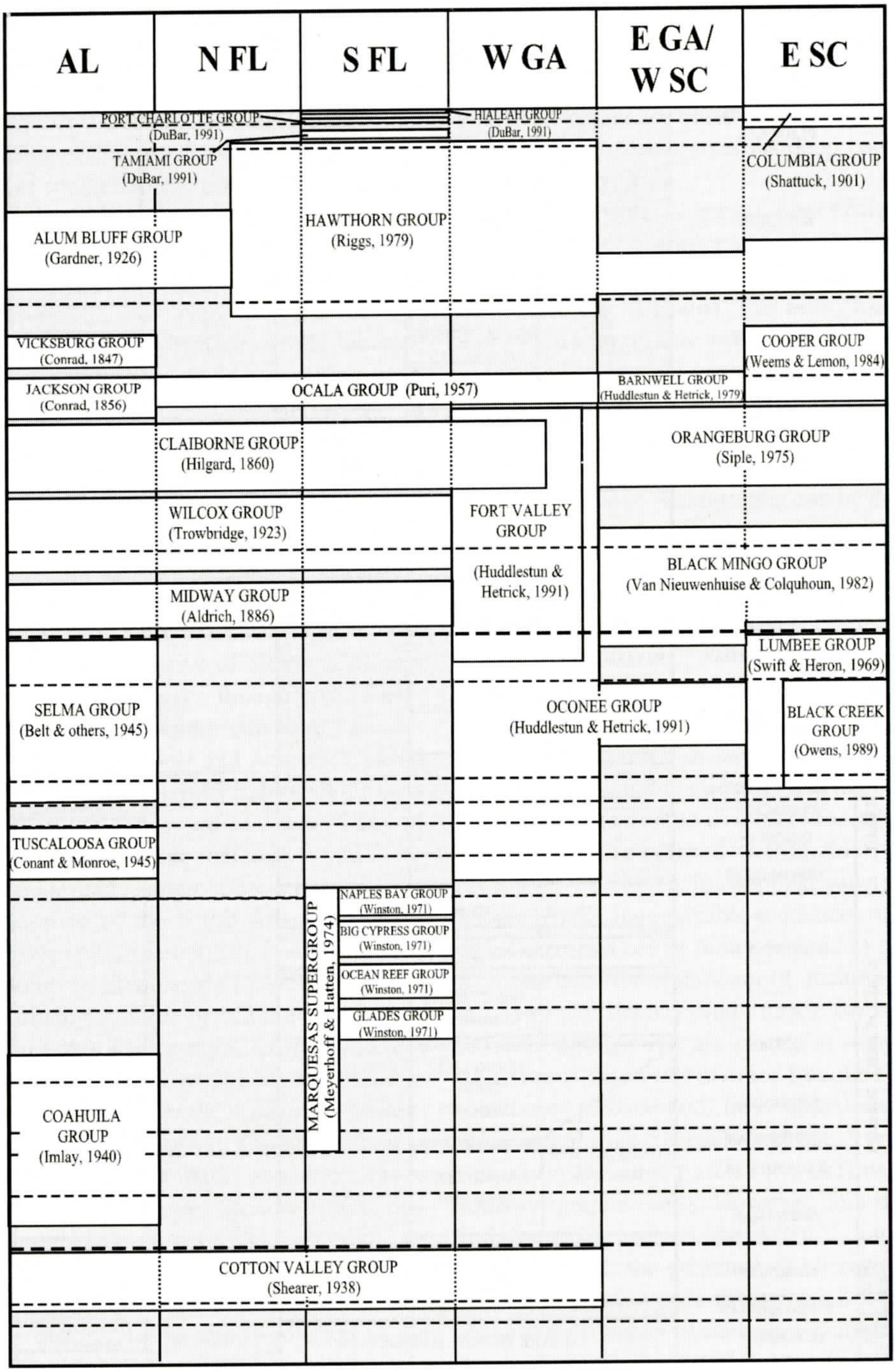


Figure 1B.

the eastern United States. The Newark Supergroup (Olsen, 1978; Froelich and Olsen, 1984; Weems and Olsen, 1997) was erected to include all strata and extrusive volcanics that formed during the early Mesozoic (Middle Triassic t Early Jurassic) pre-Atlantic rifting episode tha formed the Newark basins of eastern Nort America. The Marquesas Supergroup (Meyer

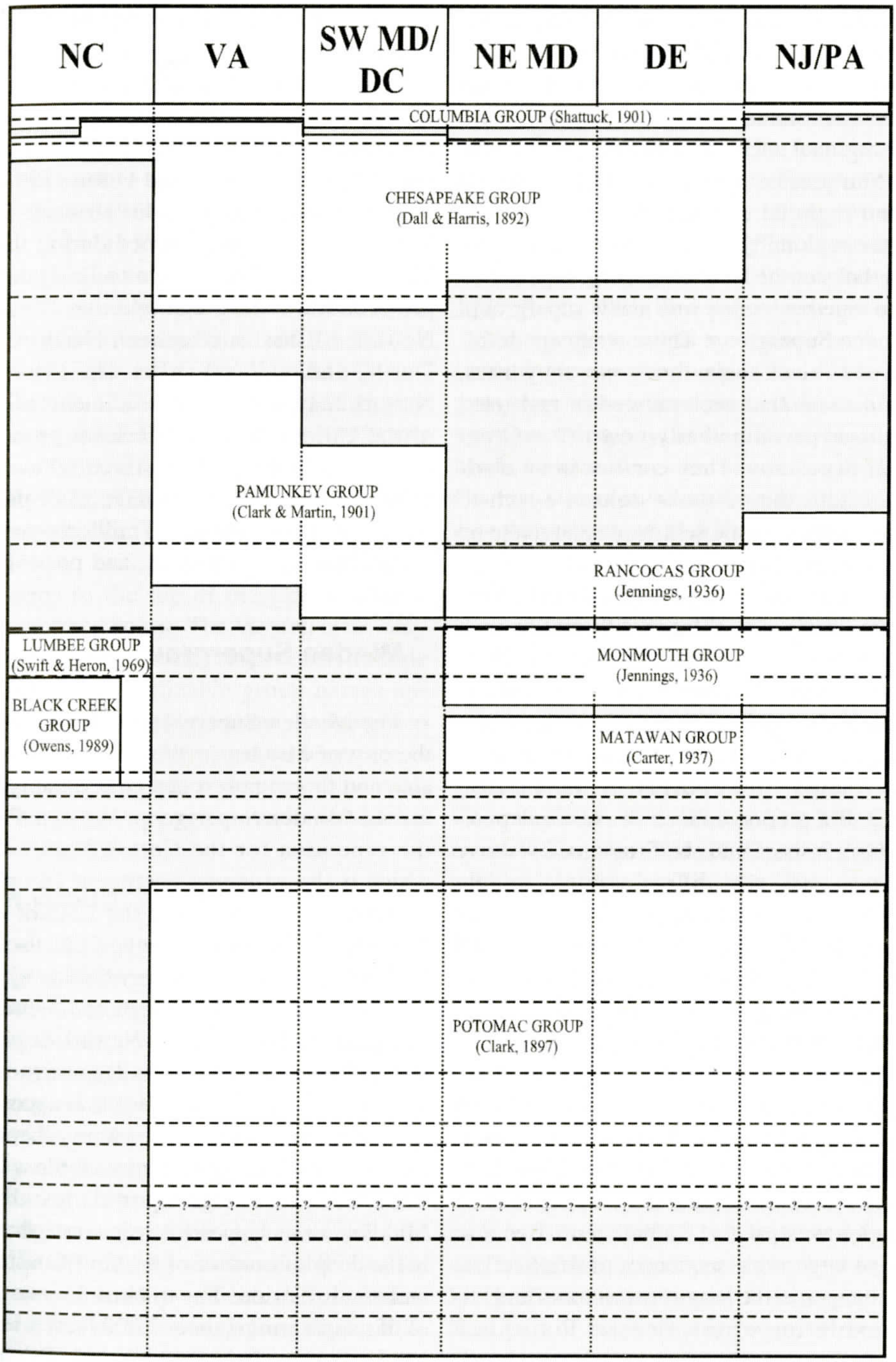


Figure 1C.

hoff and Hatten, 1974) was erected to include all carbonate and anhydrite deposits beneath south Florida that formed in what is now considered to be Early Cretaceous and earliest Late Cretaceous time in relatively restricted and shallow water environments of deposition. The bounding unconformities of the Marquesas Supergroup can be recognized throughout the

Coastal Plain region, and for this reason this name is retained in our regional framework.

The oldest (Middle? and Late Jurassic) strata in the Coastal Plains, lying stratigraphically below the regional unconformity marking the base of the Marquesas Supergroup and above the profound regional unconformity marking the top of the regionally tilted and structurally deformed rocks of the Newark Supergroup, can be grouped together readily into a new supergroup, the Minden Supergroup. These strata are dominantly red to black shale, limestone, anhydrites, and sandstones that accumulated in restricted marine to hypersaline early post-rift environments of deposition. They contrast in an obvious way with the offshore dolomite-rich to coastal-complex clastic sediments that make up the Marquesas Supergroup.

Above the Marquesas Supergroup, three more large-scale assemblages of formations can be recognized. 1) Post-Marquesas Upper Cretaceous and Lower Tertiary strata form a natural stratigraphic/tectonic package that reflects tectonic quiescence, widespread transgression of the seas across the entirety of the Coastal Plains, and a preponderance of clastic deposition in both inshore and shelf regions. 2) Above this sequence is a very different suite of middle middle Eocene to lowest Miocene sediments that overwhelmingly consist of carbonates and carbonate-rich deposits east of the Mississippi Embayment. West of the Mississippi Embayment, this interval is dominated by shales and mudstones that are notably finer than the sequence below. 3) All higher Miocene to Recent deposits reflect a return to siliciclastic-dominated sedimentation east of the Mississippi Embayment and to much coarser-grained lithologies west of the Embayment. Because these five large-scale sequences of strata reflect major changes in the long-term tectonic and climatic evolution of the Coastal Plains, we choose to recognize them as supergroup levels of organization. In maximum thickness they range between 1,000 and 7,000 feet, and in time span they range from 17 to 49 million years. These supergroups and the related Newark Supergroup are discussed and/or defined (from oldest to youngest) below.

Newark Supergroup

The Newark Group of Redfield (1856) was raised in rank to supergroup by Olsen (1978) and subsequently modified by Froelich and Olsen (1984) and Weems and Olsen (1997). The Newark Supergroup includes all strata and extrusive volcanics that formed during the early Mesozoic (Middle Triassic to Early Jurassic) pre-Atlantic rifting episode that formed the Newark rift-basins of eastern North America. During and/or shortly after deposition of the Newark Supergoup strata, sediments within all of the various basins underwent pronounced tilting and faulting. This structural event was followed by a prolonged interval of profound erosion that lasted about 30 million years (Sinemurian through Bathonian, and possibly Callovian as well).

Minden Supergroup (new name)

The Minden Supergroup is here named for the city of Minden in Webster Parish, Louisiana, and this region is designated the type area for the Minden Supergroup. Webster Parish is the type area for the Cotton Valley Group, which is the younger constituent group of the Minden Supergroup, and the Louark Group, which is its older constituent group, also occurs here below the Cotton Valley Group. The Minden Supergroup includes all sediments lying stratigraphically above the Newark Supergroup and below the Marquesas Supergroup. The Minden is defined below. Its basal unconformity corresponds to the unconformity that defines the base of the Zuni Sequence of Sloss (1963). The Minden Supergroup includes all upper Middle(?) and Upper Jurassic strata that occur in the deep subsurface of the Gulf Coastal Plain and south Florida. The thickest known section of this supergroup (about 7,000 feet) is in southern Louisiana (Imlay, 1943). No onshore subsurface deposits of this age are known definitely from the Atlantic Coastal Plain region, though unnamed red bed sequences beneath the Waste Gate Formation in eastern Maryland (Doyle, 1983) and easternmost North Carolina (Spangler, 1950; Zarra, 1989) possibly could represent this supergroup. The Minden represents the earliest post-rift deposits formed after the initial opening of the Atlantic basin. The closest places to the southeastern United States where deposits of this age are known to occur at the surface are western Cuba (Meyerhoff and Hatten, 1974) and northeastern Mexico (Murray, 1961). These deposits typically formed in marine environments and tend to be dominated by red, gray, or black shale, limestone, dolomite, anhydrite, and sandstone (Swain, 1944; Meyerhoff and Hatten, 1974).

The Minden Supergroup includes two groups, the Louark Group (Philpott, 1952) and the Cotton Valley Group (Shearer, 1938; Swain, 1944). The base of the Minden Supergroup corresponds to the base of the Louark Group as defined below, and the top of the Minden corresponds to the top of the Cotton Valley Group as defined below. The Minden is the only Coastal Plains supergroup that contains a single set of regionally applicable group names applied to its constituent formations. As the group level stratigraphy within this supergroup is long-established and relatively uncontroversial, we here integrate these groups with the Minden Supergroup as follows:

Louark Group

The Louark Group consists predominantly of red and gray shale, anhydrite, dolomite, oolitic limestone, limestone, and minor quantities of sandstone (Swain, 1944). It is of Middle? to early Late Jurassic age. Its base is marked by a profound regional unconformity; its top is separated from the overlying Cotton Valley Group by a regionally significant unconformity encompassing the lower and middle parts of the Kimmeridgian stage of the Upper Jurassic. As originally defined by Philpott (1952), the Louark unconformably overlies the pre-Jurassic Eagle Mills or Morehouse formations. Forgotson and Forgotson (1976) chose to place the base of the Louark somewhat higher, at the top of the Norphlet Formation, and Murray (1961) chose to place its base between the earlier authors' choices, at the top of the Louann Salt (Figure 3). Philpott's original and more inclusive definition is retained here. The Louark includes five formations (Figure 2) found in the deep subsurface of the Gulf Coast. The basal Werner Formation is known only from Texas to Alabama, but the overlying Louann, Norphlet, Smackover, and Haynesville formations are known from Texas to southern Florida (Hazzard and others, 1947; Eargle, 1964; Joiner and Moore, 1966; Marsh, 1967; Dickinson, 1969; Moore and Joiner, 1969; Ottman and others, 1973; Scott, 1991; Tew and others, 1993).

No type section has been designated for the Louark Group. The upper boundary of the group has been defined in the Arkansas Louisiana Gas Company, Indian Rock Gas Unit 2, Maria Finolia Flores Survey A-2 well (Upshur County, Texas) as falling at an unconformity located at a depth of 11,620 feet (Forgotson and Forgotson, 1976, p. 1120, fig. 2). All strata in this well below that depth are part of the Louark Group, but the base of the group was not reached. As the Werner Formation is the lowest unit in the Louark Group, the base of the type section of the Werner Formation also serves to define the base of the group. The base of this type section is located in the Gulf Refining Company's No. 49 L Werner Saw Mill Company well (Louann District, Union County, Arkansas). At this locality, the Werner overlies folded Paleozoic rocks at an angular unconformity (Hazzard and others, 1947).

Cotton Valley Group

The Cotton Valley Group consists predominantly of gray to red shale, limestone, and sandstone (Swain, 1944). It is of Late Jurassic (late Kimmeridgian and Tithonian) age. This unit originally was named the Cotton Valley Formation by Shearer (1938) and later raised to group rank by Swain (1944). It is separated from the overlying Marquesas Supergroup by a regionally significant unconformity that encompasses at least part of the Berriasian stage of the Lower Cretaceous (Imlay, 1936). Only two formations have been recognized so far within the Cotton Valley Group, a lower Bossier Formation and an upper Schuler Formation. These are recognized in Texas, Louisiana and Arkansas. In the eastern Gulf region, the Cotton Valley remains undivided.

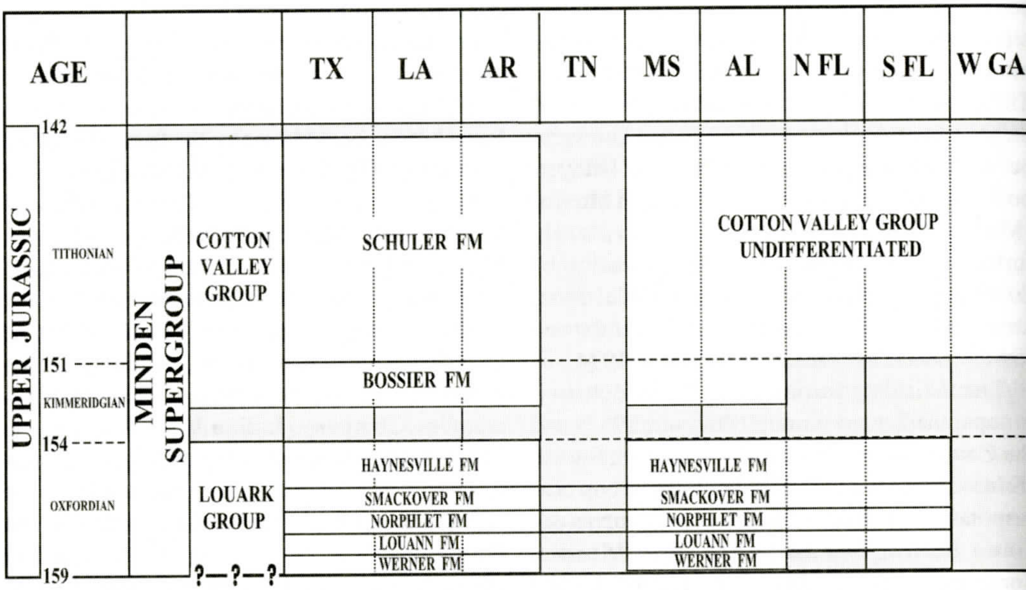


Figure 2. Groups and formations included in the Minden Supergroup and their geographic occur-rence. Time scale from International Stratigraphic Chart (2001), available at www.palaeos.com/ Mesozoic/mztimescale.html. Supplementary stratigraphic data for individual units available online in the U.S. Geological Survey Geologic Names Lexicon (Geolex), available at ngmdb.usgs.gov/Geolex, and in Coastal Plains COSUNA charts (Braunstein and others, 1983; Jordan and others, 1983).

The type locality for the Cotton Valley Group is the Cotton Valley field in Webster Parish, Louisiana. Shearer (1938) placed the top of the Cotton Valley at the base of the Hosston red beds, but did not define a base for the unit. Later, Swain (1944) defined the base of the Cotton Valley in the type area as being the top of the Buckner or Smackover Formation, depending on whichever unit was present locally. The most obvious reference section for a lower group boundary is in the type section well for its lower unit, the Bossier Formation. This is in the Phillips Petroleum Company's Kendrick No. 1 well (C, NE, SW, Sec 22, T19N, R11W, Bossier Parish, Louisiana) where the base of the Bossier (and Cotton Valley) is placed at a depth of 8,140 feet (Swain, 1944, p. 591-592). Similarly, the obvious reference section for an upper group boundary is in the type section well for its upper unit, the Schuler Formation. This is in the Lion Oil Refining Company and Phillips Petroleum Company's Edna Morgan No. 1 well (C, NE, SW, Sec 18, T18S, R17W, Union County, Arkansas) where the top of the Schuler (and Cotton Valley) is placed at a depth of 5,385 feet (Swain, 1944).

Marquesas Supergroup

Meyerhoff and Hatten (1974) proposed the name Marquesas Supergroup to encompass all sediments above the Cotton Valley Group and below the Pine Key Formation in the South Florida region, as well as in adjacent Caribbean areas. The type section of this supergroup is in the Gulf Oil Company's State of Florida-1 field (Lease 826-Y, Monroe County, Florida) from a depth of 7,720 feet to 15,475 feet. The bottom of the unit was not reached in this well, but the Amerada Petroleum Corporation Cowles Magazines-2 well (Sec 19, T36S, R40E, St. Lucie County, Florida) serves as a reference section that includes the entire unit between 6,791 feet and 12,680 feet. This 5,889 foot sequence is the thickest section reported for this supergroup. At this locality, the Marquesas Supergroup unconformably overlies metamorphic basement rocks (Meyerhoff and Hatten, 1974).

In its type area in south Florida, the Marquesas encompasses a thick sequence of dolomites, limestones, and anhydrites that generally reflect deposition in restricted shallow marine environments. As originally described, this unit was thought to include Upper Jurassic (Tithonian) through basal Upper Cretaceous (lower Cenomanian) rock units. More recent work has shown that the basal strata of this supergroup are Lower Cretaceous rather than Upper Jurassic (Attilio and Blake, 1983; Klitgord and others, 1984). The top and bottom contacts of the Marquesas are marked by major unconformities that can be traced throughout the Coastal Plains north of the type area. These unconformities also are widely recognized elsewhere in the world (Vail and others, 1977). As a northern and northwestern limit was never defined for the Marquesas Supergroup, it readily can encompass all laterally contiguous age-equivalent strata north and northwest of the type area in the Atlantic and eastern Gulf Coastal Plains, including intertonguing, dominantly clastic units that accumulated in nearshore to onshore depositional environments (Figure 3).

The Marquesas Supergroup in its type area includes four groups (Winston, 1971). While these groups are relatively thick in south Florida, their equivalent strata to the north in the Atlantic Coastal Plain are much thinner, and only one group has been recognized there (Figure 1). In the Texas Gulf Coastal Plain, five groups have been established within this interval. Units comprising the Marquesas Supergroup in Texas and the Virginia-New Jersey region represent nearshore to onshore depositional environments that existed when sea level was higher than in the Late Jurassic but lower than in the Late Cretaceous. Thus, in the Caribbean and Gulf Coast region, shallow marine environments replaced restricted (often hypersaline) environments, while in the remainder of the Coastal Plains region onshore to coastal deposition began in areas that previously had been experiencing profound erosion. The deposits represented by the Marquesas Supergroup are regionally more widespread than those of the Minden Supergroup, and represent a significant expansion of deposition landward in all areas of the Coastal Plains. Even so, in most areas these deposits are deeply buried beneath younger strata. The only significant exceptions to this generalization are in the Virginia-New Jersey region, where Lower Cretaceous strata crop out along the present Tidewater Fall Line at the extreme western edge of the present Atlantic Coastal Plain, and in the western Gulf Coastal Plain of Texas, where Lower Cretaceous strata likewise are found at the surface.

Ancora Supergroup (new name)

No name in the geological literature exists that represents the entirety of the sequence of sediments described here, so the name Ancora Supergroup is proposed herein. The Ancora encompasses all strata above the Marquesas Supergroup up to the stratigraphic level where carbonate deposition becomes dominant throughout the Coastal Plains region east of the present Mississippi River. In terms of age, this includes all strata of late Cenomanian through early Lutetian age (Figure 4). The name Ancora comes from Ancora, New Jersey, and the Ancora A and B coreholes in Camden County, New Jersey (Miller and others, 2003) are here considered the principal reference section for this supergroup (specifically the interval from 427.6 feet to 1,148.1 feet).

In picking the upper boundary for the Ancora Supergroup in these cores at 427.6 feet, we concurrently are forced to move the basal boundary of the Shark River Formation upward from 448.7 feet to 427.6 feet. Although Miller and others (2003) recognized the sequence boundary at 427.6 feet (E7/E6 boundary of Browning and others, 1997a, 1997b), they placed the base of the Shark River Formation at a different sequence boundary at 448.7 feet (E4/E3 boundary) on the basis of precedent set by earlier work (Owens and others, 1988). This was a perfectly valid formational boundary definition by the rules of stratigraphic nomenclature. However, due to the placement of our newly defined supergroup boundary, the previously designated basal boundary for the Shark River Formation would place that formation across our subsequently established supergroup boundary. This

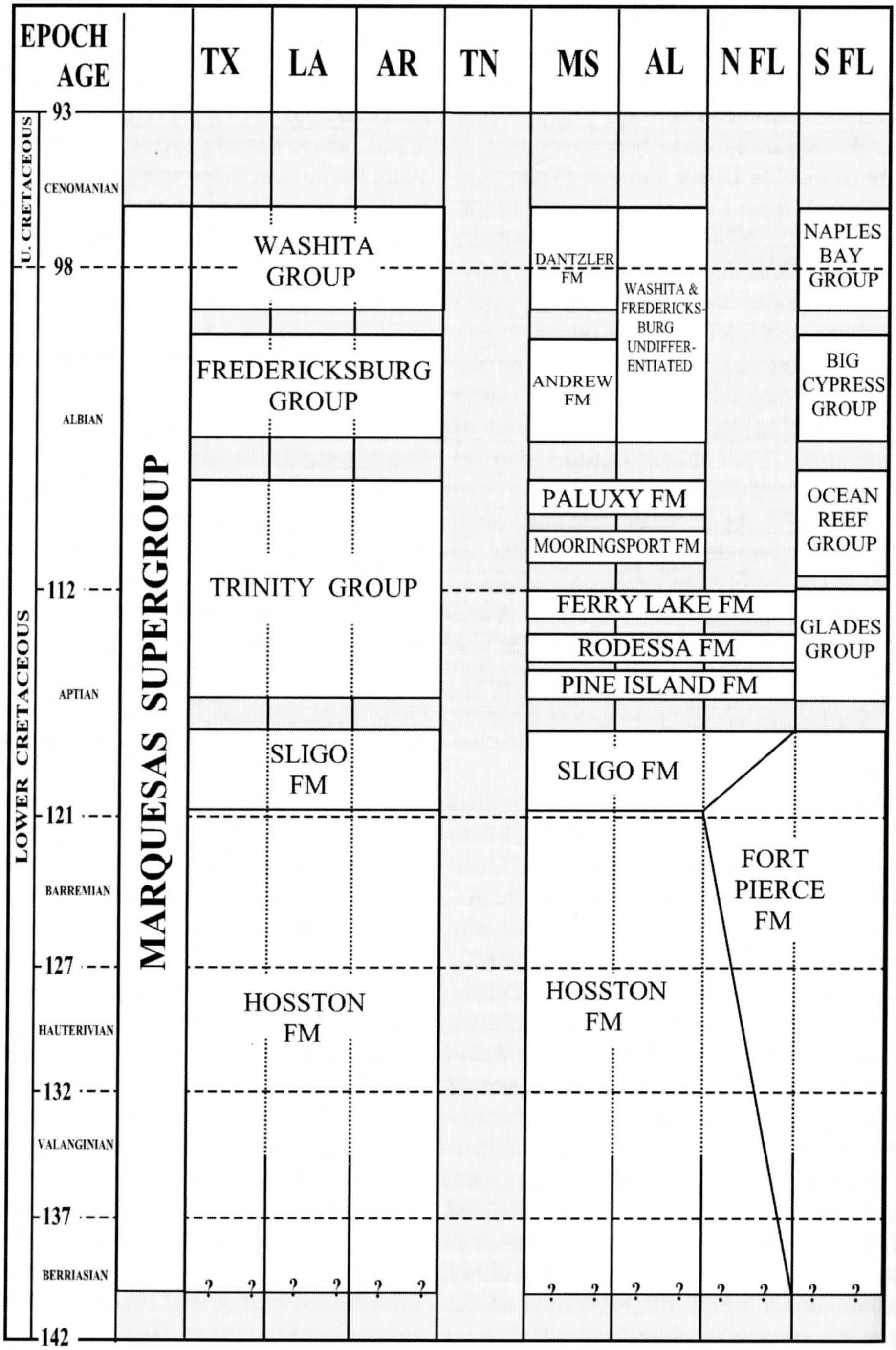


Figure 3A (3B on next page). Groups and formations included in the Marquesas Supergroup and their geographic occurrence. Time scale from International Stratigraphic Chart (2001), available at www.palaeos.com/Mesozoic/mztimescale.html. Supplementary stratigraphic data for individual units available online in the U.S. Geological Survey Geologic Names Lexicon (Geolex), available at ngmdb.usgs.gov/Geolex, and in Coastal Plains COSUNA charts (Braunstein and others, 1983; Jordan and others, 1983). Informal units K-1 through K-6 from Zarra (1989).

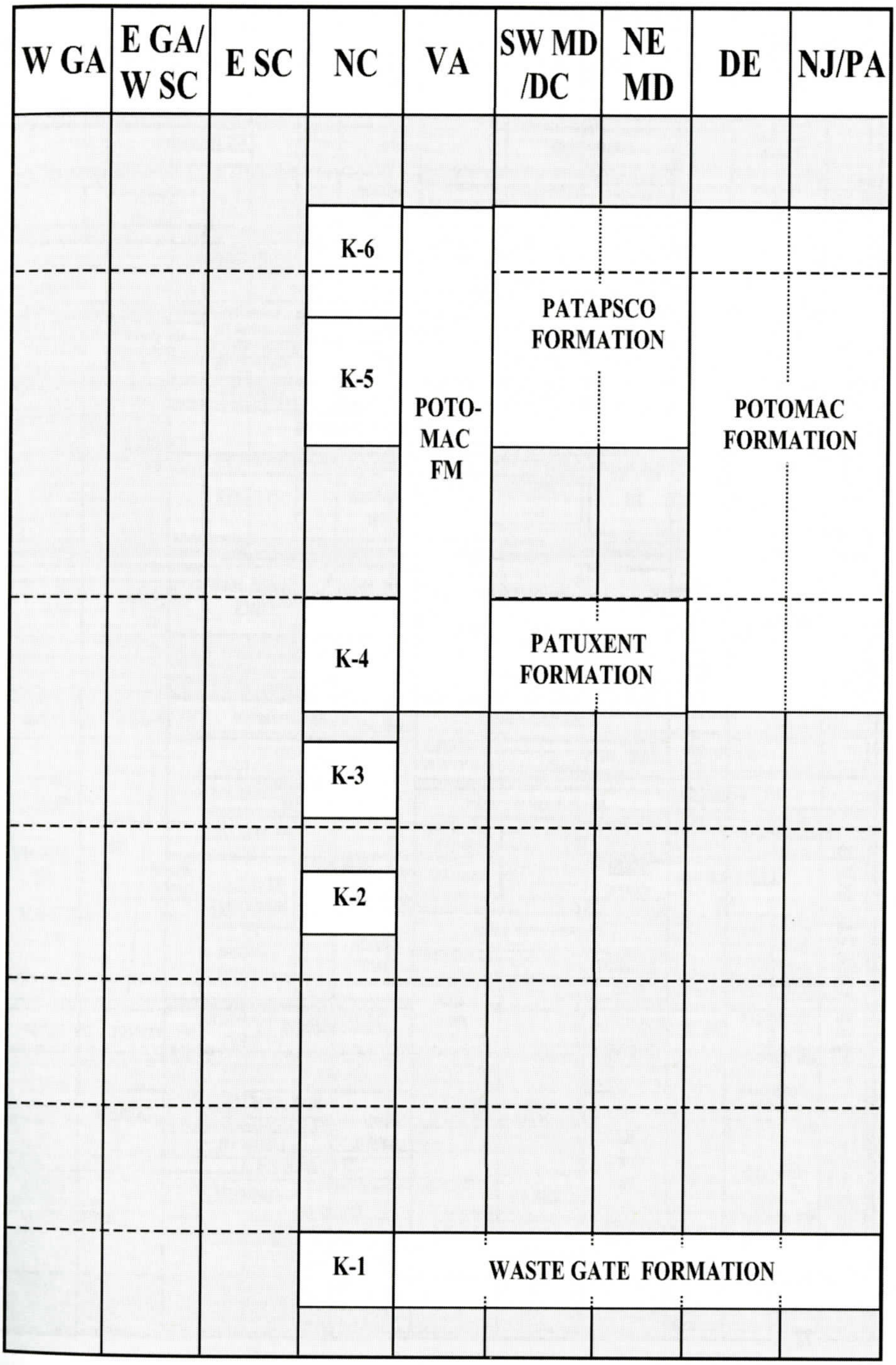


Figure 3B.

is not permitted by the North American stratigraphic code, so we therefore remove this glauconitic-porcellanitic clay interval (from 427.6 to 448.7 feet) from the Shark River Formation, so that the base of the Shark River conforms to the same horizon where major changes in lithology occur elsewhere throughout the Coastal Plains. For now, we move this interval to the

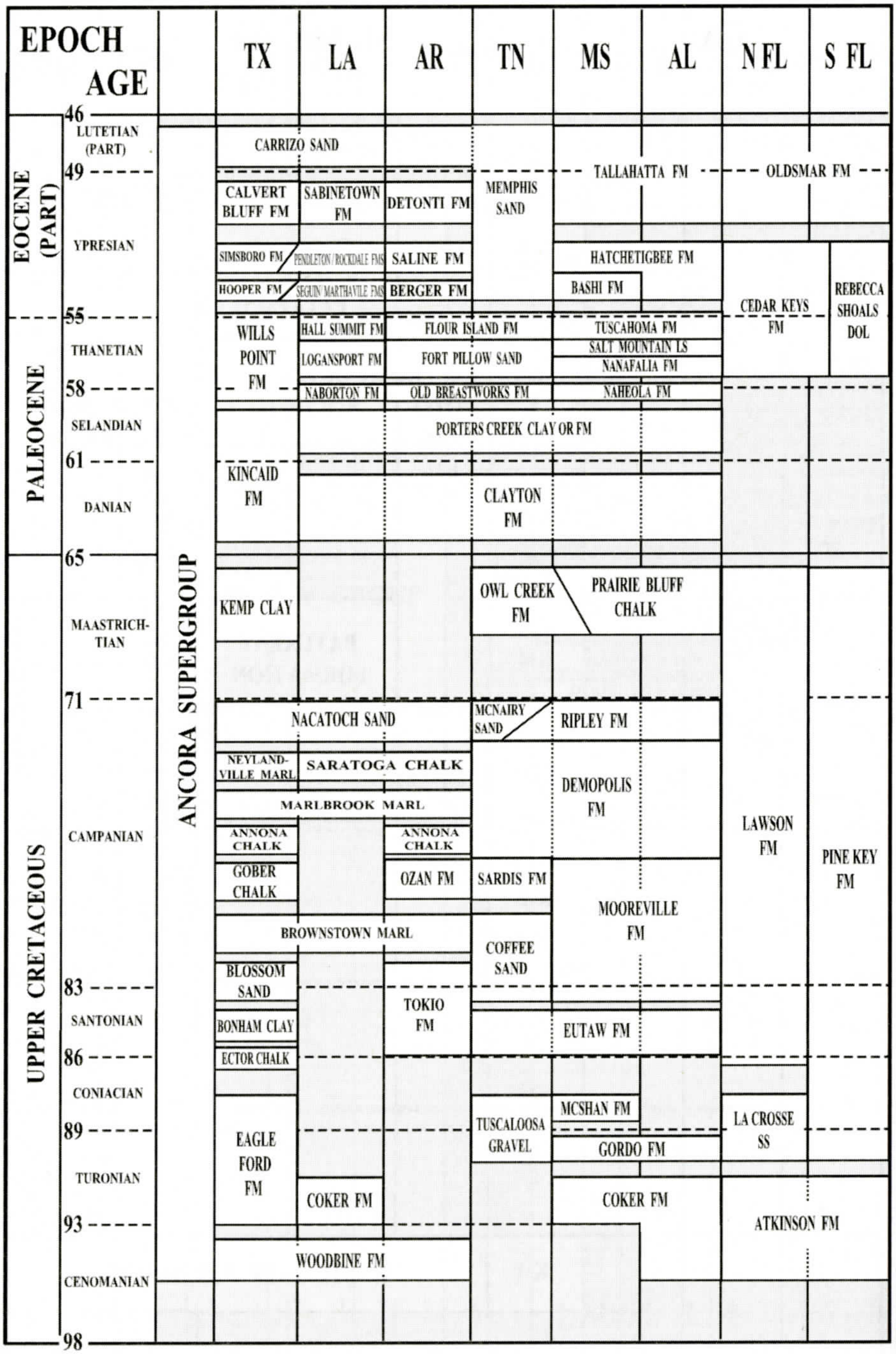


Figure 4A (4B on next page). Formations included in the Ancora Supergroup and their geographic occurrence. Time scale from International Stratigraphic Chart (2001), available at www.palaeos.com/Cenozoic/cztimescale.html and at www.palaeos.com/Mesozoic/mztimescale.html. Supplementary stratigraphic data for individual units available online in the U.S. Geological Survey Geologic Names Lexicon (Geolex), available at ngmdb.usgs.gov/Geolex, and in Coastal Plains COSUNA charts (Braunstein and others, 1983; Jordan and others, 1983). Some supplementary data also from Benson and Spoljaric (1996) and Miller and others (2003).

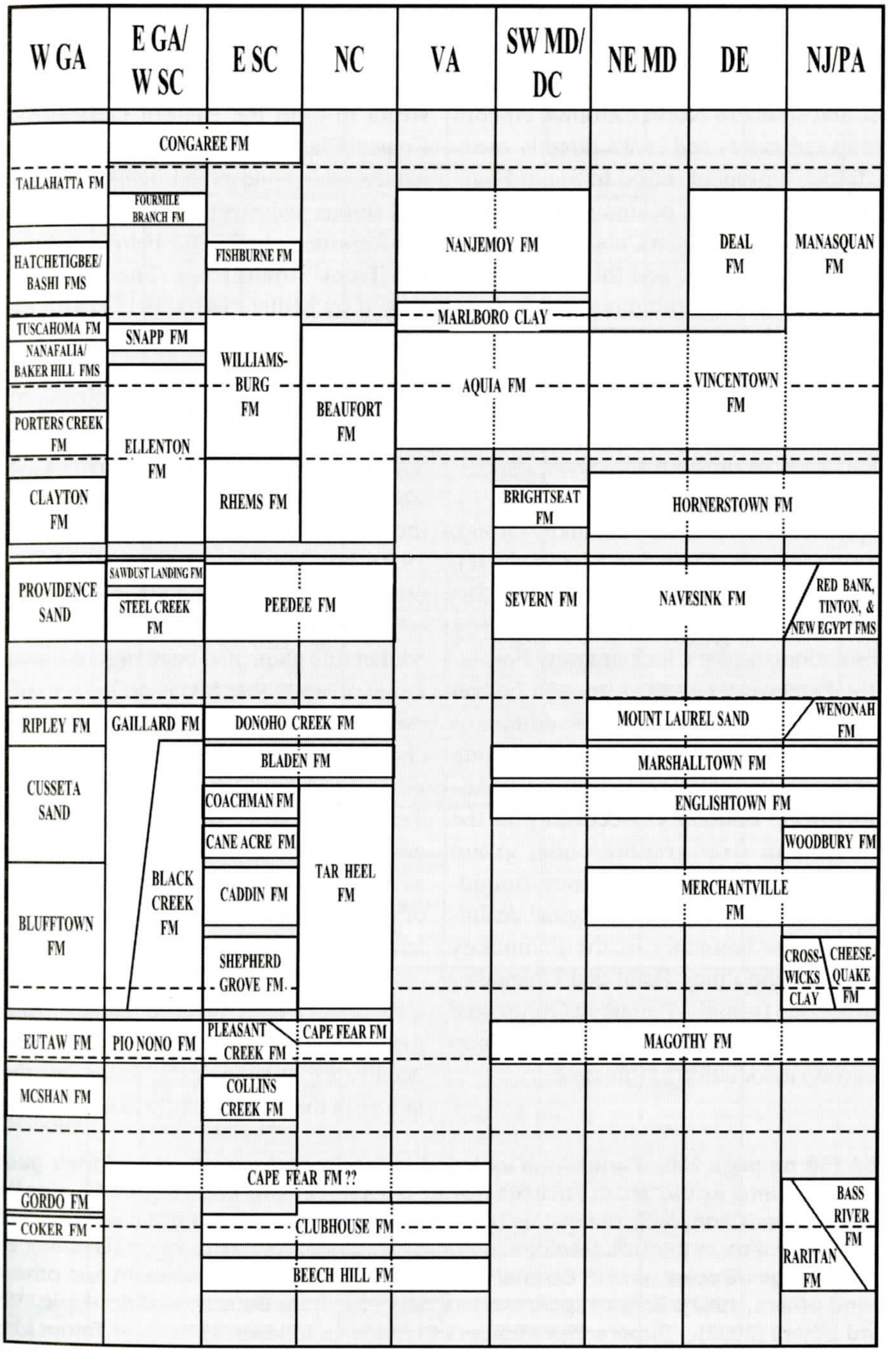


Figure 4B.

Manasquan Formation, but note that it probably warrants recognition as a new and separate unit in the future. The thickest reported section of this supergroup in the Atlantic Coastal Plain is in the Mobil #2 well, Albemarle Sound, eastern North Carolina, where a 2,340 foot section of Ancora sediment was encountered (Zarra, 1989).

A number of group names have been applied to all or part of this interval in various areas

(Figure 1). The sediments of the Ancora Supergroup widely overstep sediments of older supergroups and, throughout Georgia, South Carolina, and southern North Carolina, Ancora Supergroup sediments and rocks directly overlie pre-Minden basement rocks. In South Florida and the Caribbean, the beginning of Ancora time is marked by orogeny in Cuba, the breakup of the Bahamas platform, and the initiation of deep-water deposition throughout most of the Caribbean basin (Meyerhoff and Hatten, 1974). In the Coastal Plains, the beginning of Ancora time is marked by a pronounced expansion of fully marine environments across regions that earlier had been in onshore to coastal depositional environments.

The upper boundary of the Pamunkey Group, as originally defined (Clark and Martin, 1901), matches the upper boundary of the Ancora Supergroup. Later, Ward (1985) added the Piney Point Formation and the Chickahominy Formation to the Pamunkey Group. Although he had no way to know it at that time, the addition of these two formations to the Pamunkey group extended the Pamunkey Group across the Ancora Supergroup boundary. According to the North American stratigraphic code, group boundaries cannot cross supergroup boundaries, so we here go back to the original definition of the upper boundary of the Pamunkey Group, remove the Piney Point and Chickahominy formations from the Pamukey Group, and place them in the succeeding Trent Supergroup without group association at this time.

Trent Supergroup (new rank)

Middle Lutetian through basal Aquitani strata in both the eastern Gulf and Atlan Coastal Plains are preponderantly calcareous nature. This widespread interval of dominan calcareous sediment, bounded by regional u conformities above and below, is here term the Trent Supergroup. The Trent Marl w named by Miller (1910, 1912), who named t unit for exposures along the Trent River fro the vicinity of Trenton (Jones County), Nor Carolina, to near the junction of the Trent a Neuse rivers. This name subsequently has be applied to a number of similar-looking midd Eocene to lower Miocene calcareous deposits the North Carolina Coastal Plain (Spangle 1950; Le Grand and Brown, 1955; Hazel a others, 1977; Baum and others, 1978; Zullo a others, 1992). Ward and others (1978) conclu ed that this name had been used for such a wi range of strata that it was no longer suitable f even a group level designation. They therefo chose to abandon the name. Whereas we agr with Ward and others (1978) that the nam Trent no longer can be used as a group, th name still can be retained in its expanded sens as a supergroup encompassing this entire rang of carbonate-rich strata and their lateral equiva lents in the western Gulf Coastal Plain.

The base of the Trent Supergroup lies abov a regionally recognizable unconformity in th lower middle Eocene above the last widesprea occurrence of siliciclastic sediments that corre late with the lower middle Eocene "silica burp

Figure 5A (5B on page 206). Formations included in the Trent Supergroup and their geographi occurrence. Time scale from International Stratigraphic Chart (2001), available a www.palaeos.com/Cenozoic/cztimescale.html. Supplementary stratigraphic data for individua units available online in the U.S. Geological Survey Geologic Names Lexicon (Geolex), availabl at ngmdb.usgs.gov/Geolex, and in Coastal Plains COSUNA charts (Braunstein and others, 198 Jordan and others, 1983). Some supplementary data also from Benson and Spoljaric (1996) an Miller and others (2003). Superscript numbers indicate as follows. 1) Rank of Tatum Limeston here raised from previous usage as member of Catahoula Formation to prevent Catahoula For mation from improperly being in two separate groups. 2) Age change of Tobacco Road Sand i based on recently available biostratigraphic dating (David C. Prowell, written communication, i prep.), 3) "Delmarva beds" and "Exmore beds" were named in Powars and others (1992). Exmor beds formed geologically instantaneously, so the height of the box in this case is diagrammati only and does not reflect an estimate of the time interval during which it accumulated. 4) Ol Church age range has been extended and the name "Drummonds Corner beds" is being pro posed by Powars and others (in press.).

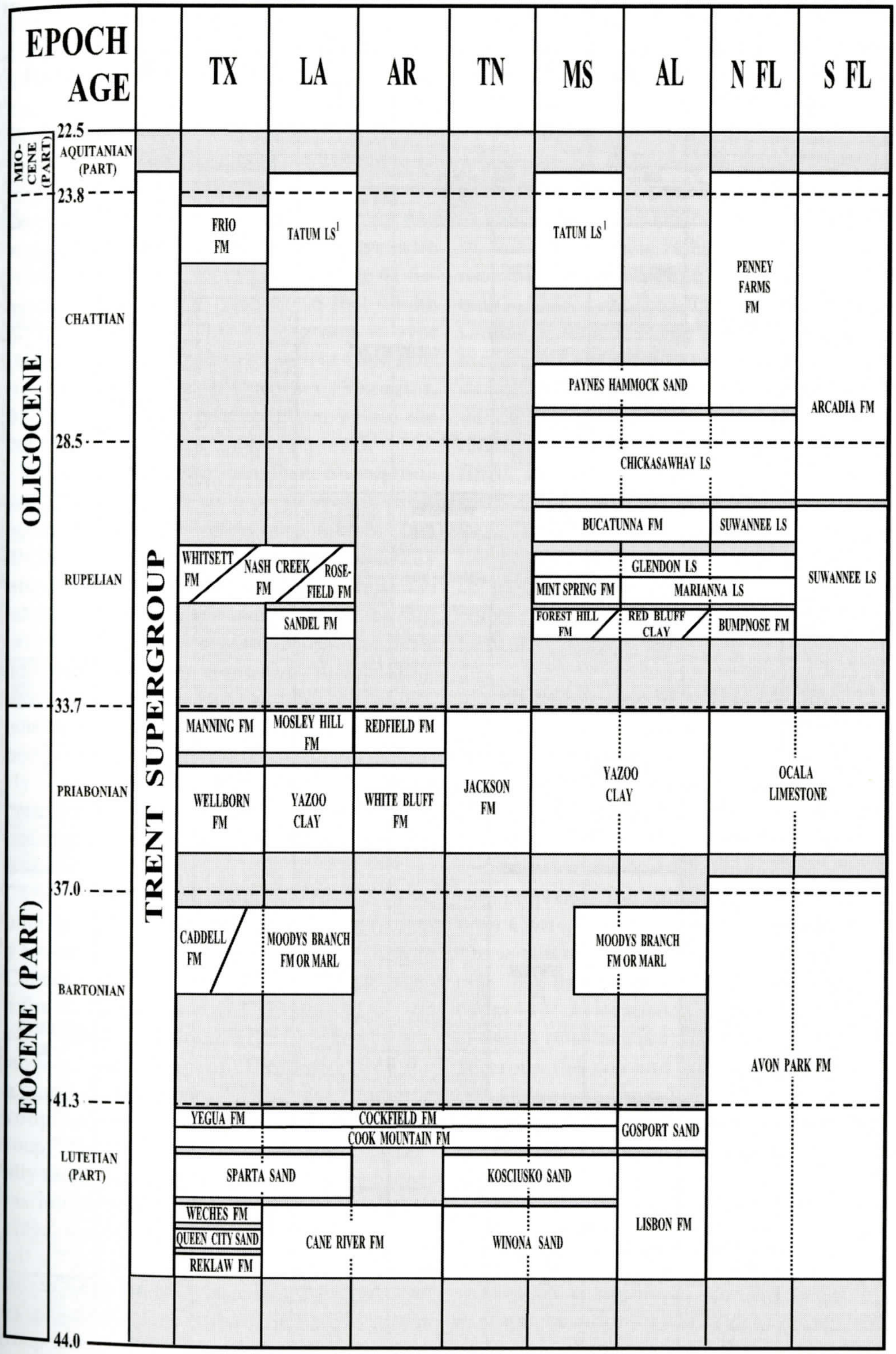

EPOCH
AGE
TX
LA
AR
TN
MS
AL
N FL
S FL
MIO-CENE (PART)
22.5
AQUITANIAN (PART)
23.8
OLIGOCENE
CHATTIAN
28.5
RUPELIAN
33.7
EOCENE (PART)
PRIABONIAN
37.0
BARTONIAN
41.3
LUTETIAN (PART)
44.0
TRENT SUPERGROUP
FRIO FM
TATUM LS[1]
TATUM LS[1]
PENNEY FARMS FM
PAYNES HAMMOCK SAND
ARCADIA FM
CHICKASAWHAY LS
BUCATUNNA FM
SUWANNEE LS
WHITSETT FM
NASH CREEK FM
ROSE-FIELD FM
GLENDON LS
MINT SPRING FM
MARIANNA LS
SUWANNEE LS
SANDEL FM
FOREST HILL FM
RED BLUFF CLAY
BUMPNOSE FM
MANNING FM
MOSLEY HILL FM
REDFIELD FM
WELLBORN FM
YAZOO CLAY
WHITE BLUFF FM
JACKSON FM
YAZOO CLAY
OCALA LIMESTONE
CADDELL FM
MOODYS BRANCH FM OR MARL
MOODYS BRANCH FM OR MARL
AVON PARK FM
YEGUA FM
COCKFIELD FM
COOK MOUNTAIN FM
GOSPORT SAND
SPARTA SAND
KOSCIUSKO SAND
WECHES FM
QUEEN CITY SAND
REKLAW FM
CANE RIVER FM
WINONA SAND
LISBON FM

Figure 5A.

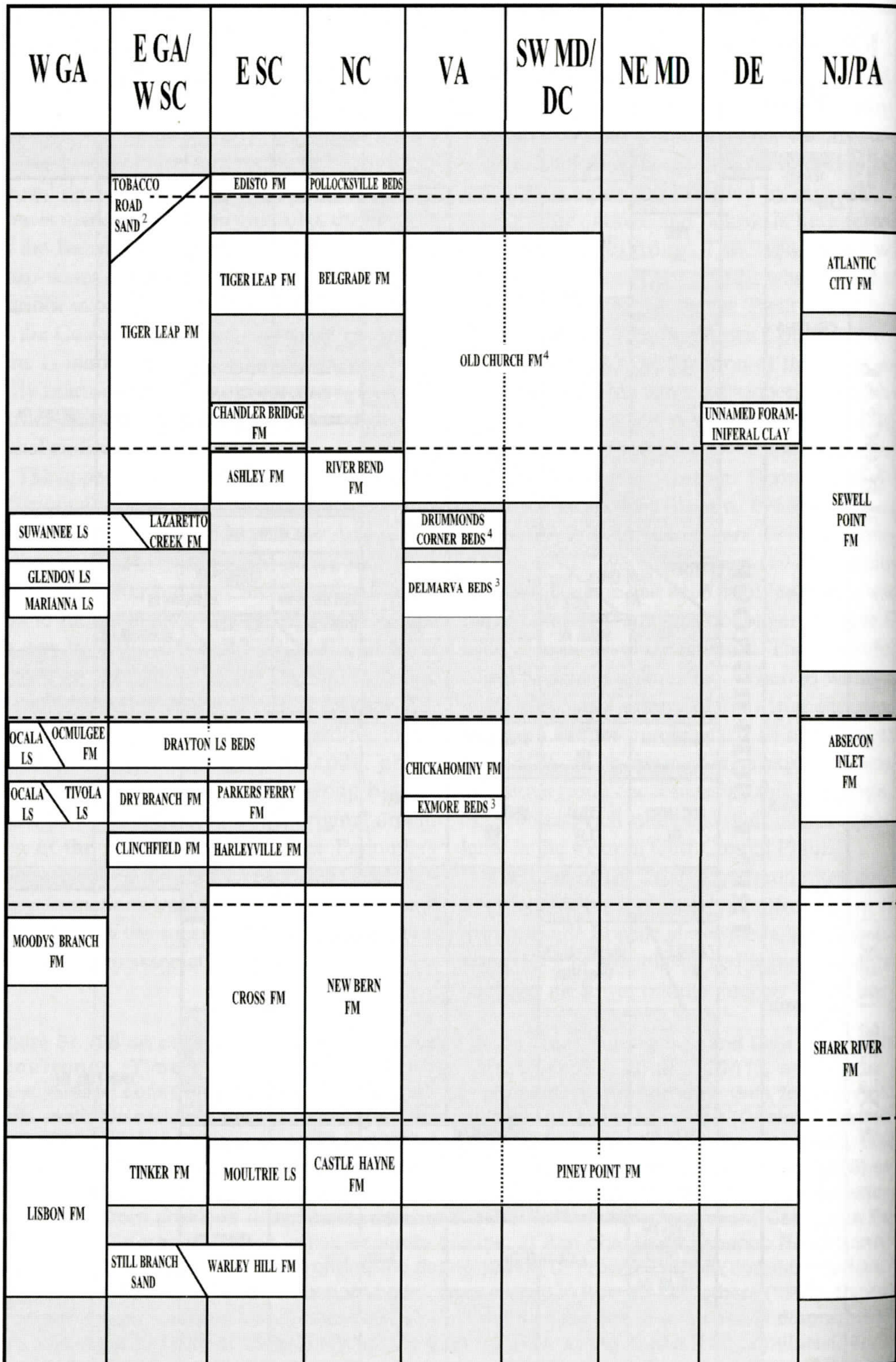

W GA
E GA/ W SC
E SC
NC
VA
SW MD/ DC
NE MD
DE
NJ/PA
TOBACCO ROAD SAND 2
EDISTO FM
POLLOCKSVILLE BEDS
TIGER LEAP FM
BELGRADE FM
TIGER LEAP FM
ATLANTIC CITY FM
OLD CHURCH FM 4
CHANDLER BRIDGE FM
UNNAMED FORAM-INIFERAL CLAY
ASHLEY FM
RIVER BEND FM
SEWELL POINT FM
SUWANNEE LS
LAZARETTO CREEK FM
DRUMMONDS CORNER BEDS 4
GLENDON LS
MARIANNA LS
DELMARVA BEDS 3
OCALA LS
OCMULGEE FM
DRAYTON LS BEDS
CHICKAHOMINY FM
ABSECON INLET FM
OCALA LS
TIVOLA LS
DRY BRANCH FM
PARKERS FERRY FM
EXMORE BEDS 3
CLINCHFIELD FM
HARLEYVILLE FM
MOODYS BRANCH FM
CROSS FM
NEW BERN FM
SHARK RIVER FM
LISBON FM
TINKER FM
MOULTRIE LS
CASTLE HAYNE FM
PINEY POINT FM
STILL BRANCH SAND
WARLEY HILL FM

Figure 5B.

(McGowan, 1989). The top of the Trent can be defined at the top of the Edisto Formation in the Givhans Ferry bluff north of the South Carolina Route 61 bridge over the Edisto River in Dorchester County, South Carolina (lectostratotype for the Edisto Formation) (Ward and others, 1979, their figure 7). The Trent Supergroup is not known to occur in its entirety at any one locality, but the best reference section available is in the Clubhouse Crossroads Corehole #1 between the depths of 14 and 410.6 feet (Gohn and others, 1977). This supergroup is over 1,400 feet thick in the Esso #1 well at Cape Hatteras in eastern North Carolina (Spangler, 1950). Units presently recognized within the Trent Supergroup are shown in Figure 5.

The establishment of the Trent Supergroup basal boundary at the widespread unconformity approximately between nannoplankton Zone NP15a and NP15b (equivalent to the boundary between foraminiferal zones P10 and P11) makes our system incompatible with the Claiborne Group, Orangeburg Group, Oconee Group and Fort Valley Group as presently defined (Figure 1). In the cases of the Orangeburg, Oconee, and Fort Valley groups, they either can be abandoned or redefined to conform with the regionally significant unconformity and shift in depositional style that marks the boundary between the Ancora Supergroup and the Trent Supergroup.

The status of the Claiborne Group is more complex. The "Claiborne sands" were named by Conrad (1847) and later changed by him to "Claiborne group" (Conrad, 1856). The type area for this sequence was Claiborne bluff and nearby outcrops at Gosport Landing and Lisbon Landing. Later, Hilgard (1860) proposed the recognition of an upper "Calcareous Claiborne group" and a lower "Siliceous Claiborne group." His "Siliceous Claiborne group" (basically the Tallahatta Formation of modern usage) was not present in the vicinity of Claiborne bridge, and it is significant that he called this unit a "group" that was different from the "group" found in the type area of the Claiborne. The repetition of the name "Claiborne" in both group names was confusing and does not conform to modern standards, but it should be kept in mind that those standards were established at a much later date and were unknown to Hilgard. Many subsequent workers did not accept the inclusion of this lower stratigraphic group interval within the definition of the Claiborne proper, but by 1920 the "Siliceous Claiborne" generally had become included in the definition of the Claiborne, which then became unified by its distinctive fauna rather than by any commonality within its suite of lithologies (Wilmarth, 1938). As the original definition of the Claiborne included only strata here placed in the Trent Supergoup, and these are the only stratigraphic horizons present in the type area of the Claiborne, we propose that the Claiborne be returned to its original definition. As thus defined, the lower boundary of the Claiborne matches the lower boundary of the Trent Supergroup, and it becomes fully compatible with the supergroup system established here. The "Siliceous Claiborne" (Talahatta) is moved to the Ancora Group without any group level assignment at the present time.

Nomini Supergroup (new name)

All sediments higher than the Trent Supergroup are treated here as a single supergroup package. No name in the geological literature exists that represents this entire sequence of sediments, so the name Nomini Supergroup is here proposed. The name derives from the Nomini Cliffs, Westmoreland County, Virginia. These cliffs provide a useful type area for the unit. The upper part of the Haynesville cores (from –181.3 elevation to top) provide additional useful reference sections for most of the supergroup (Mixon and others, 1989), and the Oak Grove core (from 199 to 66 feet depth) provides supplementary data for the lower part of the column (Reinhardt and others, 1980). This supergroup is slightly over 1,100 feet thick in the Mobile #2 well in eastern North Carolina (Zarra, 1989).

The base of the Nomini Supergroup does not correspond with the basal boundaries as defined in recent years for the Chesapeake Group of the northern Atlantic Coastal Plain or the basal boundary of the Hawthorn Group of the south-

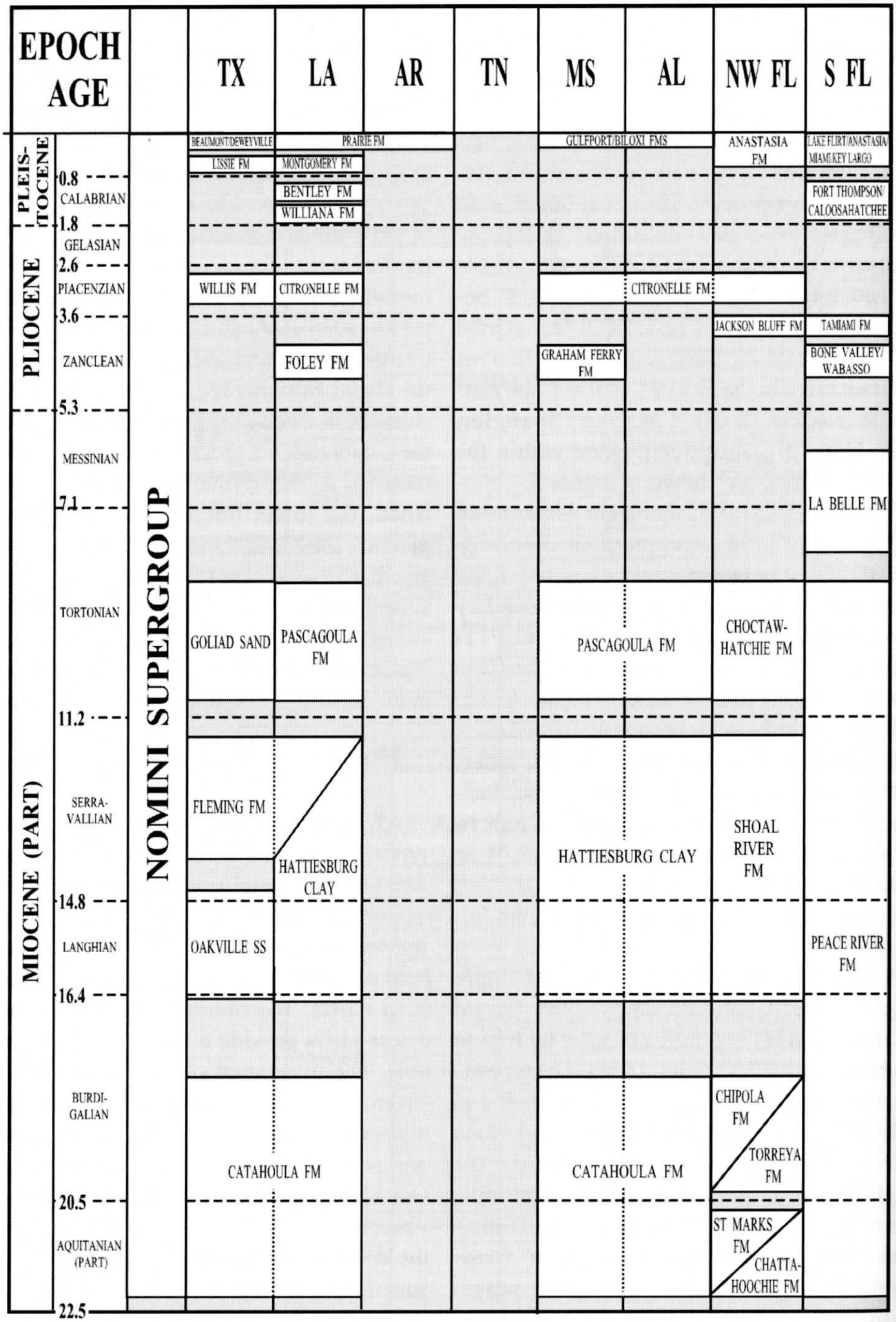


Figure 6A (6B on next page). Formations included in the Nomini Supergroup and their geographic occurrence. Time scale from International Stratigraphic Chart (2001), available at www.palaeos.com/Cenozoic/cztimescale.html. Supplementary stratigraphic data for individual units available online in the U.S. Geological Survey Geologic Names Lexicon (Geolex), available at ngmdb.usgs.gov/Geolex, and in Coastal Plains COSUNA charts (Braunstein and others, 1983; Jordan and others, 1983). Some supplementary data also from Benson and Spoljaric (1996) and Miller and others (2003).

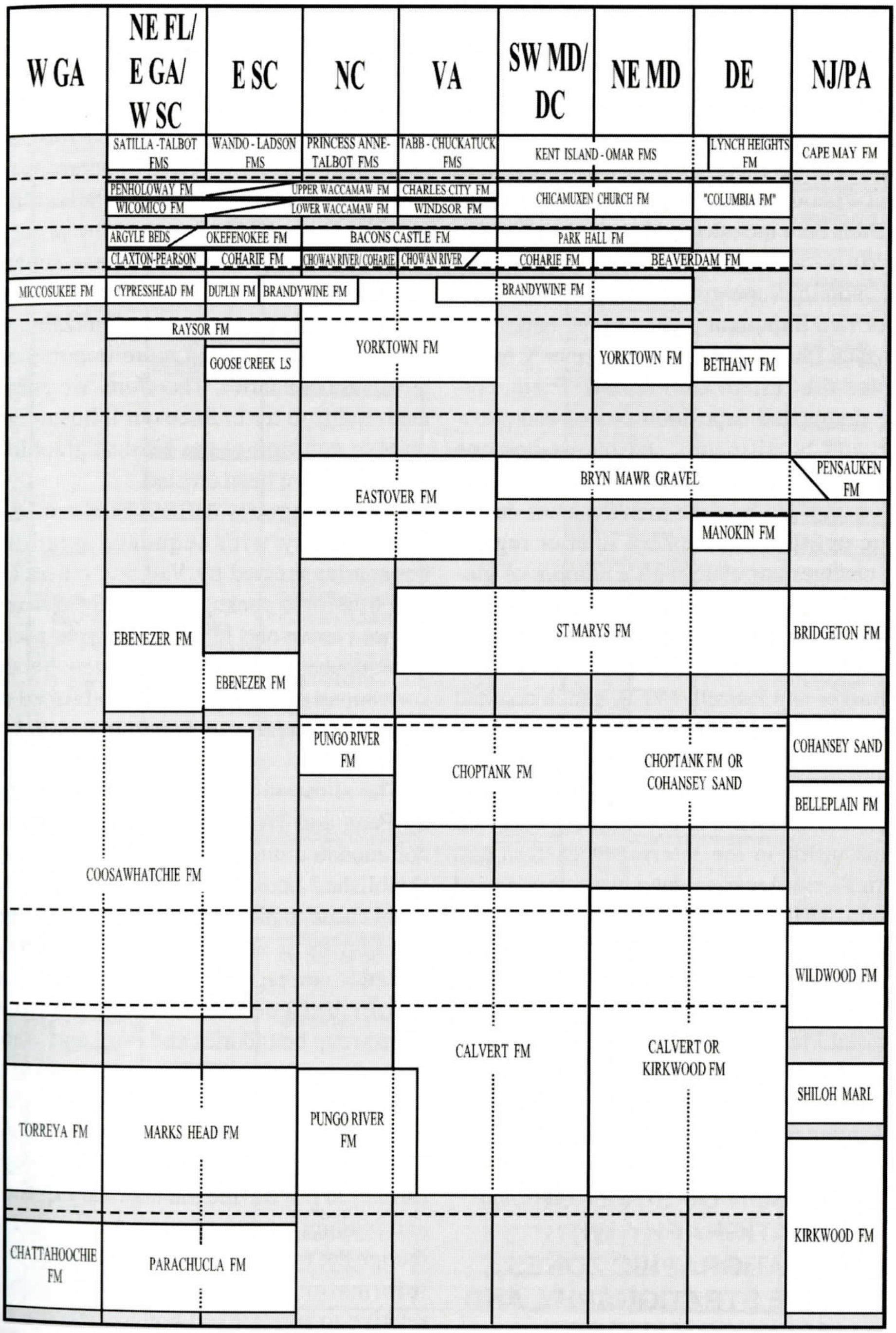


Figure 6B.

ern Atlantic Coastal Plain. According to the North American stratigraphic code, group boundaries cannot cross supergroup boundaries, so we remove the Oligocene Old Church Formation of Ward (1985) from the Chesapeake Group, and the Penney Farms unit of Scott (1988) and Tiger Leap Formation of Huddlestun (1988) from the Hawthorn Group. Although all of these units have been considered to be Miocene in age at one time or another, they now are known to be Oligocene in age (Weems and Edwards, 2001) and their lithologies conform to the definition of the Trent Supergroup. Therefore, we include them within that stratigraphic interval without group designation at the present time. Units here included within the Nomini Supergroup are shown in Figure 6.

The Nomini Supergroup represents the initiation of two important events in the history of the Coastal Plains. First, in the Atlantic Coastal Plain and the eastern Gulf Coastal Plain, carbonate-dominated deposition ceased and phosphatic and biosiliceous sediments became abundant. In the western Gulf Coastal Plain, strata on average become much coarser due to tectonic uplift in the Western Interior region. These changes correlate with a number of global changes in oceanic circulation patterns, including the opening of the Drake Passage and the establishment of the Circumantarctic Current (Barker and Burrell, 1977), which resulted in a pronounced cooling of the global climate and the initiation of abundant upwelling of cool deep-ocean waters along the entire margin of the Atlantic Coastal Plain. Second, renewed regional uplift in the interior of eastern and western North America dates from this period (Gibson, 1970). Among other effects, this uplift allowed the headwaters of the Roanoke, James, and Potomac Rivers to begin to contribute sediment from beyond the Blue Ridge to the Atlantic Coastal Plain for the first time (Newell and Rader, 1982; Naeser and others, 2002). This cyclic, warm-cold climatic pattern and uplift regime continues today.

COMPARISON OF SUPERGROUP STRATIGRAPHY WITH BIOSTRATIGRAPHIC ZONES, SEQUENCE STRATIGRAPHY, AND ALLOFORMATIONS

The supergroups defined here can be correlated with existing biostratigraphic zones as shown in Figure 7. Cretaceous supergroups correspond readily to the existing nannofossil and pollen zone boundaries, but the Cenozoic zonations are somewhat less conveniently correla ed. The boundary between the Anco Supergroup and the Trent Supergroup appea to fall within nannofossil Zone NP15 (tl boundary between NP15a and NP15b), and tl boundary between the Trent Supergroup and tl Nomini Supergroup appears to fall within na nofossil Zone NN2. Even so, the pronounce lithologic changes found at these supergrou boundaries, and the corresponding presence regionally widespread and recognizable unco formities, are accorded more importance tha biozonal boundaries. Therefore, we consider inadvisable to try to force our lithostratigraph units to conform to the biostratigraphic zon tions that have been erected.

The supergroups defined here can be corre lated readily with sequence stratigraph boundaries erected by Vail and others (1977 The lithologic packages recognized here ofte do not correspond to the supercycle packagir of sequences within the Vail system but they c correspond everywhere with established uncor formity boundaries between individual cycle (Figure 7).

The allostratigraphic formations establishe by Poag and Ward (1993) can be partially ac commodated into the lithostratigraphic syster established here. However, because Poag an Ward chose to place all of their allostratigraphi boundaries at unconformities that they pre sumed to correspond to stage boundaries, corre lation between our lithostratigraphi supergroup boundaries and Poag and Ward's a lostratigraphic boundaries cannot occur in th following two cases: their Linderkohl Allofor mation lies astride the boundary of the Ancor and Trent supergroups, and their Berkeley Allo formation lies astride the boundary of the Tren and Nomini supergroups (Figure 7). Thus, al though the relative positions of each of these al loformations generally can be establishe relative to formational boundaries, the bound aries of the supergroup system established her cannot accommodate two of the Poag and War alloformations as presently defined.

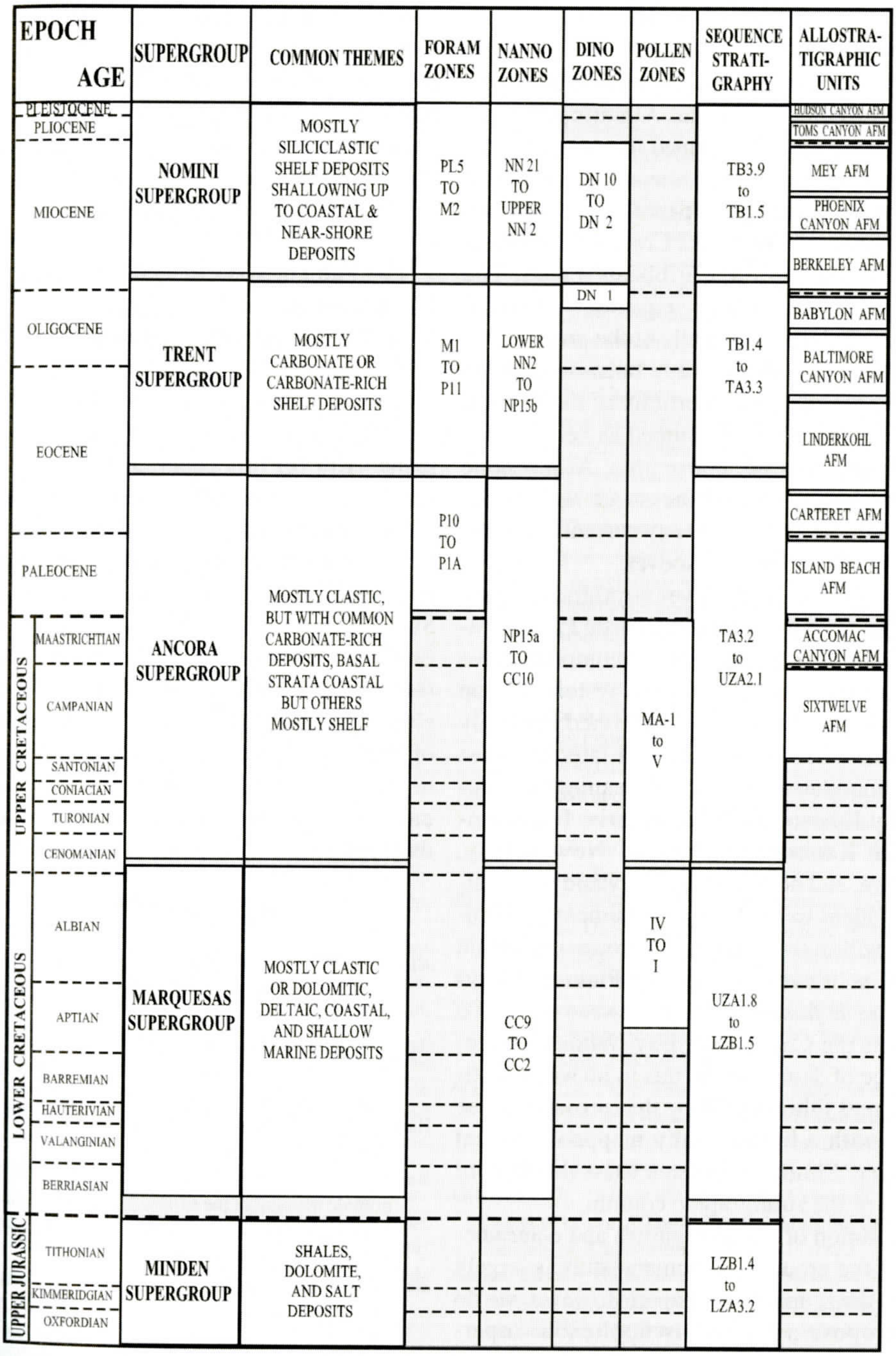


Figure 7. Correlation of supergroups to fossil zonations, sequence stratigraphic units, and allostratigraphic units. AFM = Alloformation. Fossil zonations are from Perch-Nielsen (1985a, 1985b), Sissingh (1977), and Okada and Bukry (1980) for nannofossils, Berggren and others (1995) for nannofossils and foraminifera, de Verteuil and Norris (1996) for dinoflagellates, and Doyle and Robbins (1977) for pollen. For more recent pollen zonations, see Christopher and others (1999) and Christopher and Prowell (2002). Sequence stratigraphic units are from Vail and others (1977). Allostratigraphic units are from Poag and Ward (1993).

DISCUSSION

The group and supergroup nomenclature previously established for the Atlantic and Gulf Coastal Plains was developed for use only on a subregional scale. Only one supergroup had been erected prior to this paper, and it was created to apply only to Lower Cretaceous strata in south Florida and the Caribbean region. The rest of the Coastal Plains sequence had no supergroup designations at all. At the group level, some forty-four groups have been named and applied to subregional portions of the Coastal Plains, but none are envisioned as being applicable throughout the entire area. At the same time, probably half of the strata within the Coastal Plains do not have any currently accepted group placement whatsoever.

The existing group-level stratigraphic system in the Gulf and Atlantic Coastal Plains simply cannot be integrated into a comprehensive and regional lithostratigraphic system. Group boundaries generally have been fixed vertically with considerable accuracy, but laterally most group boundaries cannot be meaningfully defined by lithostratigraphic criteria. For example, the Rancocas Group of New Jersey, Delaware, and northeastern Maryland is laterally equivalent to most of the sediments encompassed within the Pamunkey Group of Virginia and the southwestern Coastal Plain of Maryland. The *de facto* boundary between these two groups is the Chesapeake Bay. While a convenient line of demarcation, this in no way constitutes a real lithic boundary that provides these groups with a lithologically mappable mutual boundary. Similar problems exist throughout the rest of the stratigraphic column.

Resolution of the ambiguities and contradictions of the group level nomenclature is largely beyond the scope of this paper. However, we do here propose a regionally applicable supergroup level stratigraphy that is inclusive and can be successfully mapped and applied throughout the entire stratigraphic column of the Coastal Plains from southern Texas through New Jersey. This system of supergroup stratigraphic nomenclature is inclusively hierarchical, is readily learned and applied even by those unfamiliar with the Coastal Plains stratigraphic column, and reflects and emphasizes the major tectonic, climatic, and stratigraphic changes that have occurred during the course of development of the Atlantic and Gulf Coastal Plains.

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SUBSURFACE STRATIGRAPHY AND GEOMORPHOLOGY OF THE GRAND STRAND, GEORGETOWN AND HORRY COUNTIES, SOUTH CAROLINA

THOMAS R. PUTNEY

MICHAEL P. KATUNA

Department of Geology and Environmental Geosciences
College of Charleston
Charleston, South Carolina 29424

M. SCOTT HARRIS

Center for Marine and Wetland Studies
Coastal Carolina University
Conway, South Carolina 29526

ABSTRACT

The Grand Strand in northeastern South Carolina extends in a continuous, 100-km-long arc from Winyah Bay to Little River Inlet. This coastal segment is dominated by mainland beaches that are attached to eroding Pleistocene headlands. Pleistocene and Holocene deposits generally form a relatively thin veneer of unconsolidated, generally quartz-rich, sandy sediments that overlie clay, silt and fine-grained quartz sands of Late Cretaceous or early Tertiary age. These older, variably indurated "hardground" deposits are exposed in the immediate shoreface zone. Wave erosion of Quaternary deposits and the underlying older strata provides an undependable sand source for this sediment-starved coastal segment. Knowledge of the geologic framework of the Lower Coastal Plain and the inner continental shelf is extremely important in understanding long and short-term coastal changes that affect this region.

Sixteen holes were bored (maximum depth of 56 feet) along this stretch of coastline using a Geoprobe. Data collected from the analysis of these borings were incorporated with additional data compiled from geophysical logs from water wells and lithologic descriptions from power auger holes to better characterize the near-surface stratigraphy of this region. Pleistocene and Holocene sediments analyzed from these borings suggest deposition in beach, beach ridge, tidal inlet, back barrier, nearshore marine and fluviodeltaic paleoenvironments. To the south, these younger sediments overlie an erosional surface incised into fine-grained shelfal sand, silt, and clay strata of the Paleocene Black Mingo Group, whereas to the north, these deposits unconformably overlie sandy mudstones and siltstones of the late Cretaceous Peedee Formation. Coast-parallel cross sections confirm the presence of buried fluvial channels incised into these older stratigraphic units by ancestral Piedmont rivers during Pleistocene sea level low stands.

Structure contour maps, isopach maps, and geologic cross sections, were developed by integrating onshore subsurface data with offshore geophysical surveys. Stratigraphic interpretation of formational boundaries and sediment thicknesses confirm the presence of numerous paleo-channels incised into the inner continental shelf. Land-based geological and offshore geophysical surveys were integrated into a comprehensive geological model in order to better understand the geological history and modern-day processes that influence the Grand Strand.

INTRODUCTION

Long Bay, or what is more commonly re-

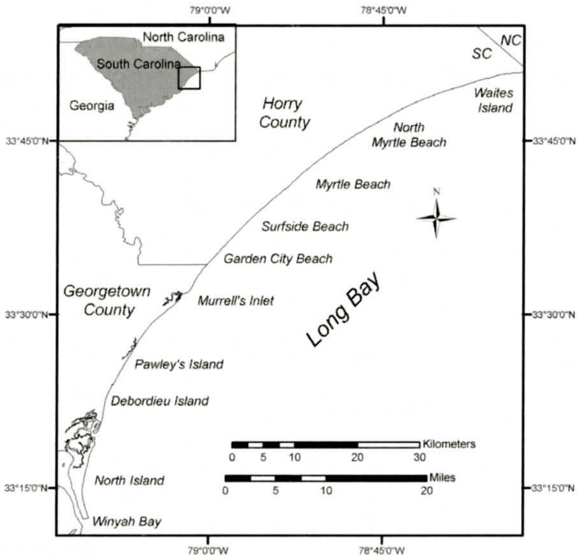

Figure 1. Location map of the Grand Strand study area.

ferred to as the Grand Strand of South Carolina, extends from Winyah Bay to the North Carolina border, a distance of approximately 100 km (62 mi). This coastal segment includes the popular resort cities of Myrtle Beach, North Myrtle Beach, and other coastal communities in Georgetown and Horry Counties (Figure 1).

Average shoreline erosion rates along much of the Grand Strand have been relatively low (~1 m (3.3 ft) /yr) over the last hundred years except near the few existing tidal inlets (Hubbard *et al.*, 1977a, 1977b). Even relatively low erosion rates have posed a problem for the extensive commercial and residential development in the region. Hurricanes such as Hugo in 1989, and non-tropical storms (northeasters) periodically impact the area and may cause several years of coastal erosion in a matter of days. In response, some developed coastal localities have been largely stabilized with seawalls and revetments.

Since the 1980s the preferred solution to beach erosion in South Carolina has been beach renourishment, which involves pumping or dumping of sand from onshore or offshore borrow sites onto the beach. The most recent Grand Strand renourishment project was completed in 1998 and involved the placement of 6.4 million cubic yards of sand on 24 miles (39 km) of coastline between Murrell's Inlet and North Myrtle Beach, at an estimated cost of $54 million (U.S. Army Corps of Engineers, 1997).

The Grand Strand is not receiving primary, first-cycle sediments due to a lack of Piedmont-draining rivers discharging sediment into Long Bay (Hayes, 1994). Today the only naturally occurring "new" sediment is derived from erosion of older subaerial Pleistocene beach deposits and variably indurated Tertiary and Cretaceous strata, which crop out on the continental shelf. The occurrence and distribution of these pre-Holocene deposits strongly influence the supply of sediment to the beaches and the adjacent continental shelf.

Geologic data from onshore and from the adjacent continental shelf are needed to help estimate the longevity of nourishment projects, to identify "hot spots" which may require more frequent renourishment, and to identify potential borrow sites for future renourishment projects. The objectives of this study are to describe and characterize Quaternary and pre-Quaternary stratigraphic units that occur at shallow depths beneath the present day coast, to determine their regional distribution, and to locate pre-Holocene fluvial paleochannels.

COASTAL GEOMORPHOLOGY

The Grand Strand is the arcuate portion of the northern South Carolina coast, and it is characterized by its relative lack of barrier islands and associated tidal inlets, and its relatively narrow, poorly developed salt marshes, when compared to the coastal morphology of the central and southern South Carolina coast (Brown, 1977). Except for relatively narrow barrier islands that are present at the extreme southern and northern ends of the study area, the present day beaches are attached directly to the mainland, which is composed of Pleistocene headlands.

The Grand Strand is located on the northern margin of the Georgia Bight, a broad shoreline arc which borders North Carolina, South Carolina, Georgia and Florida. Wave and tidal conditions along the arcuate strand grade between the relatively low wave energy mesotidal central South Carolina coast and the high wave energy microtidal coast of North Carolina (Hayes, 1994). Areas near the head of the Georgia Bight (*i.e.*, the central and southern South Carolina coast) are characterized by more numerous tidal inlets and mixed energy regressive barrier islands, reflecting the larger tidal influence in these areas (Hayes, 1994). The spring tidal range along the Grand Strand is microtidal (< 2 m (6.6 ft)), and the mean wave height is 1.2 -1.3 m (3.9 - 4.3 ft), indicating that the study area is a mixed-energy (wave-dominated) coastline according to Hayes (1994).

The Lower Coastal Plain of northeastern South Carolina is characterized by a series of relict Pleistocene barrier island systems, which decrease in age toward the present day coast. These relict shorelines record the position of sea level, which has fluctuated greatly in response to glacial and interglacial episodes during the last 2 million years. Data from measurements of coral terraces in New Guinea indicate that two major glacial episodes occurred in the Late Quaternary at about 150,000 and 20,000 years B.P. and caused sea level to drop as much as 150 m (492 ft) below present levels (Aharon and Chappell, 1986).

The Holocene transgression began at the end of the Wisconsinan glacial stage (about 20,000 years B.P.) when sea level began to rise at rates greater than 30 mm (0.1 ft) per year (Williams *et al.*, 1998). Sea level continued to rise but the rate decreased markedly at about 6,000 years B.P. Detailed archaeological and marsh stratigraphic studies indicate that, since about 6,000 years B.P., sea level in South Carolina has fluctuated between 1 and 4 m (3.3-13.1 ft) below present levels (Colquhoun and Brooks, 1986; Colquhoun *et al.*, 1995).

The effects of Quaternary sea level fluctuations are recorded in the geomorphology of the South Carolina Lower Coastal Plain and in the stratigraphy of the submerged continental shelf. Exposed relict barrier island systems record periods when relative sea level was 3 to 30 m (approximately 10 to 100 ft) above present day sea level (Colquhoun, 1974), and they represent shorelines during earlier Pleistocene interglacial periods. The effects of large sea level declines during Wisconsinan glaciation and earlier glacial periods are represented by ancient river channels incised into older marine sediments and the deposition of fluvial sequences on the exposed continental shelf.

REGIONAL GEOLOGY

The Grand Strand lies on the southern flank of the Cape Fear Arch (Figure 2), an area of tectonic uplift that has affected both the thickness and distribution of Late Cretaceous to late Tertiary strata in the southeastern Atlantic Coastal Plain (Prowell and Obermeier, 1991). Cretaceous through Holocene strata reach a combined thickness of about 500 m (1640 ft) along the crest of the arch, but thicken to over 1000 m (3280 ft) in the Charleston Embayment to the southwest (Gohn, 1988). Tertiary stratigraphic units are absent along the axis of the Cape Fear Arch, but Paleocene and younger units are present on its flanks to the northeast and southwest. The deformation of relict Pleistocene barrier island complexes indicates that uplift on the Cape Fear Arch continued through Pliocene and Pleistocene time (Winker and Howard, 1977).

The structure contour and isopach maps of the South Carolina Coastal Plain by Colquhoun

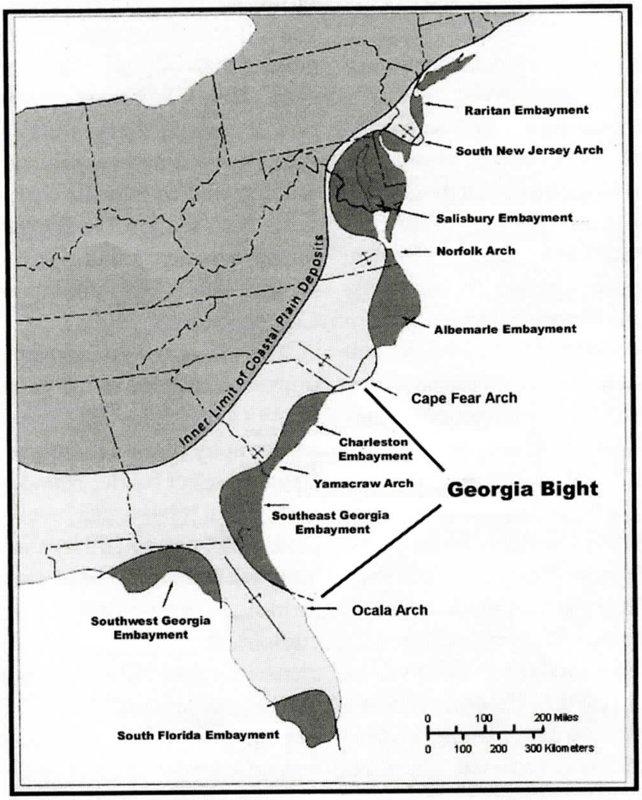

Figure 2. Map of the Atlantic Coastal Plain, showing the location of the Georgia Bight, which is bordered by the Cape Fear Arch and the Ocala Arch. Modified from Ward and Strickland (1985).

et al. (1983) indicate that the Grand Strand is underlain by stratigraphic units ranging in age from Late Cretaceous (Peedee Formation) to Paleocene (Black Mingo Group). Isopachs drawn on Paleocene and younger Tertiary units are subparallel to the trend of the Cape Fear Arch. The spatial trends reflect the influence of the Cape Fear Arch on the distribution patterns of the Late Cretaceous and Tertiary units. Regional unconformities between and within these stratigraphic groups have been traced in the subsurface throughout the South Carolina Coastal Plain. These unconformities or diastems often serve as a framework for regional correlation of stratigraphic units in the subsurface (Colquhoun *et al.*, 1983).

In the Lower Coastal Plain, these pre-Quaternary strata are overlain by a veneer of fluvial and nearshore marine, Neogene sediments, that were deposited as sea level fell approximately 70 m (230 ft) in a descending step-like fashion from early Pliocene through Holocene time (Colquhoun *et al.*, 1991).

Cretaceous and Paleogene Stratigraphy

Peedee Formation

The Peedee Formation is the oldest shallow subsurface stratigraphic unit in the study area, and has been assigned to the Late Cretaceous (middle-upper Maastrichtian). Ruffin (1843) named the "Peedee bed" (Table 1) for exposures along the Pee Dee River in eastern South Carolina, and a lectotype of these beds, near Burches Ferry in Florence County, South Carolina, was assigned to the "Burches Ferry Phase" by Sloan (1908).

Swift and Heron (1969) included the Burches Ferry beds in the Peedee Formation of the

Table 1. Cretaceous and Paleogene Stratigraphic Correlation Chart for Northeastern South Carolina.

	Age	Stage	Ruffin, 1843	Sloan, 1908	Cooke, 1936	Swift and Heron, 1969	Van Nieuwenhuise and Colquhoun, 1982	Sohl and Owens, 1991
Tertiary	Eocene	Ypresian		Black Mingo Phase: Upper: Williamsburg Pseudobuhr; Rhems Shale	Black Mingo Formation		Black Mingo Group: Unnamed Ypresian Unit	
Tertiary	Paleocene	Thanetian		Black Mingo Phase: Upper: Williamsburg Pseudobuhr; Rhems Shale / Lower: Black Mingo Shale	Black Mingo Formation		Black Mingo Group: Williamsburg Formation: Chicora Member, Lower Bridge Member	
Tertiary	Paleocene	Danian		Black Mingo Phase: Lower: Black Mingo Shale	Black Mingo Formation		Black Mingo Group: Rhems Formation: Perkins Bluff Member	
Cretaceous	Upper	Maastrichtian	Peedee Bed	Burches Ferry Phase	Peedee Formation	Lumbee Group: Peedee Formation	Peedee Formation	Peedee Formation; Black Creek Group: Donoho Creek Formation
Cretaceous	Upper	Campanian		Black Creek Phase	Black Creek Formation	Lumbee Group: Black Creek Formation		Black Creek Group: Bladen Formation; Tar Heel Formation
Cretaceous	Upper	Santonian		Black Creek Phase	Tuscaloosa Formation	Lumbee Group: Middendorf Formation		Black Creek Group: Middendorf Formation

middle to late Cretaceous Lumbee Group. Swift *et al.* (1969) described the Peedee as a fine to very fine muddy sand with sandy mud horizons that disconformably overlie interbedded laminated clays and sands of the Black Creek Formation along a ravinement surface.

Sohl and Owens (1991) further refined the Cretaceous stratigraphy of the Carolinas, based on biostratigraphic data. They identified sediments deposited in coeval deltaic to shelf environments and assigned them formational status. They elevated the Black Creek Formation to group status and subdivided it into the Tar Heel, Bladen and Donoho Creek Formations (Table 1). The Peedee lacks deltaic facies and represents deposition in shelfal or nearshore marine environments when the shoreline may have been as far inland as the present day fall line (Sohl and Owens, 1991).

Black Mingo Group

The Black Mingo Group unconformably overlies the Peedee Formation. The term "Black Mingo shales" was originally applied by Sloan (1908) to shales exposed in Black Mingo Creek, a tributary of the Black River in Williamsburg and Georgetown Counties, South Carolina. Sloan (1908) later expanded the term to "Black Mingo phase" to include all Lower Eocene strata east of the Santee River, and divided it into two parts: the Lower Black Mingo ("Black Mingo shale") and the Upper Black Mingo, which included the "Lang Syne beds", the "Williamsburg pseudobuhr" and the

"Rhems shale" (Cooke, 1936). Cooke (1936) lumped the units defined by Sloan into the Black Mingo Formation, which included all Eocene strata in South Carolina older than the McBean Formation. Later revisions resulted in the placement of the Black Mingo in the Paleocene (Van Nieuwenhuise and Colquhoun, 1982).

The Paleocene-lower Eocene stratigraphy of South Carolina was further refined by Van Nieuwenhuise and Colquhoun (1982), who elevated the Black Mingo to group status and designated stratotype localities for two formations and four members. Van Nieuwenhuise and Colquhoun (1982) established the Black Mingo Group as consisting of the Rhems Formation, the Williamsburg Formation, and a lower Eocene unit they did not name.

The Rhems Formation consists of a lower arenaceous shale and argillaceous sand (Browns Ferry Member) overlain by pelecypod-rich clayey sands (Perkins Bluff Member). The Williamsburg Formation consists of arenaceous shale and fossiliferous, argillaceous sand (Lower Bridge Member) overlain by fossiliferous sands and mollusk-rich bioclastic limestones (Chicora Member) (Van Nieuwenhuise and Colquhoun, 1982). Biostratigraphic data indicate that the Rhems is Danian and the Williamsburg is Thanetian in age. The unnamed lower Eocene unit has since been assigned to the Fishburne Formation, which is only known to occur in the subsurface to the southwest of the Charleston-Summerville area (Gohn *et al.*, 1983).

Neogene Stratigraphy

Lower Coastal Plain sediments in the study area consist of a relatively thin veneer of marine, estuarine, and fluvial deposits, which overlie the older Cretaceous and Tertiary strata described above (Colquhoun *et al.*, 1991). Due to the relatively young age of these sediments, back barrier marsh, lagoon and barrier-island deposits are still recognizable as geomorphic units in this part of the coastal plain. The study of the Quaternary stratigraphy of the Lower Coastal Plain has evolved from tracing relict shorelines by the elevation of geomorphic surfaces (terraces) to mapping allostratigraphic units associated with different sea levels. However, there is still no true consensus on the stratigraphic nomenclature for the Lower Coastal Plain. Of the many geologic maps that have been produced for the study area (Cooke, 1930, 1936; Colquhoun, 1965, 1969; DuBar *et al.*, 1974; McCartan *et al.*, 1984; Colquhoun *et al.*, 1987; and Owens, 1989), none share a common stratigraphic nomenclature (Table 2). The complex stratigraphic nomenclature results from the discontinuous nature of the strata, their lateral and vertical variability and the general lack of datable material or distinctive fossil assemblages (Colquhoun *et al.*, 1991).

Cooke (1930,1936) identified seven terraces on the South Carolina Coastal Plain, at elevations ranging from 8 m (25 ft) to 82 m (270 ft) above present sea level. Cooke (1930, 1936) believed that the highest elevations of the different terraces represent marine deposition along abandoned Pleistocene shorelines. The contacts between formations on his geologic map were located largely on the basis of the presence and elevation of ancestral beach scarps, with the formations occupying the areas between the toes of adjacent scarps (terraces). Of interest to this study are the Wicomico, Penholoway, Talbot and Pamlico terraces that make up the Lower Coastal Plain physiographic subprovince.

Working in central South Carolina, Colquhoun (1974) utilized geomorphic, subsurface, and outcrop data to define 'cyclic units' that retained Cooke's terrace terminology for the Lower Coastal Plain (Table 2). Colquhoun identified four transgressive-regressive cyclic units in the Lower Coastal Plain, including the Wicomico-Penholoway, Talbot-Pamlico, Princess Anne, and Silver Bluff units.

DuBar (1971) and DuBar *et al.* (1974) developed a localized stratigraphic sequence based on type localities in northeastern South Carolina. The stratigraphic units were correlated with geomorphic features (relict barrier island systems), which occur throughout this part of the Lower Coastal Plain. DuBar *et al.* (1974) identified the following formations seaward of the Surry Scarp: Bear Bluff-"Marietta", Wacca-

Table 2. Neogene Stratigraphic Correlation Chart for Central and Northeastern South Carolina.

<table>
<tr><th colspan="2" rowspan="2">Age</th><th rowspan="2">Cooke, 1936</th><th rowspan="2">DuBar et al., 1971, 1974</th><th rowspan="2">Colquhoun, 1974</th><th colspan="2">McCartan et al., 1984, 1990</th><th rowspan="2">Owens, 1989</th></tr>
<tr><th>Unit</th><th>Estimate</th></tr>
<tr><td rowspan="9">Quaternary</td><td>Holocene</td><td>Recent</td><td>'Waiter Island" "Ocean Forest Peat"</td><td>Holocene</td><td>Unit Q1</td><td>< 8 ka</td><td>Holocene</td></tr>
<tr><td rowspan="8">Pleistocene</td><td rowspan="3">Pamlico</td><td rowspan="4">Socastee</td><td>Silver Bluff</td><td rowspan="3">Unit Q2 (Wando)</td><td rowspan="3">~ 100 ka</td><td rowspan="3">Wando</td></tr>
<tr><td>Princess Anne</td></tr>
<tr><td rowspan="4">Talbot-Pamlico</td></tr>
<tr><td rowspan="3">Talbot</td><td>Unit Q3</td><td>~ 200 ka</td><td rowspan="2">Socastee</td></tr>
<tr><td rowspan="2">Canepatch</td><td rowspan="2">Unit Q4</td><td rowspan="2">~ 450 ka</td></tr>
<tr><td>Canepatch</td></tr>
<tr><td>Penholoway</td><td rowspan="2">Waccamaw</td><td rowspan="2">Wicomico-Penholo-way</td><td>Unit Q5</td><td>> 730 ka</td><td>Penholoway</td></tr>
<tr><td>Wicomico</td><td>Unit Q6</td><td>>1 Ma</td><td>Waccamaw</td></tr>
<tr><td rowspan="2">Tertiary</td><td rowspan="2">Pliocene</td><td>Duplin Marl</td><td>Bear Bluff – "Marietta"</td><td>Okefenokee</td><td colspan="2" rowspan="2"></td><td>Bear Bluff</td></tr>
<tr><td></td><td>Duplin</td><td>Duplin</td><td>Duplin</td></tr>
</table>

maw, Canepatch, Socastee, "Ocean Forest Peat" and "Waiter Island".

The Pliocene Bear Bluff is named for exposures on the Waccamaw River about 10 miles east of Conway, South Carolina, and it consists of a sequence of calcareous sandstones, sandy limestones, subarkosic sands and calcareous silts, which unconformably overlie the Pliocene Duplin Formation or the Cretaceous Peedee Formation (DuBar, 1971). The Bear Bluff may be continuous with subarkosic to quartzose sands and clays of the "Marietta unit" which forms interfluve surfaces on the Middle Coastal Plain, between the Surry and Mechanicsville Scarps (DuBar *et al.*, 1974). Campbell (1992) correlated the Bear Bluff with the middle Pliocene Goose Creek Limestone, and recommended the abandonment of the Bear Bluff Formation as a formal lithostratigraphic name.

Fossil-rich sands of the lower Pleistocene Waccamaw Formation unconformably overlie or abut the Bear Bluff-"Marietta". The Waccamaw was named by Dall (1892) for fossiliferous marine deposits exposed along the Waccamaw River in Horry County, South Carolina. The Waccamaw occurs as erosional remnants over lows in the Bear Bluff or Peedee Formations, as well as beneath the Jaluco-Cainhoy and Myrtle Beach Barrier systems, and it consists of shelly, semi-indurated, fine to coarse sand with up to 70% carbonate by weight (DuBar *et al.*, 1974). The faunal assemblages indicate brackish water to shallow shelfal environments and warm to semi-tropical water temperatures (DuBar *et al.*, 1974).

The Middle-Late Pleistocene Canepatch Formation forms the surface of the Jaluco-Cainhoy and Conway barrier systems and consists of complex deposits of sand, silt, clay, and peat which represent deposition in barrier island, back barrier lagoon, tidal flat, estuary, tidal inlet, patch reef, and freshwater swamp environments (DuBar *et al.*, 1974).

The Socastee Formation, the youngest Pleistocene unit identified by DuBar *et al.* (1974), consists of quartz sands, clayey and silty sands, and clays that form the surface of the Myrtle Beach barrier system bordering the present coast.

Holocene deposits are the youngest units in the stratigraphic sequence of Dubar *et al.* (1974). The "Ocean Forest Peat" consists of peat exposed on the intertidal beach near Ocean Forest, and the "Waiter Island Formation" is an informal unit that consists of recent barrier and back barrier deposits, such as those on Waites Island.

McCartan *et al.* (1984) mapped the area from Charleston to Orangeburg, South Carolina at a scale of 1:250,000, which includes the southern portion of the Grand Strand study area. McCartan *et al.* (1990) used informal map units (Q1-Q6, from youngest to oldest) to map the Quaternary stratigraphy of the Lower Coastal Plain. Each numbered Quaternary unit was subdivided into beach, back barrier, fluvial, and swamp depositional lithofacies, with each lithostratigraphic unit representing a depositional cycle (McCartan *et al.*, 1990).

Owens (1989) mapped the Florence-Cape Fear region at a scale of 1:250,000. This map covers the majority of the Grand Strand study area. Owens (1989) used a combination of DuBar's terminology (Bear Bluff, Waccamaw, Socastee), Colquhoun's terminology (Penholoway) and added the Wando Formation, named for upper-most Pleistocene deposits near Charleston (McCartan *et al.*, 1980). Owens restricted DuBar's Canepatch to its type locality on the Intracoastal Waterway, and showed it without surface expression. Several stratigraphic units that had been previously identified by DuBar *et al.* (1974) were reassigned to different formations by Owens (1989).

PREVIOUS GEOLOGIC FRAMEWORK STUDIES

Regional Studies

Numerous coastal studies have investigated the role of the underlying geologic framework in the evolution of various portions of the present day U. S. Atlantic Coast and inner continental shelf. Demarest and Leatherman (1985) and Belknap and Kraft (1985) studied the influence of geologic framework on the development of the Delmarva Peninsula (Delaware, Maryland, and Virginia) and the barrier island systems of northern Delaware, respectively. Hine and Snyder (1985) integrated onshore and offshore vibracore data with seismic data from the inner shelf to map paleochannels in the shoreface and inner shelf off Bogue Banks, North Carolina. Riggs *et al.* (1992) utilized vibracore data to identify depositional sequences, which were correlated with reflectors on high resolution seismic profiles, to study the Quaternary evolution of estuarine and barrier island systems in northeastern North Carolina.

The influence of the geologic framework on hardgrounds exposed in the active shoreface has been the subject of several recent studies conducted on the north flank of the Cape Fear Arch in Onslow Bay, North Carolina (Cleary *et al.*, 1996; Riggs *et al.*, 1995, 1996, 1998; Marcy, 1997). Schwab *et al.* (2000) used high-resolution sea floor mapping methods on the inner continental shelf to investigate sediment transport and coastal erosion trends along a portion of Long Island, New York. Thieler *et al.* (2001) studied the shoreface and inner continental shelf offshore of Wrightsville Beach, North Carolina, and were able to identify sediment from old renourishment projects on the inner shelf. Boss *et al.* (2002) used high-resolution seismic profiles and vibracoring to map the ancestral Roanoke/Albemarle fluvial system on the inner shelf offshore of northeastern North Carolina.

South Carolina Studies

Several framework-related studies have also been conducted within and near the study area in South Carolina. Brown *et al.* (1980) used sediment analyses of samples from the inner continental shelf to identify the location of paleochannels of Piedmont rivers that were incised during sea level low stands. The general locations of these paleochannels were correlated with channels present in the subsurface onshore.

Domeracki (1982) studied the geologic history and stratigraphy of Pawley's Island and identified a fluvial channel of the ancestral Black River beneath the island. This channel controls depositional environments and the morphology of the island (Domeracki, 1982).

Frankenburg (1987) studied the sedimentary characteristics of hardgrounds and overlying unconsolidated sediments exposed on and offshore near Myrtle Beach, and determined that hardgrounds there consist of carbonate-cemented continental shelf deposits of possible Tertiary age. Offshore geophysical studies confirmed the presence of sediment starved hardgrounds located along the inner shelf off the Grand Strand coast (Donovan-Ealey *et al.*, 1997a, b), and identified paleochannels of the Peedee River on the inner shelf offshore of Murrell's Inlet (Gayes *et al.*, 1992).

Idris and Henry (1995) combined high-resolution seismic data with well data to map the shallow Cenozoic stratigraphy of the continental shelf of central and southern South Carolina. Fields *et al.* (1999) studied the role of antecedent topography to barrier island formation along the central South Carolina coast. They noted the apparent relationship between the location of barrier islands and tidal inlets to the position of paleovalleys and topographic highs (interfluves) that underlie the modern barrier island coastline.

Recently, high-resolution seafloor mapping of the inner continental shelf and shoreface along the Grand Strand have been conducted as part of the South Carolina-Georgia Coastal Erosion Study (Baldwin, 2002; Baldwin *et al.*, 2002; Morton *et al.*, 2002; Gayes *et al.*, 2002). These studies mapped fluvial incisions, areas of outcropping pre-Quaternary units, sediment thickness, and other features of the inner shelf and shoreface.

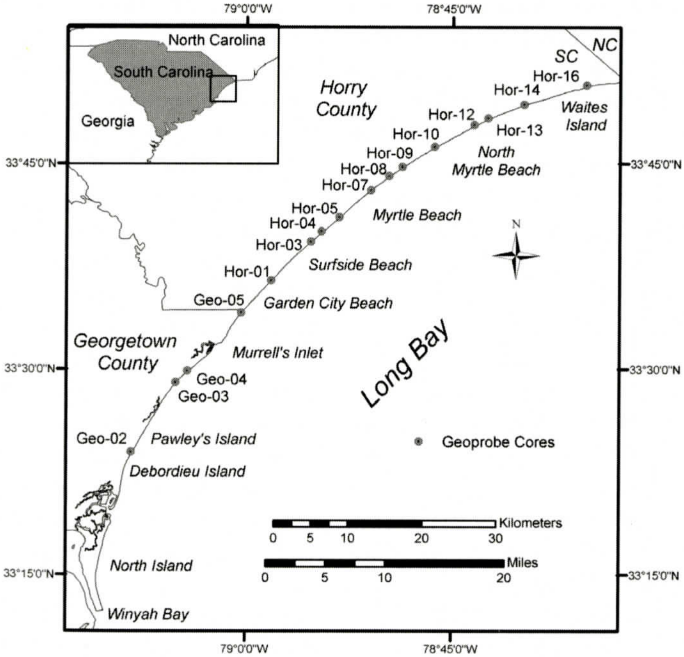

Figure 3. Geoprobe core locations.

FIELD AND LABORATORY METHODS

Sixteen holes were bored along the Grand Strand in order to investigate the near surface stratigraphy underlying the present day coast (Figure 3). A track-mounted Marl Technologies Model 5T Geoprobe rig that uses hydraulic equipment to push a steel core barrel into soft sediment was utilized for coring purposes. At the point where it can be pushed no further, the barrel is hydraulically hammered to its final depth of refusal. This method returns 4-foot (1.2 m) long continuous cores in unconsolidated materials within 1.5 in. (3.8 cm) diameter plastic tubes.

Cores were split, described and sampled for sediment analysis and stratigraphic interpretation. The cores were logged at a scale of 1"=1 foot, and each interval was described in terms of its color, composition, grain size, sorting and sand content. Sedimentary structures and fossils present were identified, and special attention was paid to lithologic relationships along unconformable contacts.

Additional borehole data were acquired for 93 water wells (obtained from the Land and Water Conservation Division-South Carolina Department of Natural Resources) and 48 power auger holes (D.J. Colquhoun's data) that are located within 3-5 mi (5-8 km) of the coastline in Horry and Georgetown Counties. When available, lithologic and geophysical logs for water wells and auger holes were used to interpret the depth to the base of the Quaternary section. The most useful geophysical logs for this study were gamma ray logs, which provide a measure of the natural radiation within a formation. In the South Carolina Coastal Plain, accumulations of glauconite and phosphate along erosional contacts generally produce significant gamma ray spikes that are often used to delineate major stratigraphic divisions.

Subsurface data were input to a geographic information system (GIS) using ArcView 8.2 software developed by Environmental Systems Research Institute (ESRI). Data tables of drill hole information were utilized to create ArcView shape files that show the location of the borings (Table 3). ArcView Spatial Analyst Ex tension was used to create regional structura contour maps of stratigraphic horizons includ ing the top of the Peedee Formation, the top o the Black Mingo Group and the base of th Quaternary sediments. Also, coast parallel geo logic cross-sections were created using core da ta, and selected auger and water wel information (Figures 4A and 4B).

Several geophysical data sets for the inne continental shelf immediately offshore of the Grand Strand were also provided by the USGS These included recently collected sidescan sonar and seismic reflection profiles. Geophysica data and interpretations for the southern part o the study area are contained in Baldwin (2002). Recently generated offshore geophysical data for the northern portions of the study area are unpublished at this time, but have been referenced in Morton *et al.* (2002) and Baldwin *et al.* (2002).

STRATIGRAPHIC INTERPRETATION

Cretaceous and Paleogene Units

Peedee Formation

In the northern portion of the study area, cores that penetrated the Quaternary section intersected the Cretaceous Peedee Formation at depths ranging from 20.5 to 38 feet. The Peedee Formation is primarily composed of variably indurated (calcite-cemented) sandy clays (Hor-16) to clayey sands (Hor-5, Hor-7). Internal and external molds, shell fragments, foraminifera tests and other microfossils are locally abundant. Silt and clay comprise from 30 to 80% by weight of sediment, and the coarser fraction consists predominantly of fine to very fine-grained quartz sand. Muscovite is common and glauconite and phosphate typically occur in trace amounts. The Peedee is generally massive, lacking internal stratification possibly due to extensive bioturbation, and is believed to represent deposition in marine shelf environments (Gohn, 1988).

The upper surface of the Peedee is inclined to the south-southwest probably reflecting uplift of the Cape Fear Arch and the development of

Table 3. Summary of Geoprobe cores drilled along the Grand Strand.

Hole Number	Latitude Longitude (WGS84)	Collar Elevation* (Feet MSL)	Total Depth (Feet)	Depth to Base of Quaternary (Feet)	Stratigraphic Unit At Bottom of Hole
Geo-02	33.3996 -79.1389	6	56	44	Black Mingo (Paleocene)
Geo-03	33.4840 -79.0850	6	29	28	Black Mingo (Paleocene)
Geo-04	33.4982 -79.0709	6	27	24	Black Mingo (Paleocene)
Geo-05	33.5687 -79.0057	6	51.5	51	Black Mingo (Paleocene)
Hor-01	33.6078 -78.9694	10	22.5	21	Black Mingo (Paleocene)
Hor-03	33.6552 -78.9213	7	21.5	20.5	Peedee (Cretaceous)
Hor-04	33.6677 -78.9086	10	40	>40	Fluvial channel (Pleistocene)
Hor-05	33.6849 -78.8869	10	33	32	Peedee (Cretaceous)
Hor-07	33.7177 -78.8489	13	36	35.5	Peedee (Cretaceous)
Hor-08	33.7349 -78.8266	16	31.5	>31.5	Socastee (Pleistocene)
Hor-09	33.7460 -78.8108	21	27	>27	Shell lag (Pleistocene)
Hor-10	33.7703 -78.7718	7	33	>33	Fluvial channel (Pleistocene)
Hor-12	33.7972 -78.7237	15	38.5	37.5	Peedee (Cretaceous)
Hor-13	33.8053 -78.7068	12	29	>29	Waccamaw (Pleistocene)
Hor-14	33.8219 -78.6631	9	44	>44	Waccamaw (Pleistocene)
Hor-16	33.8452 -78.5870	8	48	38	Peedee (Cretaceous)

the Charleston Embayment. In the vicinity of Myrtle Beach, the upper Peedee surface is relatively flat except where the unit has been incised by Pleistocene fluvial channels. However, the inclination of this surface begins to increase in the vicinity of Surfside Beach where the Peedee is onlapped by the Paleocene Black MingoGroup(Figure5).

Black Mingo Group

South of Surfside Beach, cores intersected sediments of the Paleocene Black Mingo Group at depths ranging from 21 to 51 feet. The Black Mingo in this area consists of variably indurated (calcite cemented), muddy phosphatic sands and sandy clays. These sediments contain 25 to 90% silt and clay by weight, and commonly contain shell fragments and fossil molds. Shelly moldic limestone occurs as locally thin interbeds, but detailed characterization of the bedding was prevented by poor core recovery. Lithostratigraphic maps constructed by Colquhoun et al. (1983) suggest that these sediments are part of the Browns Ferry Member of the Rhems Formation. A thin interval of white sandy fossiliferous mud that unconformably overlies phosphatic sands (Geo-02) may represent the updip limit of the Lower Bridge Member of the Williamsburg Formation. The Black Mingo Group in this area represents deposition in deep siliciclastic marine shelf environments (Colquhoun *et al.*, 1983).

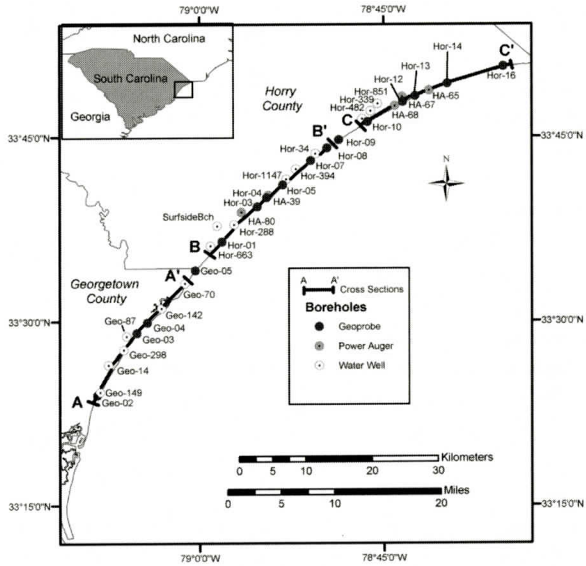

Figure 4A. Location of boreholes and cross sections.

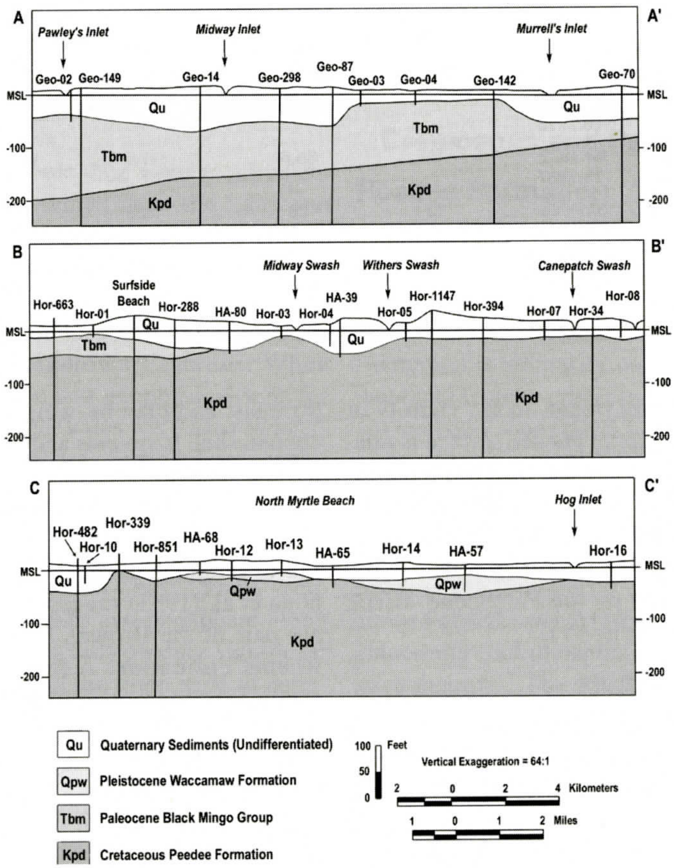

Figure 4B. Geologic cross sections of study area.

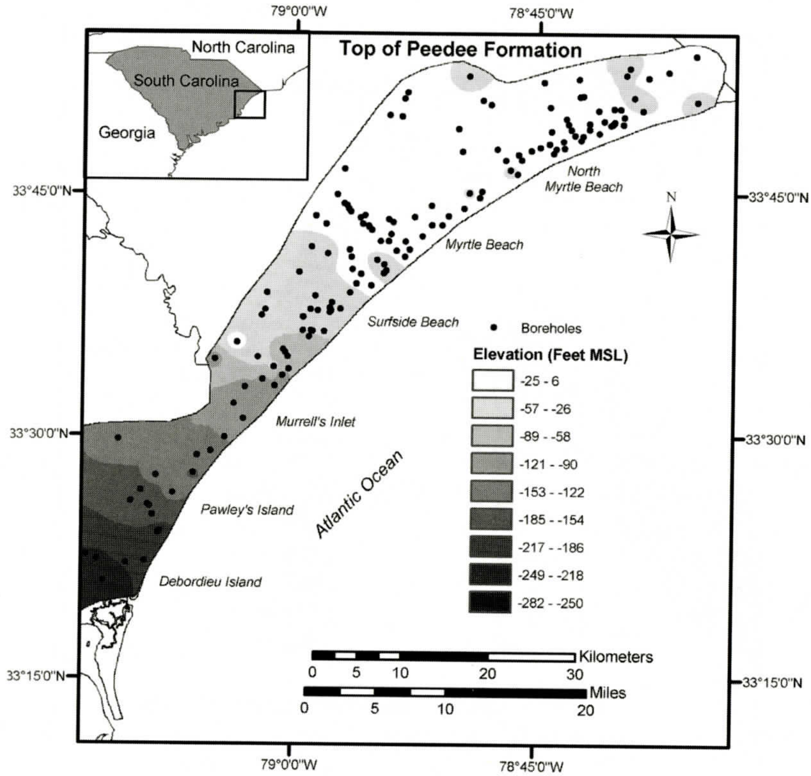

Figure 5. Structural contour map of the top of the Peedee Formation.

A regional map of the top of the Black Mingo Group (Figure 6) indicates that these sediments extend southward from the vicinity of Surfside Beach where they onlap the Cretaceous Peedee Formation. The upper surface of the Black Mingo is highly irregular due to the presence of at least three major fluvial paleochannels. Where the Black Mingo occupies interfluves between these channels it is present at elevations ranging from –11 to –22 feet (-3.4 to -6.7 m), whereas in the channel proper its elevation may be as low as –71 feet (-21.6 m).

The Black Mingo thickens to the south as the depocenter of the Charleston Embayment is approached.

Quaternary Units

Waccamaw Formation

The early Pleistocene Waccamaw Formation was intersected in three cores obtained from the northern portion of the study area (Hor-12, Hor-13, and Hor-14) at depths ranging from 20 to 32 feet. The boring at Hor-12 penetrated the Waccamaw and intersected the underlying Peedee Formation. At this locality the unit is about 12 feet (3.7 m) thick. The Waccamaw is a distinctive carbonate-rich unit that is characterized by abundant shell material. It is a light gray to white, variably indurated calcarenite containing fragments of bivalves, gastropods, encrusting bryozoans, echinoid spines and corals. Where present, the Waccamaw either appears to infill paleochannels or occurs as erosional remnants overlying the Peedee Formation. Partial induration of the unit may have made it more resistant to erosion, allowing for the preservation of erosional remnants during subsequent sea level low stand events. According to Ward *et al.* (1991) the Waccamaw Formation was deposited as shoals on a shallow shelf within a warm-temperate to subtropical sea.

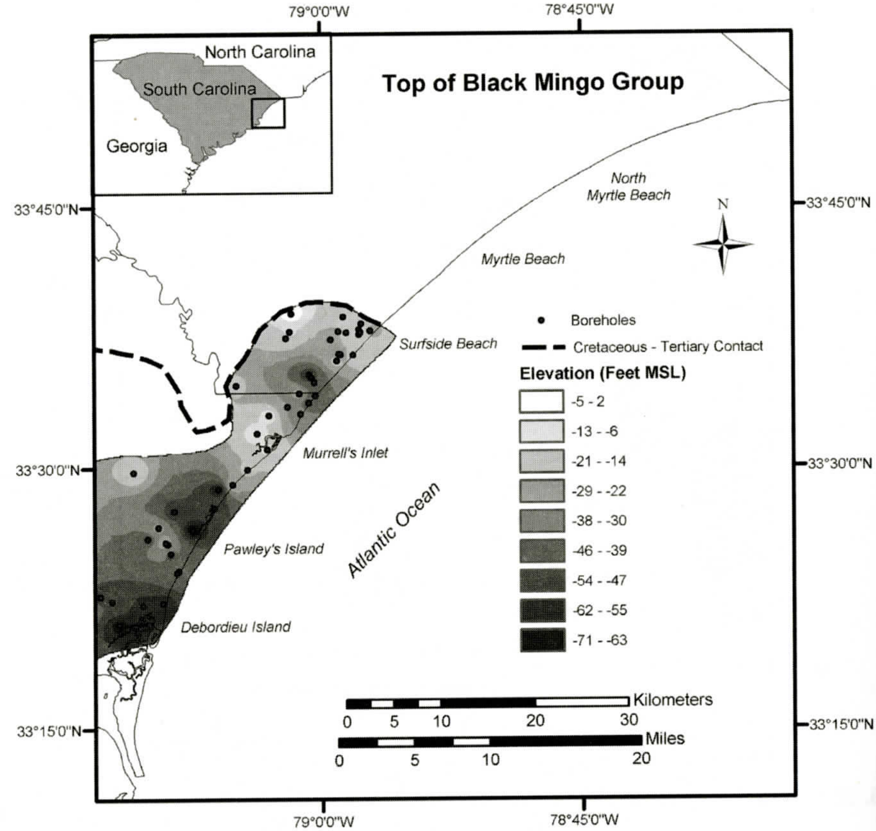

Figure 6. Structural contour map of the top of the Black Mingo Group. Cretaceous-Tertiary contact modified from Colquhoun et al. (1983).

Undifferentiated Quaternary Sediments

Younger Pleistocene sediments were deposited in a variety of depositional environments, these include; beach ridge and dune systems, back barrier tidal flat, and nearshore marine and lower shoreface deposits. The coarsest sediments consist of poorly sorted pebbly sands that appear to have infilled fluvial channels that were incised into the pre-Quaternary shelf sediments during sea level low stands. Overlying these channel fill deposits are beach and nearshore sediments related to the Myrtle Beach Barrier system. The Myrtle Beach Barrier is believed to be the youngest pre-Holocene barrier system along the Grand Strand. These lithofacies are tentatively assigned to the Socastee Formation, but definitive correlation of these sediments will require additional age dating or biostratigraphic analyses.

The youngest deposits in the study area are Holocene sediments that represent deposition in environments typical of modern barrier island systems. The youngest deposits are beach and dune sands, which locally contain peat layers. In several cores (Geo-02, Geo-03, Geo-05, Hor-16) these sands overlie Holocene sandy muds and muddy sands that were deposited in back barrier environments. Hole Geo-02, which was drilled near the southern end of Pawley's Island, intersected a tidal inlet fill sequence resulting from the lateral migration of the Pawley's Island spit.

FLUVIAL PALEOCHANNELS

A structural contour map of the base of the

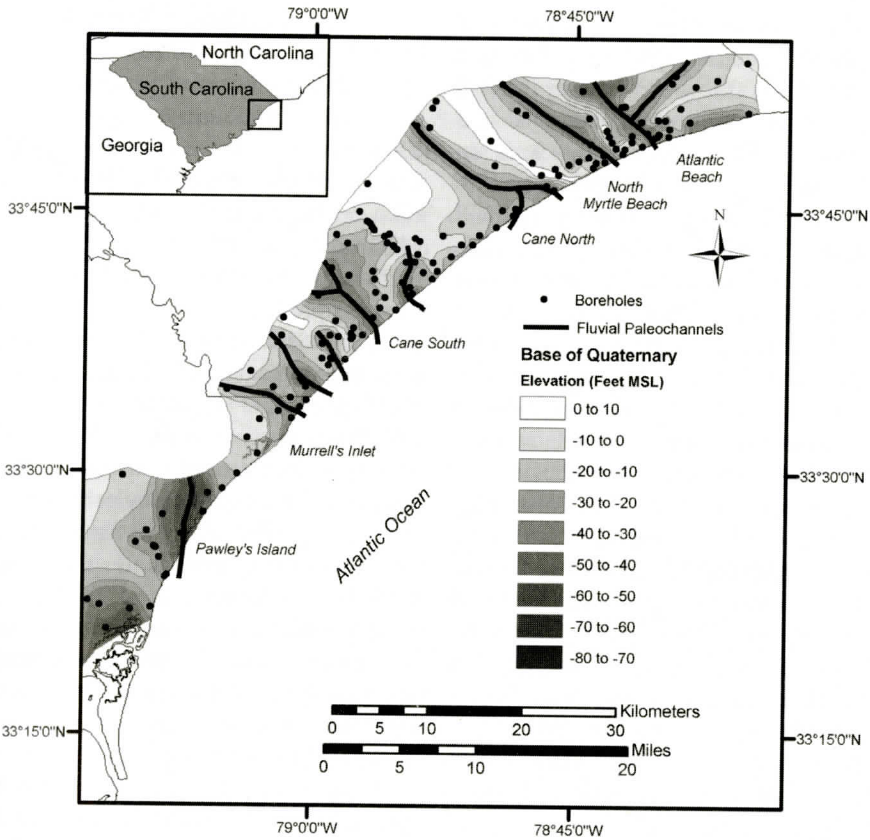

Figure 7. Location of major fluvial paleochannels along the Grand Strand.

Quaternary shows several ancient fluvial channels that underlie the Pleistocene and Holocene barrier island systems (Figure 7). Major paleoriver channels include the Pawley's, Murrell's Inlet, Cane South, Cane North, Atlantic Beach and North Myrtle Beach channels that are incised to elevations ranging from –30 to –60 feet (-9 to –18 m) relative to mean sea level. The overall depth of incision within these paleochannels appears to increase from north to south across the study area.

The channels are well-defined where there is sufficient drill hole data but the actual orientation of the channels inland is speculative due to a lack of onshore and offshore control. Fluvial drainage appears to have been to the southeast approximately perpendicular to the northeast-southwest orientation of the modern day Pee Dee and Waccamaw Rivers. This study confirms the presence of major fluvial channels entering Long Bay in the vicinity of Myrtle Beach that were first indicated on maps by Brown *et al.* (1980).

The location of onshore paleochannels and interfluves corresponds well with those identified offshore by Baldwin et al. (2002) in the southern two thirds of the study area. The north-northeast-trending Pawley's Island channel is aligned with a north-south depression (3.5-7.5 m deep) trending parallel to Debordieu and Pawley's Islands as indicated by offshore geophysical studies. The presence of this paleochannel was first identified by Domeracki (1982) who suggested that it had been formed by the ancestral Black River.

A broad interfluve separates the Pawley's Island channel from the next major paleochannel system that lies to the north and just offshore of Murrell's Inlet. Two core holes (Geo-03 and Geo-04) intersected shelly, variably indurated muddy calcareous sandstone and moldic limestone of the Paleocene Black Mingo Group at shallow depths (–20 to –22 feet elevation) in this area. The presence of these indurated fine-grained rocks may account for the lack of significant fluvial erosion in this region.

The Murrell's Inlet "channel" correlates with a zone, approximately 7.5 miles (12 km) wide, of nested incisions identified by seismic surveys on the inner shelf. These incisions are evidence for the existence of a major fluvial drainage system that once traversed this area during Pleistocene low stands. Gayes *et al.* (1992) first identified these channels and proposed that they represented an ancestral Pee Dee River valley. Baldwin (2002) also interpreted these channels as being related to the Pee Dee River, and postulated that it crossed this area up until the development of the Myrtle Beach Barrier system about 130,000 years ago. During subsequent sea level low stands the Pee Dee was diverted around the Myrtle Beach Barrier to the southwest and drained into Winyah Bay, as it does presently. Channel fill deposits intersected in cores are composed mainly of unconsolidated, poorly sorted quartz sand with rounded granules and pebbles of quartz and rock fragments, and shell material.

Another undissected interfluve occurs to the north of the Murrell's Inlet channel in the vicinity of Surfside Beach, and separates it from a small unnamed channel and the larger Cane South paleochannel located offshore of Myrtle Beach. Core hole Hor-01 was drilled into the interfluve and encountered well consolidated, slightly sandy, weakly calcareous, mudstones of the Paleocene Rhems Formation (Black Mingo Group) at an elevation of about -11 feet (-3.4 m). The formation appears to persist offshore onto the shelf where tilted and folded outcrops have been identified in seismic profiles (Baldwin *et al., 2002)*. This area is also where the Paleocene Black Mingo pinches out as it onlaps the Cretaceous Peedee Formation. The smaller and shallower channel appears to occupy the inferred projection of the Cretaceous-Tertiary contact on the shelf, while the Cane South Channel is incised into the Peedee Formation.

Core hole Hor-03 intersected clayey to silty calcareous sandstones of the Cretaceous Peedee Formation at about –14 feet (-4.3 m) elevation on a relatively narrow interfluve between the unnamed channel and the deeper Cane South Channel. Hor–04, which is located about 1.1 miles (1.8 km) north of Hor-03, appears to have been drilled along the axis of the Cane South Channel. It was drilled to a depth of 40 feet and bottomed in Pleistocene fluvial sands, failing to intersect pre-Quaternary bedrock. However the depth of this channel can be inferred from surrounding drill holes. HA-39 located 0.25 miles (0.4 km) north of Hor-04 intersected the Peedee Formation at an elevation of –50 feet (-15.2 m), and a recently drilled rotasonic core (not described here) located 0.2 miles (.3 km) south of Hor –04, was drilled to –70 feet (-21.3 m) without intersecting pre-Quaternary strata. The Cane South channel is one of the better-defined paleochannels on the inner shelf and is the deepest one identified onshore. Its proximity to the Murrell's Inlet drainage system suggests that it may also be related to the location of the ancestral Pee Dee River.

An interfluve, 4.5 miles (7.2 km) wide, separates the Cane South and Cane North Channels. Two widely spaced core holes (Hor-05 and Hor-07) intersected variably indurated, muddy, very fine-grained calcareous sandstone of the Peedee Formation at an elevation of about –22 feet (-6.7 m) along this coastal segment. Although the Cane North channel is well defined on the inner shelf, onshore its location is poorly constrained due to a lack of borehole data. Two additional paleochannels have been tentatively identified in the vicinity of Atlantic Beach and North Myrtle Beach between core locations Hor-12 and Hor-14. No corresponding paleochannels have been identified from offshore seismic data. These cores penetrated highly indurated shelly carbonate sands of the early Pleistocene Waccamaw Formation.

Hor-16, the northernmost core hole in the study area, was drilled on Waites Island, a Holocene barrier island located south of Little River Inlet. This hole intersected calcareous sandy mudstones of the Peedee Formation at an elevation of –30 feet (-9.1 m).

CONCLUSIONS

Compilation of onshore geologic data from coastal areas of Horry and Georgetown Counties confirms the presence of numerous ancient fluvial channels that were incised into older, variably indurated, fine-grained marine shelf deposits of the Cretaceous Peedee Formation and the Paleocene Black Mingo Group. These older units are a major influence on coastal erosion and accretion in the region. Offshore exposures of these stratigraphic units serve as a source of "new" sediment for the eroding coastline as well as form offshore hardgrounds that serve to divert or concentrate current and wave energy to selective coastal segments. At present major rivers (such as the Pee Dee) do not discharge into Long Bay. This is probably due to the influence of the Cape Fear Arch and the presence of Pleistocene barrier island systems that appear to have caused diversion of these rivers from their former southeasterly courses. Therefore, the only natural sediment sources for the modern beaches are from the erosion of onshore Pleistocene barrier island deposits, or from offshore fluvial channel fill and older marine shelfal deposits.

Knowledge of the geologic framework along a stretch of coastline is essential in providing a better understanding of the modern day physical processes that affect shoreline stability. The assessment of the regional framework is a necessary first step in providing the background geological information that is required to understand the response of the present day coastline to coastal erosion. High-resolution seafloor and sub-bottom mapping off the Grand Strand by the USGS has provided detailed data on the inner continental shelf and shoreface and has confirmed the presence of paleovalleys and areas of outcropping pre-Quaternary strata. In most cases, well-defined offshore fluvial incisions correlate with less well-constrained onshore paleochannels.

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THE COLLINS CREEK AND PLEASANT CREEK FORMATIONS: TWO NEW UPPER CRETACEOUS SUBSURFACE UNITS IN THE CAROLINA/GEORGIA COASTAL PLAIN

JEAN M. SELF-TRAIL

U.S. Geological Survey
926A National Center
Reston, VA 20192
jstrail@usgs.gov

DAVID C. PROWELL

U.S. Geological Survey
Peachtree Business Center
3039 Amwiler Rd., Suite 130
Atlanta, GA 30360-2824

RAYMOND A. CHRISTOPHER

Department of Geological Sciences
Clemson University
Clemson, SC 29634-1908

ABSTRACT

This paper formally defines two new Upper Cretaceous subsurface units in the southern Atlantic Coastal Plain of North Carolina, South Carolina and Georgia: the Collins Creek Formation and the Pleasant Creek Formation. These units are confined to the subsurface of the outer Coastal Plain, and their type sections are established in corehole CHN-820 from Charleston County, S.C.

The Collins Creek Formation consists of greenish-gray lignitic sand and dark-greenish-gray sandy clay and is documented in cores from Allendale, Beaufort, Berkeley, Dorchester, Jasper and Marion Counties, South Carolina, and from Screven County, Georgia. Previously, Collins Creek strata had been incorrectly assigned to the Middendorf Formation. These sediments occupy a stratigraphic position between the Turonian/Coniacian Cape Fear Formation (?) below and the proposed upper Coniacian to middle Santonian Pleasant Creek Formation above. The Collins Creek Formation is middle and late Coniacian in age on the basis of calcareous nannofossil and palynomorph analyses.

The Pleasant Creek Formation consists of olive-gray sand and dark-greenish-gray silty to sandy clay and is documented in cores from New Hanover County, North Carolina, and Berkeley, Charleston, Dorchester, Horry and Marion Counties, South Carolina. The strata of this unit previously were assigned incorrectly to the Middendorf Formation and (or) the Cape Fear Formation. These sediments occupy a stratigraphic position between the proposed Collins Creek Formation below and the Shepherd Grove Formation above. The Pleasant Creek Formation is late Coniacian and middle Santonian in age on the basis of its calcareous nannofossil and palynomorph assemblages.

INTRODUCTION

The purpose of this paper is to define and describe two new subsurface Upper Cretaceous formations in the southern Atlantic Coastal Plain of North Carolina, South Carolina and Georgia. These units are herein named the Collins Creek Formation and the Pleasant Creek Formation. These two formations are defined from a series of continuously cored, stratigraph-

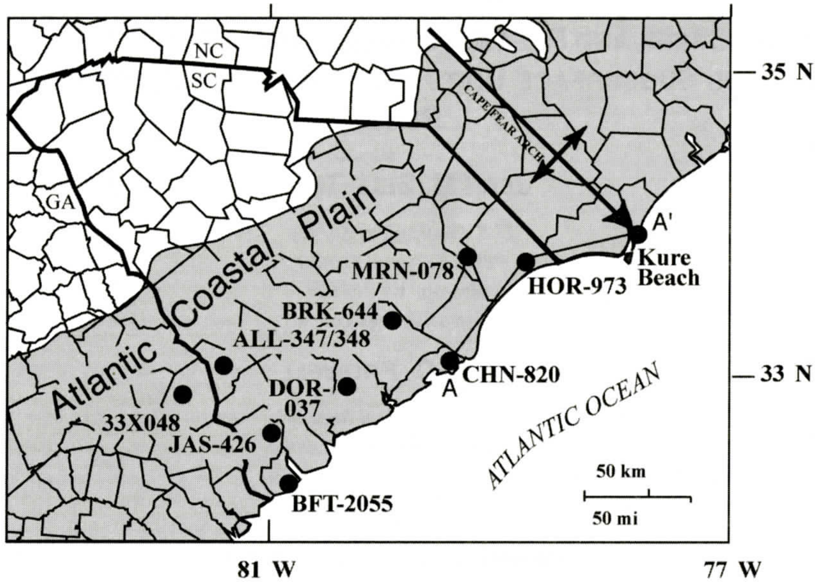

Figure 1. Map showing the location of coreholes drilled by the U.S. Geological Survey in the Atlantic Coastal Plain and utilized in this study.

ic test holes drilled under cooperative agreements between the U.S. Geological Survey, the South Carolina Department of Natural Resources (SCDNR), the North Carolina Department of Natural Resources (NCDNR), and the Georgia Department of Natural Resources (GDNR). The coreholes analyzed for this study include 33X048 in Georgia, ALL-347/348, BFT-2055, BRK-644, CHN-820, DOR-037, HOR-973, JAS-426, and MRN-078 in South Carolina, and Kure Beach in North Carolina (see Figure 1). All of these holes were continuously cored with the exception of BFT-2055 and JAS-426, which were sidewall-cored at regular intervals.

During analysis of these cores, a number of formations were identified that have no known surface exposure. One of these units, herein defined as the Collins Creek Formation, had been erroneously mistaken with the Middendorf Formation by Swift and Heron (1969), Sohl and Owens (1991) and Gohn, (1992). This fact was discovered when the type section of the Middendorf was reexamined and redefined by Prowell and others (2003). The other unit, herein defined as the Pleasant Creek Formation, was previously unrecognized as a definable formation, and it was commonly grouped with other units under a variety of names such as Middendorf or Cape Fear. The purpose of this report is to formally define and characterize these two units as new formations and offer evidence of their regional continuity.

HISTORICAL BACKGROUND

At the turn of the twentieth century, pioneers of southeastern Coastal Plain geology such as Sloan (1908), Stephenson (1923) and Cooke (1936) used both lithostratigraphy and paleontology to define broadly delineated, areally extensive formations. Since their pioneering work, and with the advent of the North American Code of Stratigraphic Nomenclature, delineation of formations in the Carolina Coastal Plain has become more rigorous. The modern definition of formations relies more heavily on regional studies that often take into account the physical attributes of the formation, its chronostratigraphy, the sedimentalogical processes involved in its deposition, and the direct influence that sea-level fluctuations have on sediment deposition patterns (e.g. Zarra, 1989; Sohl and Owens, 1991; Dockal and others, 1998; Prowell and others, 2003). Additionally, deep coring of

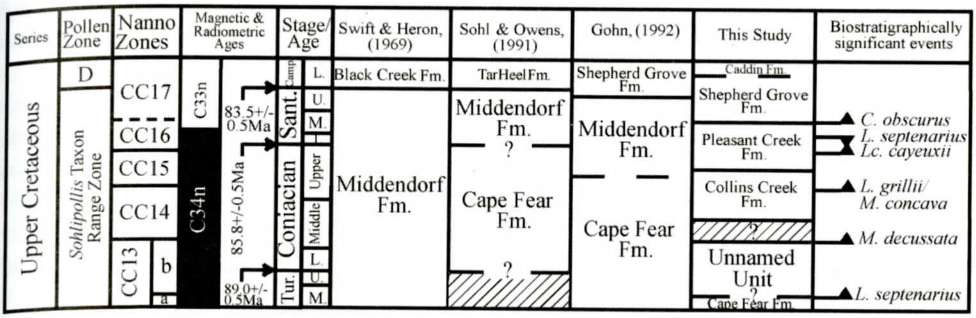

Figure 2. Correlation of calcareous nannofossil zones to Upper Cretaceous strata of South and North Carolina and to biostratigraphically significant events of the Turonian through Santonian. Note changing lithostratigraphic concepts through time. Calcareous nannofossil zones are after Sissingh (1977) and Perch-Nielsen (1985), and radiometric dates and magnetostratigraphy are from Gradstein and others, (1995). Pollen zones are after Christopher and others, (1999). Angled line pattern represents missing sediments. Question marks indicate questionable boundaries.

sediments and improved geophysical techniques have provided a means for identifying and correlating subsurface Coastal Plain formations that rarely, if ever, have surface expression (Gohn, 1992; Gohn and Campbell, 1992; Zarra, 1989; Sugarman and others, 1995; Powars and Bruce, 1999).

The sedimentary sequence herein defined as the Collins Creek Formation was originally included in the Middendorf Formation of Hazel and others (1977), Gohn and others (1977), Aucott and others (1987), Sohl and Owens (1991), Gohn (1992), Castro and others (1995), Self-Trail and Bybell (1997),Temples and Engelhardt (1997), and Falls and Prowell (2001), and in the Pio Nono Formation of Huddlestun and Hetrick (1991). An unnamed sedimentary sequence described by Kuntz and others (1989) from the ALL-347/348 well also is relegated to the Collins Creek Formation (Figure 2). Sediments here assigned to the Collins Creek in BRK-644 and CHN-820 have not been previously described. Examination of additional cored wells from Aiken, Florence and Orangeburg Counties, including several from the western part of the Savannah River Site (SRS), show that the Collins Creek is absent at these localities.

The sedimentary sequence herein defined as the Pleasant Creek Formation was originally included in the Black Creek Formation of Hazel and others (1977), Aucott and others (1987), and Hattner and Wise (1980), in the Middendorf and Shepherd Grove Formations of Gohn (1992) and Christopher and others (1999), and in the Middendorf Formation, Shepherd Grove Formation, and Black Creek Group of Gohn and others (1992). Sediment descriptions of the Pleasant Creek Formation in coreholes BRK-644, CHN-820, and Kure Beach were heretofore unpublished.

DEFINITION OF FORMATIONS

The Collins Creek and Pleasant Creek Formations are herein defined from corehole CHN-820 (Santee Coastal Reserve #2) in northeastern Charleston County, S.C. The exact location of the CHN-820 drill site is 33°09'10"N latitude and 79°21'30"W longitude; the land surface elevation is 9.91 ft. The core is stored at the South Carolina Geological Survey core storage facility in Columbia, South Carolina as of 2003.

Collins Creek Formation (Type Locality)

The type section of the Collins Creek Formation in corehole CHN-820 is designated as the 89.7 ft of strata recovered above the top of the Cape Fear Formation (?), starting at 1,511.2 ft (-1,501.3 ft msl) up to the base of the newly defined Pleasant Creek Formation at 1,421.5 ft (-1,411.6 ft msl) (Figure 3A). The name of the

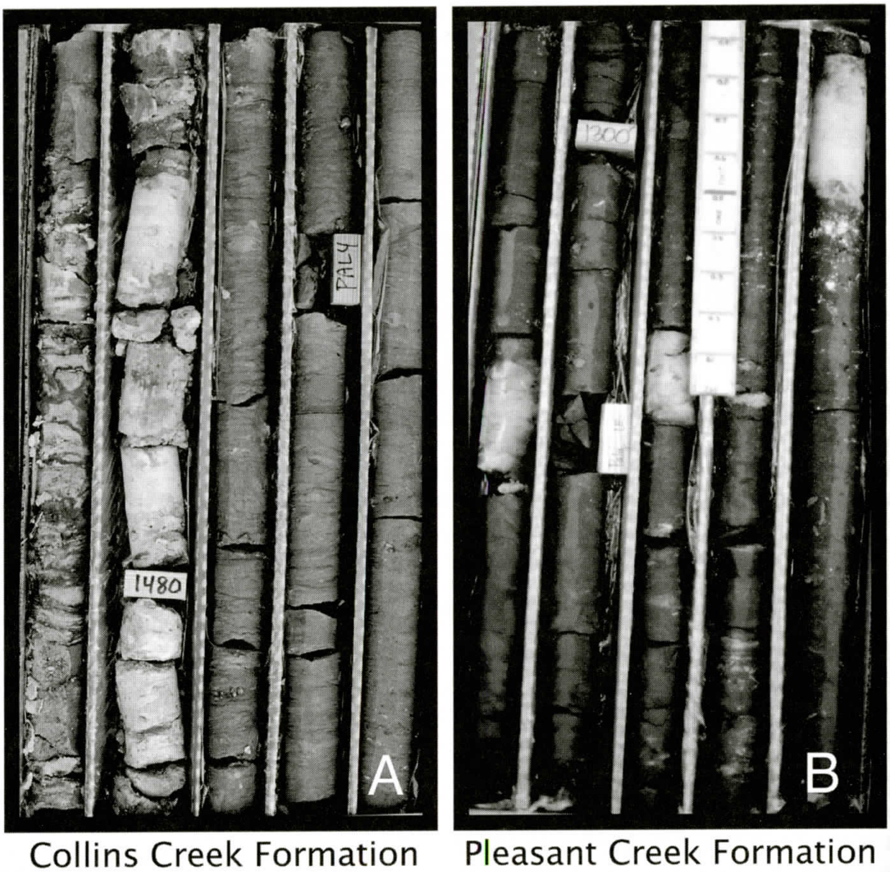

Figure 3. Core samples from the Collins Creek and Pleasant Creek Formations. A, lignitic sand and sandy clay of the Collins Creek Formation. B, Silty to sandy clay of the Pleasant Creek Formation. Top is to the left and up; bottom to the right and down.

formation is taken from Collins Creek, located approximately 1.5 miles northwest of the CHN-820 drill site in the Santee 1:24,000 topographic quadrangle.

The interval from 1,511.2 to 1,520.0 ft in the CHN-820 drill hole is one of core loss and no geophysical logs are available at this depth. This core loss means that the contact with the underlying Cape Fear Formation (?) and the basal few feet of Collins Creek strata cannot be described at the type section. Elsewhere, the contact between the Cape Fear (?) and the Collins Creek is abrupt and generally lacks an extended lag bed of reworked strata, although a small basal bed consisting of large quartz pebbles is commonly present. The interval from 1,300.0 ft to 1,301.6 ft of the Collins Creek Formation in BRK-644 is typical of the basal contact with the Cape Fear Formation (?).

Above the short unrecovered section, the basal Collins Creek Formation consists of poorly-sorted, lignitic, fine- to coarse-grained sand with (locally) up to 10 percent mica, sparse glauconite, and pyrite nodules. This sand contains thin, wavy clay seams similar to flaser bedding commonly associated with shallow water marine environments. Above the basal lignitic sand, the type Collins Creek is generally a sandy clay grading upwards into clayey sand. The sandy clay that is common in the lower part of the formation is massive and dark-greenish gray, with approximately 10 percent fine-grained sand. Accessory minerals include mica, glauconite, opaque heavy minerals, and small pyrite nodules. Shell fragments are common, and some beds are strongly bioturbated. Burrows are commonly backfilled with sand. This bioturbation produces a mottled texture, which tends to obscure the horizontal bedding. Calcareous microfossils are also abundant in the fine-grained strata. Cemented zones up to 2 feet thick, consisting of sand and abundant shells in a calcite cement, are present throughout the lower half of the formation. These cemented zones most likely represent shell lag deposits that were indurated by secondary calcium carbonate. The characteristics described above suggest that the sandy clay facies of the Collins Creek Formation represents a continental shelf depositional environment.

The sandy clay beds described above alternate with olive-gray, lignitic sands similar to the basal sand. The lignitic sand beds are composed of moderately to well sorted, sub-angular to sub-rounded, fine- to medium-grained quartz sand. Accessory minerals include a few percent of mica, glauconite, and sparse pyrite nodules. Fine lignite typically forms about 5 percent of the matrix, but it can be as high as 30 percent, changing the typical olive-gray color of the strata to greenish-black. Thin clay seams provide a wavy appearance to the overall bedding, and crossbedding was observed in the thicker sand beds. The lignitic sand beds predominate in the upper part of the formation, which is generally free of calcium carbonate. These lignitic sands most likely reflect deposition in a restricted marine depositional environment where tidal effects are prevalent (Figure 3A).

The Collins Creek Formation tends to alternate between sediments formed in restricted marine and shallow marine depositional environments, with the former dominating in the upper strata of the formation. The only major change in the bulk mineral assemblage is that the calcium carbonate in the lower half of the formation gives way to abundant finely disseminated lignite in the upper half of the formation. This shift from calcium carbonate to lignite is indicative of increasing proximity to a terrestrial sediment source; an interpretation supported by the upsection trend in bulk grain size from finer to coarser.

The presence of calcareous microfossils, shell fragments, horizontal beds, and strong bioturbation in the sandy clay beds in the lower part of the formation suggest deposition in an open-marine environment such as a shallow shelf or delta front. These sandy clay beds alternate with sands that exhibit (1) a dominance of sedimentary structures such as wavy bedding and crossbedding over biogenic features, (2) a complete absence of marine micro- and macrofossils, (3) a general absence of calcium carbonate, and (4) a large influx of lignitic material, which suggests a marine depositional environment of fluctuating current velocity and a terrestrial sediment source that encroached on the area of the CHN-820 drill site. This suite of sediments appears to represent a restricted marine paleoenvironment that prograded into a shallow marine environment on the continental margin, possibly in concert with a fluctuation and/or overall regression of sea level. An alternative, but less likely, scenario is that the absence of carbonate-producing fossil remains and the general paucity of calcium carbonate in the sands could be an effect of differential leaching and thus this section could represent a regressive section where lignitic sand is episodically washed onto the shelf.

Pleasant Creek Formation (Type Locality)

The type section of the Pleasant Creek Formation in CHN-820 is designated as the 237 ft of strata between the top of the proposed Collins Creek Formation at 1,421.5 ft (-1,411.6 ft msl) and the base of the Shepherd Grove Formation at 1,184.5 ft (-1,174.6 ft msl) (Figure 3B). The name of the formation is taken from Pleasant Creek, located approximately 0.75 miles north-northeast of the CHN-820 drill site in the Minim Island 1:24,000 topographic quadrangle.

The basal contact of the Pleasant Creek Formation with the underlying Collins Creek Formation is sharp. Directly overlying this contact is a 0.5-ft-thick bed of phosphate pebbles, coarse quartz sand, and sparse well-rounded garnets in a silica-cemented matrix. This basal bed is interpreted as an erosional lag deposit. The immediately overlying beds consist of 35 ft of poorly-sorted, sub-angular to angular, fine- to coarse-grained quartz sand containing minor amounts of glauconite and trace amounts of mica and dark heavy minerals. Silica-cemented zones, from 0.5 ft to 1.5 ft thick and consisting of sand with sparse shell material, are scattered throughout the basal Pleasant Creek. These are most prevalent in the basal 5 feet of the section. This basal sand is massive and contains rare specimens of the oyster *Ostrea cretacea*.

Above the basal sand, the Pleasant Creek consists of 201.5 ft of dark greenish-gray sandy to silty clay. The contact between this upper clay and the underlying sand is sharp and distinct, with trace amounts of phosphate present. An abrupt increase in the gamma radiation detected on geophysical logs correlates with this lithologic change. The clay in the upper part of the Pleasant Creek is dry and tight and has a distinct conchoidal fracture when broken. It contains up to 25 percent of well sorted, fine- to very-fine grained quartz sand and silt and up to 3 percent mica and trace amounts of glauconite and pyrite. Many beds are intensely bioturbated and consequently have a massive appearance (Figure 3B). Shell fragments are common throughout, locally up to 20 to 30 percent in concentrations, and often have a nacreous luster. Calcium carbonate indurated beds of sand, silt and shell fragments up to 3 ft thick are common throughout the upper section of the formation. Microfossils (benthic foraminifera and ostracodes) are visible in trace amounts.

The sand beds at the base of the Pleasant Creek Formation are shallow marine in origin, as indicated by the presence of *Ostrea cretacea* and sparse amounts of glauconite. These deposits formed shortly after late sea-level lowstand and are limited in subsurface extent, occurring in CHN-820, BRK-644 and HOR-973. Subsequent flooding caused by rapid sea-level rise during the transgressive phase resulted in the deposition of the sandy, silty marine clay that comprises the bulk of the Pleasant Creek Formation. The presence of calcareous microfossils, shell fragments, texture mottling, and bioturbation all suggest deposition in a middle- to outer-neritic paleoenvironment for the bulk of Pleasant Creek sediments.

BIOSTRATIGRAPHY

Collins Creek Formation

Paleontological evidence suggests that the Collins Creek Formation was deposited during the middle to late Coniacian (Late Cretaceous). Calcareous nannofossils and palynomorphs were recovered from samples spanning the entire formation.

Calcareous Nannofossils

Eight cores from the Georgia and South Carolina Coastal Plain penetrated the Collins Creek Formation, but only two cores (CHN-820 and JAS-426) yielded calcareous nannofossils. Preservation of nannofossil assemblages is moderate to poor. The sediments of the remaining six cores (ALL-347/348, BFT-2055, BRK-644, DOR-037, MRN-078, and 33X048) were barren of calcareous nannofossils due to an inhospitable depositional paleoenvironment and perhaps to diagenetic leaching of carbonate.

Basal Collins Creek sediments are assigned to middle to late Coniacian calcareous nannofossil Zone CC14 based on the presence of *Micula decussata*, the basal Zone CC14 marker species, and on the absence of *Reinhardtites anthophorus* and *Micula concava*, marker species for Zone CC15. Calcareous nannofossil assemblages in the Collins Creek Formation are typically sparse, most likely due to the nearshore depositional environment of the sediments.

The first occurrence of *R. anthophorus* and *M. concava* at 1,460.3 ft in CHN-820, along with the co-occurrence of *Lithastrinus septinarius* and the absence of *Lucianorhabdus cayeuxii*, the basal Zone CC16 marker species, place the interval from 1,460.3 ft to 1,415.6 ft in late Coniacian Zone CC15. However, one of the basal Zone CC15 marker species, *Lithastrinus grillii*, is noticeably absent from the Collins Creek and does not occur at CHN-820 until higher in the section. This interval is absent or non-diagnostic from other cores in the study area.

Palynomorphs

Palynomorphs were examined from five

cores encountering the Collins Creek in South Carolina (ALL-347/348, BFT-2055, DOR-037, JAS-426, and MRN-078). Palynomorph assemblages in the formation are assigned to the *Sohlipollis* Taxon Range Zone of Christopher and others (1999), equivalent to pollen Zone V of Doyle (1969), based on the presence of the genus *Sohlipollis* (formerly *Porocolpopollenites* spp.). The Collins Creek Formation was not examined for palynomorphs in cores 33X048 (Screven County, GA) and BRK-644 (Berkely County, SC). However, this unit in BRK-644 is inferred to belong in the *Sohlipollis* Zone because it is bracketed by samples from the Cape Fear Formation (?) below and the Pleasant Creek Formation above that contain assemblages consistent with that pollen zone.

Sidewall core samples from BFT-2055 between 2,775.0 ft and 2,494.0 ft contain specimens of *Complexiopollis* spp. and *Sohlipollis* spp., which indicate assignment to the *Sohlipollis* Zone. The presence of *Sohlipollis* spp. at 1,451 ft in ALL-347/348 also places this sample within that zone.

Summary

Calcareous nannofossils from the Collins Creek Formation are from Zones CC14 and CC15, which span the Coniacian-Santonian Stage boundary of the Late Cretaceous according to Perch-Nielsen (1985); however, Burnett (1998) and Lees (2002) incorporate both of these zones within their Coniacian Stage. The Coniacian-Santonian boundary is not well-documented, and there is some confusion in the literature as to precisely where calcareous nannofossil biostratigraphic events fall with regard to this boundary. Herein, we follow the chronostratigraphy of Burnett (1998) and Gradstein and others (1995), who place the boundary at 85.8 Ma (Figure 2) and calcareous nannofossil Zones CC14 and CC15 in the Coniacian.

Palynomorphs place the Collins Creek Formation in the *Sohlipollis* Taxon Range Zone of Christopher and others (1999; equivalent to pollen zone V of Doyle, 1969), which begins in the mid-Turonian and terminates near the top of the Santonian Stage of the Late Cretaceous. Thus, both fossil groups are compatible with one another and a Coniacian age can be assigned to the Collins Creek Formation based on the more refined nannofossil zone placement.

Pleasant Creek Formation

Paleontological evidence suggests that the Pleasant Creek Formation was deposited in the late Coniacian to middle Santonian. Calcareous nannofossils, palynomorphs, and macrofossils were recovered from samples spanning the entire formation.

Calcareous Nannofossils

Zone CC16 is defined as the interval from the first occurrence of *Lucianorhabdus cayeuxii* to the first occurrence of *Calculites obscurus* (Figure 2). However, Burnett (1998) documents that *Lucianorhabdus* preferred relatively shallow-water conditions, making correlation between temporally equivalent oceanic settings and epeiric seas difficult due to a diachronous first occurrence. Consequently, the base of Zone CC16 often is not a discrete temporal boundary. Five cores from South Carolina (BRK-644, CHN-820, DOR-037, HOR-973, MRN-078) and one core from North Carolina (Kure Beach core) penetrated Upper Cretaceous sediments of the Pleasant Creek Formation. Basal Pleasant Creek sediments are assigned to calcareous nannofossil Zone CC15 based on the occurrence of *Lithastrinus grillii* and (or) the occurrence of *Micula concava* (both used to delineate the base of Zone CC15) and on the concurrent absence of *Lucianorhabdus cayeuxii*, the basal marker species for Zone CC16. *Eprolithus floralis* is commonly present in these basal sediments, as is *Lithastrinus septinarius*, but *E. floralis* occurs only rarely above the basal section, and thus is a useful proxy for identifying basal Zone CC15 sediments. Originally, Perch-Nielsen (1985) used the first occurrence of *Reinhardtites anthophorus* to define the base of Zone CC15. However, Bralower and others (1995) and Burnett (1998; personal comm.), questionably place the first occurrence of *Reinhardtites anthophorus* much earlier in the Turonian; thus the first occurrence of this species is not considered to be a reliable marker.

The occurrence of *L. cayeuxii* in the Pleasant Creek Formation is sporadic in HOR-973 and MRN-078, and *L. cayeuxii* doesn't appear until after the first occurrence of *Calculites obscurus* (the Zone CC17 basal zonal marker) in BRK-644 and DOR-037. This suggests a hiatus in BRK-644 at 1,083.0 ft and possibly between 1,750.0 and 1,719.0 ft in DOR-037, although most of this interval was not recovered during drilling. Background species and events useful in documenting Zone CC16 include the last occurrence of *Lithastrinus septinarius*, which occurs in mid-Zone CC16 in CHN-820, HOR-973, and Kure Beach, the presence of *Flabellites oblongus* which occurs in CHN-820, HOR-973 and Kure Beach, and the first occurrence of *Gartnerago* sp. A near the top of the zone, which is present in CHN-820 and Kure Beach. Perch-Nielsen (1985) used the last occurrence of *Eprolithus floralis* as a proxy marker for the top of Zone CC16, but Varol (1992) documented its last occurrence just above the base of CC16, near the Coniacian/Santonian boundary. In CHN-820, HOR-973, and DOR-037, the last occurrence of *E. floralis* occurs near the base of the Pleasant Creek Formation, barely into Zone CC16, and therefore corroborates the findings of Varol (1992). Therefore, calcareous nannofossil assemblages from the Pleasant Creek Formation are assigned predominantly to Zone CC16 of Sissingh (1977) and Perch-Nielsen (1985), although the base of the formation in the type section may be assigned provisionally to Zone CC15.

Palynomorphs

Palynomorphs were examined from the Pleasant Creek Formation in five cores in South Carolina (BRK-644, CHN-820, DOR-037, HOR-973, and MRN-078). Assemblages from these cores are assigned to the upper part of the *Sohlipollis* Taxon Range Zone of Christopher and others (1999) based on the presence of the genus *Sohlipollis*. The *Sohlipollis* taxon range zone is equivalent to pollen Zone V of Doyle (1969) and Christopher (1977, 1979), which starts in the mid-Turonian and ends near the top of the Santonian Stage of the Late Cretaceous.

Macrofossils

Whole specimens of *Ostrea cretacea*, a small marine mollusk associated with Santonian calcareous nannofossil Zone CC16 (Puckett, 1994), are reported from the CHN-820, DOR-037, and HOR-973, cores in South Carolina and from the Kure Beach core in North Carolina. In the CHN-820 and DOR-037 cores, this species occurs at the base of the Pleasant Creek within calcareous nannofossil Zone CC15 and thus is representative of the latest Coniacian. In HOR-973, between 876 and 848 ft, *O. cretacea* occurs near the middle of the Pleasant Creek Formation in Zone CC16. A questionable specimen of *O. cretacea* is recorded from the Kure Beach core at 982 ft, within Zone CC16.

Summary

Calcareous nannofossil assemblages from the Pleasant Creek Formation are assigned predominantly to Zone CC16 of Sissingh (1977) and Perch-Nielsen (1985), although assemblages near the base of the formation may be assigned provisionally to Zone CC15. This zonal assignment places the bulk of the Pleasant Creek strata in the Santonian Stage of the Late Cretaceous, but the Pleasant Creek may extend down into the late Coniacian. Palynomorphs place the Pleasant Creek Formation in the *Sohlipollis* Taxon Range Zone of Christopher and others (1999), which begins in the middle of the Turonian and terminates at the top of the Santonian Stage of the Late Cretaceous. The presence of *Ostrea cretacea* suggests placement of the middle part of the Pleasant Creek Formation in the Santonian. Thus, the three fossil groups are compatible with one another and a late Coniacian to middle Santonian age can be assigned to the Pleasant Creek based on the more refined nannofossil zone placement.

REGIONAL CHARACTERISTICS AND DISTRIBUTION

Recognition of the Collins Creek and Pleasant Creek Formations in coreholes across 200 miles of the Coastal Plain indicates that these formations are extensive and laterally continuous lithologic units. The changing lithologic

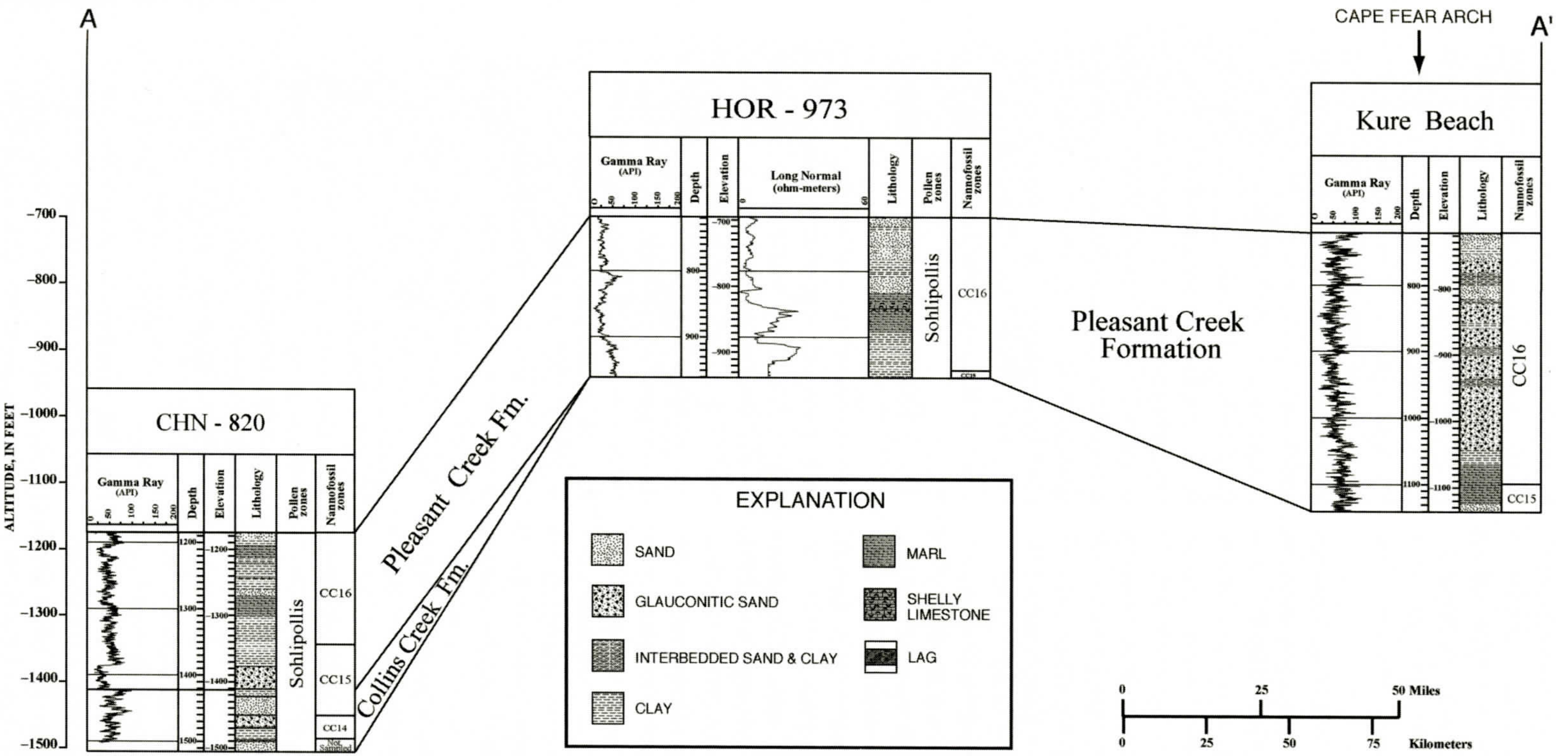

Figure 4. Cross-section showing thickness and lithology of the Collins Creek and Pleasant Creek Formations across the southern Cape Fear arch. Palynomorph and calcareous nannofossil zones are shown for comparison. Resistivity and long normal logs are not available for CHN-820 and the Kure Beach corehole. Note the increase in thickness of the Pleasant Creek Formation at the expense of the Collins Creek Formation in the Kure Beach corehole. Datum level is sea level.

character of these formations between the coreholes illustrates that they contain a number of different depositional facies. A summary of the facies characteristics and information about the distribution of the formations and their facies can be found in the maps presented in the following sections.

The relationship between the two formations is illustrated by a geologic cross-section through coreholes CHN-820, HOR-973, and Kure Beach (Figure 4). The prominent features of this section are: (1) the great increase in elevation of the formations from southwest to northeast, (2) the thickening of their combined sections from southwest to northeast, and (3) the extreme thickening of the Pleasant Creek Formation in HOR-973 and Kure Beach at the expense of the Collins Creek strata.

The increase in elevation of the formations is the direct result of uplift along the Cape Fear arch (Figure 1), whose northwest-southeast axis is near Kure Beach (Prowell and Obermeier, 1991). This arching began sometime in the Late Cretaceous and continued well into the Tertiary (Owens and Gohn, 1985; Gohn, 1988; Colquhoun and Muthig, 1991; Harris and Zullo, 1991; Ward and others, 1991). However, the thickening of the total stratigraphic section from southwest to northeast indicates that the region surrounding the Cape Fear arch was a depocenter during Coniacian and Santonian time. Hence, an area of subsidence and deposition was subsequently transformed into a broad arch by crustal tectonism (Prowell and Obermeier, 1991).

While thickening of the total stratigraphic section suggests this region was a depocenter during the Coniacian and Santonian, the extreme localized thickening of the Pleasant Creek Formation in CHN-820, HOR-973 and Kure Beach at the expense of the Collins Creek strata is most likely due to post-depositional erosion of the Collins Creek. Two methods of erosion present viable scenarios. Erosion could have occurred with the onset of Pleasant Creek sedimentation. Swift marine currents sweeping along the continental shelf could have resulted in downcutting and erosion of the Collins Creek strata, with subsequent infilling of the channel occurring during transgression of the Pleasant Creek sea. Alternatively, evidence of valley cutting (see following sections) suggests that landscape development on the top of the Collins Creek Formation probably occurred during a low stand of the sea prior to the transgression of the Pleasant Creek sea. Therefore, a disconformity is most likely present between the Collins Creek and Pleasant Creek Formations even though its presence cannot be confirmed paleontologically. The paleovalley at Kure Beach is by far the most prominent of the topographic lows, suggesting that a large incised river system possibly existed in southern North Carolina during the early Late Cretaceous. However, although evidence favors valley cutting as the most likely scenario, it is impossible to determine the exact method of channeling based on evidence from only one (Kure Beach) corehole.

Collins Creek Formation

The subsurface Collins Creek Formation strikes roughly east-west and dips southward (Figure 5A). It is present only in the seaward third of the Coastal Plain and extends eastward from Georgia to a point near the South Carolina – North Carolina state line at the modern shoreline (Figure 5A). The thickness of the Collins Creek Formation varies from 39 ft in corehole 33X048 in Georgia to a maximum of 248 ft in well BFT-2055 in southernmost South Carolina (Table 1). The thickness, however, is variable across the region with a locally thickened section at BRK-644 (Figure 5B). The shape of this thickened section suggests that infilling of preexisting topography may have influenced the present geometry of the Collins Creek. Irregularity of the inner margin of the Collins Creek Formation suggests that erosion of the formation during a subsequent regressive cycle was also a prominent mechanism in determining the present thickness of the formation (Figures 5A & 5B).

The Collins Creek Formation is an unconformity-bounded unit that consistently overlies the Cape Fear Formation (?) throughout its geographic extent in South Carolina and Georgia, so far as known. The Collins Creek Formation

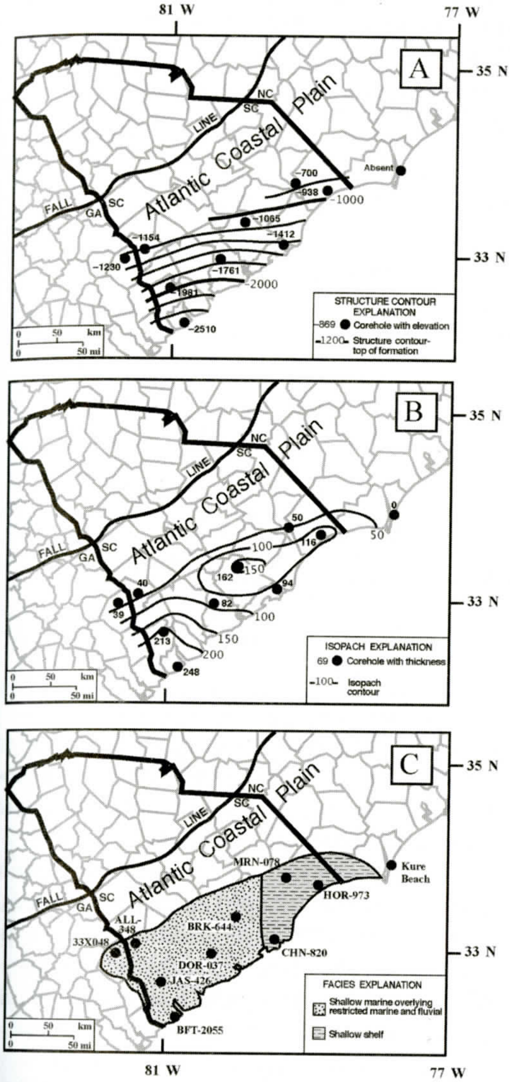

Figure 5. Map showing the known subsurface extent of the Collins Creek Formation: (A) Structure contours show altitude of the top of the formation. Contour interval is 200 ft and datum is sea level. Numbers adjacent to corehole locations show precise altitude of the top of the formation in that locality. (B) Isopach lines show thickness of formation. Contour interval is 50 ft. Number adjacent to corehole indicates exact thickness of formation in that locality. (C) Generalized facies map.

is overlain by the Pleasant Creek Formation throughout this same region, except in western South Carolina and easternmost Georgia. The contact between the Collins Creek and the Pleasant Creek is typically sharp and commonly lacks an obvious lag bed except in CHN-820 and BRK-644. The Collins Creek type section typically consists of sands or clayey sands overlying sandy clays (BRK-644, DOR-037). However, at the type locality (CHN-820) the Collins Creek-Pleasant Creek contact occurs between a sand and a cemented zone. The surface is not obviously disconformable, and it is unclear how much time is missing across this boundary.

In Allendale County, SC (well ALL-347/348) and in Screven County, GA (well 33X048), the updip limit of the Collins Creek is overlain by the Cane Acre Formation (Falls and Prowell, 2001). The disconformable contact with the Cane Acre is between a clayey sand below and a sand above. In Beaufort County (well BFT-2055) and Jasper County (well JAS-426), the Collins Creek probably is overlain by the Shepherd Grove Formation. The available data are inadequate to make a precise determination of the formations in these wells. The contact with the Shepherd Grove Formation is placed at a shift on the geophysical logs in BFT-2055 (Temples and Engelhardt, 1997), but this change in geophysical signatures is less obvious in JAS-426 (Self-Trail and Bybell, 1997).

The Collins Creek Formation is interpreted to represent restricted-marine and shallow-marine paleoenvironments (Figure 5C). In BRK-644, basal sediments are poorly sorted restricted marine sands. Above this basal sand are lignitic sands of restricted marine (estuarine?) origin. This facies is prominent at the base of the formation in all of the observed drill hole cores, with the exception of BRK-644. Above this basal lignitic sand, tongues of fossiliferous shallow-marine sandy clay are interbedded with the lignitic sand. Therefore, an encroaching sea probably buried the shallower water deposits, possibly in ancient valleys, and then experienced episodic fluctuations until its final retreat from the region.

Examination of marine microfossils and palynomorphs from cores in South Carolina and Georgia corroborates this interpretation. The Collins Creek Formation is barren of calcareous nannofossils in ALL-347/348, BFT-2055, BRK-644, DOR-037, MRN-078, and 33X048.

Table 1. Thickness of the Collins Creek Formation in coreholes from South Carolina and Georgia. Included are latitude and longitude coordinates of coreholes discussed in text and top and base of the formation in the subsurface. Depth and thickness in feet.

DNR #	Name	Latitude (N)	Longitude (W)	Depth (top)	Depth (base)	Thickness
ALL-348	DNR/DOE C10A	33° 01' 30"	81° 23 '03"	1436.0	1475.5	39.5
BFT-2055	Hilton Head Water test	32° 11' 29"	80° 42'14"	2520.0	2768.0	248.0
BRK-644	USGS/DNR St. Stephen	33° 24' 15"	79° 56' 04"	1140.0	1301.6	161.6
CHN-820	USGS Santee Coastal Reserve #2	33° 09' 10"	79° 21' 30"	1421.5	1515.0	93.5
DOR-037	USGS Club-house Cross-roads 1	32° 53' 17"	80° 21' 33"	1779.0	1861.0	82.0
JAS-426	DNR/DOE C15	32° 37' 04"	80° 59' 45"	2044.0	2257.0	213.0
MRN-078	USGS Brittons Neck	33° 51' 27"	79° 19' 30"	730.0	780.0	50.0
33X048	USGS Mill-haven	32° 53' 25"	81° 35' 43"	1340.0	1379.0	39.0

Hazel and others (1977) report the absence of ostracodes, foraminifera, and calcareous nannofossils from what is now redefined as the Collins Creek Formation in DOR-037, but record the presence of pollen and sparse dinoflagellates. This indicates a very nearshore, brackish-water environment of deposition. Temples and Englehardt (1997) and Christopher (this report) report a palynomorph assemblage characteristic of the lower Santonian from BFT-2055, but this interval is barren of calcareous marine fossils. Christopher (this report) reports that samples examined from BFT-2055 contain significant numbers of marine palynomorphs, and that fluctuating organic matter is indicative of oscillations between open marine and nearshore conditions.

Even in Collins Creek sections that contain marine microfossils (CHN-820 and JAS-426), populations are sparse and species richness is moderate to low. This paucity of marine microfossils often indicates a nearshore, marginal-marine setting. Calcareous nannofossils typically do best in outer neritic to bathyal settings, and planktonic foraminifera flourish only in water depths greater than 600 ft. In nearshore settings, species richness of calcareous nannofossils declines considerably and planktonic foraminifera are typically absent.

Thus, the depositional history of the Collins Creek Formation is one of alternating restricted marine sedimentation and shallow marine deposition. The abundance of carbonaceous material (kerogen and lignite) identified from examination of core material, bedding structures and mica suggests deposition occurred very near a terrestrial source that alternately was flooded by seawater and subaerially exposed.

Pleasant Creek Formation

The Pleasant Creek Formation is a subsurface unit that strikes roughly east-west and dips to the south (Figure 6A). Drill hole data indicate that it extends westward from Kure Beach, North Carolina to east-central South Carolina. The Pleasant Creek Formation was not identified in southernmost South Carolina or Georgia, but this may be the result of the selective

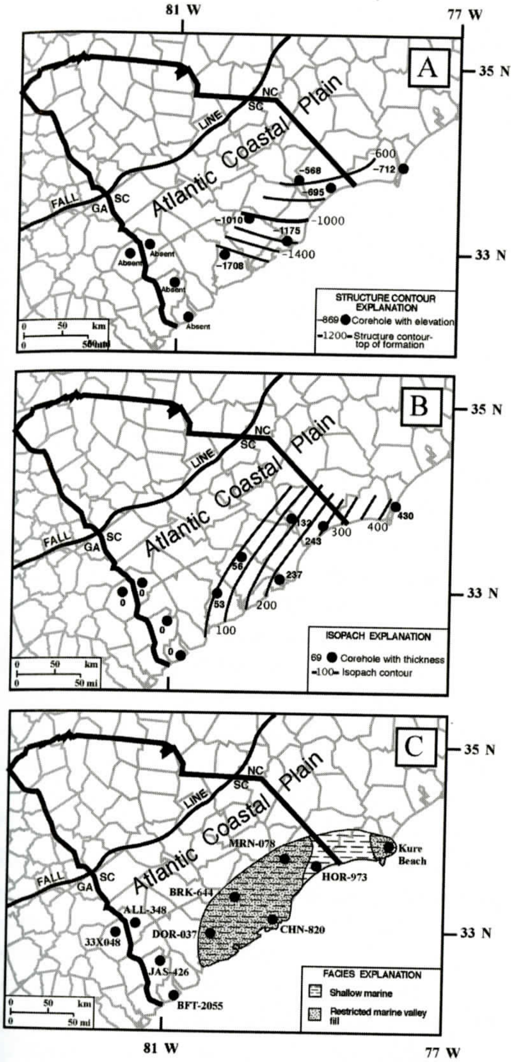

Figure 6. Map showing the known subsurface extent of the Pleasant Creek Formation. (A) Structure contours show altitude of the top of the formation. Contour interval is 200 ft and datum is sea level. Numbers adjacent to corehole locations show precise altitude of the top of the formation in that locality. (B) Isopach lines show thickness of formation. Contour interval is 50 ft. Number adjacent to corehole indicates exact thickness of formation in that locality. (C) Generalized facies map.

sidewall-core samples from the BFT-2055 and JAS-426 wells. The thickness of the Pleasant Creek Formation varies from 53 ft in well DOR-037 in South Carolina to a maximum of 429.6 ft in the Kure Beach well in North Carolina (Figure 6B; Table 2).

The Pleasant Creek Formation overlies the Collins Creek Formation throughout most of its extent in South Carolina, but it overlies the Cape Fear Formation (?) in HOR-973 and an unnamed unit in North Carolina at Kure Beach. The contact between the Pleasant Creek and the Collins Creek appears sharp wherever it was recovered in cores. The contact with the unnamed unit in North Carolina is sharp with a bed of coarse conglomerate (lag) forming the lower 2 ft of the Pleasant Creek. The Pleasant Creek is overlain by the Shepherd Grove Formation throughout its entire geographic extent. The upper contact of the Pleasant Creek with the Shepherd Grove is an erosional transgressive-marine disconformity that probably represents less than 1.0 m.y. of missing time.

In the broadest sense, the Pleasant Creek represents coarse-grained transgressive strata overlain by a finer grained but coarsening-upward, regressive sequence. Basal sands at MRN-078, CHN-820, BRK-644, DOR-037 and HOR-973 most likely represent valley-fill deposition during a late relative sea-level lowstand, followed by a gradual change from a sand dominated system to a fine-grained marine sequence of sediments (Figure 6C). This model is supported by the occurrence of sand containing *O. cretacea* in the lowermost parts of the formation in CHN-820, DOR-037, HOR-973, and Kure Beach. The shallow marine environment that supported *Ostrea cretacea* was later encroached, through transgression, by shelfal environments in which microfossil-rich calcareous strata accumulated. The comparatively minor regression that followed this deposition allowed shallow marine glauconitic sand to accumulate at the top of the formation.

Marine microfossils in CHN-820, BRK-644, DOR-037, HOR-973, and MRN-078 are common to abundant. However, in the Pleasant Creek Formation interval in DOR-037, Hazel and others (1977) report the absence of planktic foraminifera, and Hattner and Wise (1980) report an interval barren of calcareous nannofossils from 1,779.0-1,754.0 ft. Moderate abundances and diversity of dinoflagellates from 1,781-1,700 ft in DOR-037, coupled with

Table 2. Thickness of the Pleasant Creek Formation in coreholes from South Carolina and North Carolina. Included are latitude and longitude coordinates of coreholes discussed in text and top and base of the formation in the subsurface. Depth and thickness in feet.

DNR #	Name	Latitude (N)	Longitude (W)	Depth (top)	Depth (base)	Thickness
BRK-644	USGS/DNR St. Stephen	33° 24' 15"	79° 56' 04"	1,084.5	1,140.0	55.5
CHN-820	USGS Santee Coastal Reserve #2	33° 09' 10"	79° 21' 30"	1,184.5	1,421.5	237.0
DOR-037	USGS Clubhouse Crossroads 1	32° 53' 17"	80° 21' 33"	1,726.0	1,779.0	53.0
HOR-973	DNR Myrtle Beach	33° 43' 21"	78° 54' 12"	718.0	977.0	259.0
MRN-078	USGS Brittons Neck	33° 51' 27"	79° 19' 30"	598.0	730.0	132.0
NH-C-1-2001	USGS Kure Beach	33° 58' 24"	77° 55' 01"	716.6	1,146.2	429.6

abundant ostracodes and calcareous nannofossils above 1,754 ft suggest middle neritic to hemipelagic conditions. The HOR-973 core records an upward trend from offshore marine sedimentation to nearshore shallow marine sedimentation. A diverse planktic marine flora and fauna was described by Gohn and others (1992) at the base of the Pleasant Creek, which became less diverse upward as quartz sand and macrofossil (*Ostrea cretacea*) content increased.

Thus, the bulk of the Pleasant Creek Formation is interpreted as representing a restricted marine to outer neritic marine paleoenvironment. Basal sediments are poorly-sorted quartz sands in a clay matrix with trace amounts of glauconite and organic matter. These sands are massive and bioturbated, with scattered sharks teeth and shell fragments scattered throughout.

Above the basal sands, sediments of the Pleasant Creek Formation formed in middle-to outer-marine shelf environments. They consist predominantly of sandy and silty clays alternating with cemented shell hash that probably represents maximum flooding of the landmass. The abundance of calcareous nannofossils, ostracodes, and planktic and benthic foraminifera support this interpretation.

SUMMARY

Sedimentary units situated stratigraphically above the Cape Fear Formation (?) and below the Shepherd Grove Formation are herein named the Collins Creek and Pleasant Creek Formations. The Collins Creek Formation is a subsurface unit in South Carolina and Georgia that is not known to crop out subaerially and has not been reported from North Carolina. It consists predominantly of greenish-gray lignitic sands alternating with dark-greenish gray sandy clays that probably formed in fluvial, restricted marine, and shallow marine depositional environments. The Collins Creek contains a calcareous nannofossil flora characteristic of Zone CC14 and Zone CC15 (middle to late Coniacian) throughout its known extent and is assigned to the *Sohlipollis* Taxon Range Zone of Christopher and others (1999).

The Pleasant Creek Formation is a subsurface unit that is not known to crop out subaerially. Sediments of the Pleasant Creek Formation are typically olive-gray, massive sands alternating with dark greenish-gray silty and sandy clays. The formation has a calcareous nannofossil assemblage characteristic of Zones CC15 and CC16 (late Coniacian to middle Santonian) and palynomorphs characteristic of the *Sohlipollis* Taxon Range Zone. The Pleasant Creek Formation formed in restricted marine to outer neritic depositional environments.

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INTEGRATED SEQUENCE STRATIGRAPHY OF PALEOGENE OUTCROP AND SUBSURFACE STRATA OF THE NORTH CAROLINA COASTAL PLAIN, SOUTHEASTERN U.S.A.

BRIAN P. COFFEY[1] AND J. FRED READ

Department of Geological Sciences, Virginia Tech, Blacksburg, VA 24061-0420 USA (bcoffey@sfu.ca, jread@vt.edu)

1. Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, B.C. V5A 1S6

ABSTRACT

The sequence stratigraphy and facies of the Paleogene interval in the subsurface of the Albemarle Basin, North Carolina was defined using 1600 thin-sections of plastic impregnated well-cuttings (3 m to 5 m sample intervals) from 24 wells, along with wireline logs, published biostratigraphic data and seismic data. The facies formed on a swell-wave dominated open-shelf with a distinctive profile of a shallow inner shelf, inner-shelf break, deep shelf (depths in excess of 200 m), and continental slope. The inner shelf was characterized by quartz sand and sandy mollusk facies inshore, passing seaward into a broad wave-swept abrasional shelf, and then into storm-influenced bryozoan-echinoderm limestones to depths of several tens of meters. Deeper water fine-grained carbonates and marls were deposited on the deep shelf, but also formed on the inner-shelf during major highstands. Deep shelf marls were widespread throughout sequence development, with erosion and reworking of sediment bodies by deep shelf boundary currents during sea-level highstands.

Thickness trends were strongly controlled by greater differential subsidence of crustal blocks within the Albemarle Basin, which considerably modified but did not obliterate the effects of eustatic sea-level changes. Paleocene sediments form a supersequence composed of at least two sequences. It consists of deep shelf marl across much of the basin, with coeval glauconitic sands updip. Sediments developed in response to global warming after latest Cretaceous Antarctic glaciation.

Lowered sea-levels near the Paleocene-Eocene boundary formed a seismically defined lowstand wedge. Two Eocene supersequences (one Lower Eocene and one Middle to Upper Eocene) have been recognized, comprised of at least 8 component third order sequences. Each supersequence consists of widespread bryozoal shelf carbonates, which formed a major transgressive buildup 50 km wide by 100 m thick at the inner-shelf break. Supersequence development occurred in response to global warming and resultant eustatic rise. With warming, there was renewed shelf submergence, followed by highstand progradation of quartzose sands and bryozoan limestones that filled remaining accommodation space across the basin. On the deep shelf, the ancestral Gulf Stream eroded and redistributed Eocene deeper water sediments into strike-parallel lobes.

The Lower Oligocene supersequence boundary developed following Upper Eocene cooling and onset of global icehouse conditions. Oligocene sediments were deposited significantly seaward of the updip limits of Paleocene and Eocene strata. Deposition was initiated with localized lowstand sedimentation off the terminal Eocene inner-shelf margin, followed by global warming and a significant sea-level rise. This eustatic rise drowned the inner shelf and is recorded by deposition of a regional marl, overlain by locally progradational sequences of near-shore sandy molluscan facies. Localized Upper Oligocene lowstand deposition occurred

along the earlier Oligocene terminal inner-shelf break, followed by widespread deposition of progradational sequences of sandy molluscan facies over the shallow shelf during long-term sea-level fell. The thickness and distribution of Oligocene deep shelf units were heavily modified by ancestral Gulf Stream scour during supersequence highstands.

INTRODUCTION

This paper presents data compiled from an integrated sequence stratigraphic study of outcrop, core, well, and seismic data from the Paleogene section of the Albemarle Basin, North Carolina coastal plain (Fig. 1). Lithologic information collected from well-cuttings, when constrained by biostratigraphic and seismic reflection data, provide valuable insight into the complicated stratigraphy exposed in quarries and updip portions of the basin by revealing regional facies relationships from much thicker portions of the basin. This approach has broad application in basins with sparse outcrop coverage, but relatively thick, laterally extensive subsurface sections. Discussions of depositional settings and global sequence stratigraphic context have been minimized in order to focus on the relationships observed between outcrop and subsurface lithologic data from the Albemarle Basin. Descriptions of facies present and supersequence characteristics have been summarized in table format, but are discussed in greater detail in Coffey (1999) and Coffey and Read (in review). While limitations in age control (both depositional and through diagenetic modification) prevent direct correlation of depositional sequences mapped across the basin with updip outcrops, stratal stacking patterns observed in well cuttings from the much thicker subsurface section provide valuable insight into the regional sequence stratigraphic significance of facies and sedimentary features observed in outcrop (Fig. 2).

Detailed study of plastic-impregnated thin

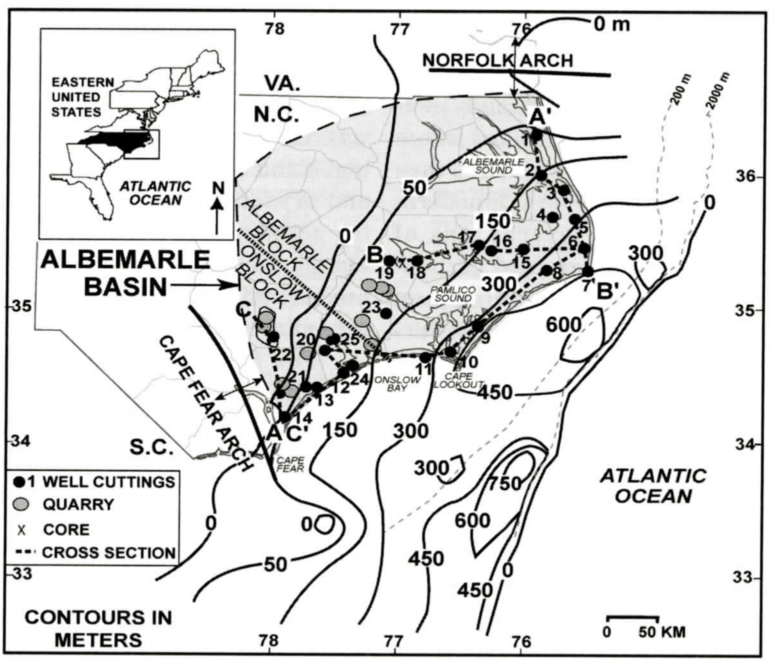

Figure 1. Location of Albemarle Basin, eastern U.S.A. (inset map) study area, showing major structural features and isopachs (in meters) of the Paleogene interval (Modified from Popenoe 1985; Brown *et al.* 1972). Locations of wells, outcrops, and cores used in stratigraphic cross-sections (A-A', B-B', and C-C', dashed bold) are shown. Isolated updip outliers were not included in the isopach mapping.

sections of well cuttings provided vital lithologic control on the variable quality vintage seismic and wireline log datasets available from the basin. Thin sectioning was necessary to preserve friable units in this mixed carbonate-siliciclastic succession and to differentiate downhole lithologies from drilling mud coatings. This dataset, while providing valuable lithologic information from the basin, is highly dependent on all available seismic and biostratigraphic control to guide correlation of sequences in this dynamic shelf setting.

The Paleogene stratigraphy of North Carolina is noteworthy because it formed on a distally steepened ramp or open shelf dominated by warmer water bryozoal carbonates, which generally are more typical of 'cooler water' carbonate shelves (cf. Collins, 1988; James, 1997; Read, 1985). The study area also straddles the broad transition zone between the cooler water, siliciclastic-dominated shelf successions to the north, and the warmer water, carbonate-dominated successions to the south. Consequently, facies commonly are mixed carbonate-siliciclastic types. Finally, the shelf succession records the effects of the ancestral Gulf Stream (Popenoe, 1985; Riggs, 1984; Lynch-Stieglitz *et al.*, 1999), which influenced water temperatures, nutrient supply, and eroded deep shelf sediment bodies for hundreds of kilometers along strike. The North Carolina margin also provides an excellent opportunity to document the shelf impact of a major shelf boundary current system within a sequence stratigraphic context. The methodology of integrating well cuttings data with seismic outlined in this paper provides a more thorough, integrated approach to subsurface mapping, which is widely applicable to Tertiary carbonate-prone basins worldwide.

REGIONAL SETTING

The Paleogene sediments of the study area lie within the Albemarle Basin, North Carolina. This basin is bounded on the south by the Cape Fear Arch and on the north by the Norfolk Arch (Fig. 1; Bonini and Woollard, 1960; Harris, 1975). Two main structural blocks, separated by the southeast-trending Neuse hinge, underlie the basin and influenced depositional patterns (Harris and Laws, 1997). These blocks include the structurally high Onslow Block to the south, which passes southwestward into the Cape Fear Arch, and the generally low-lying Albemarle Block to the northeast, which passes northward into the Norfolk Arch (Fig. 1). In addition, the basement is cut by east-west trending faults that were active in the Paleocene, which are overprinted by more recently active northeast trending faults (Graingers Wrench System; McLaurin and Harris, 2001). These formed a series of small horsts and grabens that influenced local thickness patterns in the Paleogene.

Low Cenozoic subsidence rates on this passive margin (1.4 to 4 cm/ky; Steckler and Watts, 1978) postdate the bulk of thermotectonic subsidence related to Mesozoic rifting. Paleogene strata form a seaward-thickening wedge, with erosional remnants near the present fall line (Fig. 2). This wedge thickens to 750 m along the basin axis beneath the present continental shelf (Fig. 1). The Paleogene shelf shows a distinctive evolving profile on seismic profiles, consisting of an inner-shelf and inner-shelf break, as well as a deeper outer shelf, which breaks seaward onto the continental slope. Paleogene sediments are erosionally terminated at or beneath the modern continental shelf break (Popenoe, 1985). A thick basin-fan complex lies at the foot of the continental slope and is composed of deep water sediments with a major component of resedimented shelf material (Poag, 1992).

During mid-late Paleogene sea-level highs, the ancestral Gulf Stream became active, cutting across Florida via the Suwannee Straits during sea-level highstands, and then flowing northeastward along the southeastern U.S. margin (Pinet and Popenoe, 1985; Huddleston, 1993). This provided relatively constant warm waters to the shelf during sea-level highstands. Northward drift of the North American plate during the Paleogene positioned the North Carolina shelf between 30 and 36 degrees north latitude, placing it north of the tropical latitudes (Scotese, 1997; Smith *et al.*, 1994).

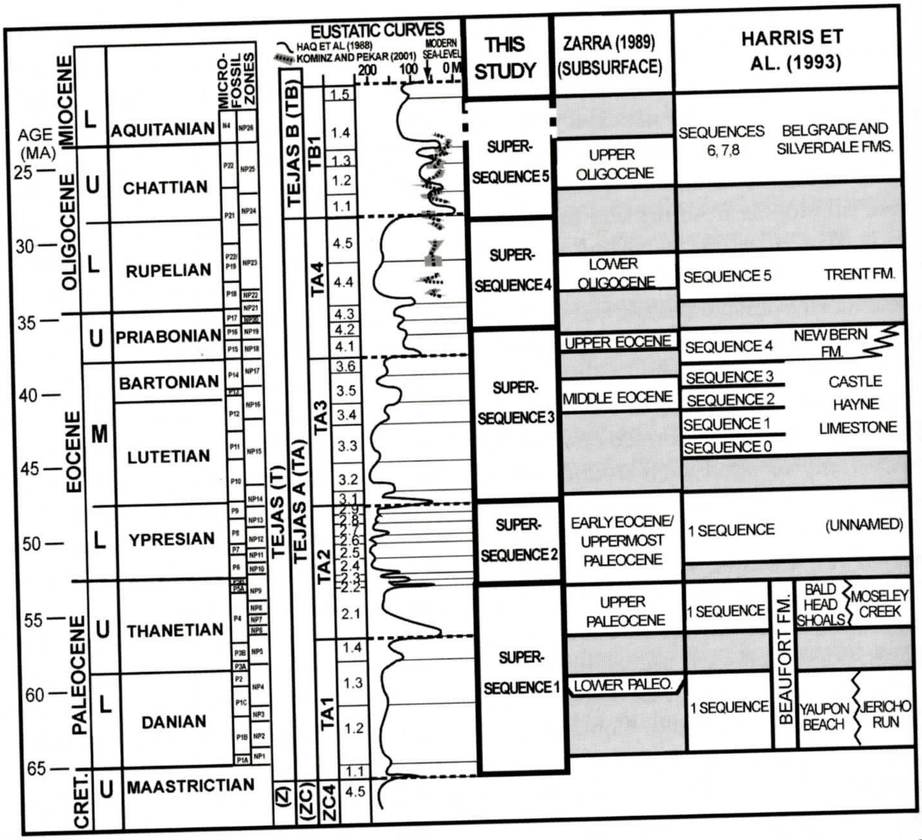

Figure 2. Regional stratigraphic framework for the Paleogene of the North Carolina coastal plain. Global and regional eustatic curves of Haq et al (1988) and Kominz and Pekar (2001) are included for comparisons in the text and Table 2. Biostratigraphic zonations and radiometric time scale are from Berggren *et al.* (1995).

STRATIGRAPIC FRAMEWORK

Previous studies of the North Carolina Paleogene concentrated on thin exposures on the Cape Fear Arch and updip outliers (Fig. 3; Thayer and Textoris, 1972; Baum *et al.*, 1978; Ward *et al.*, 1978; Otte, 1981; Zullo and Harris, 1987), on offshore seismic data (Popenoe, 1985; Snyder *et al.*, 1994) or on the biostratigraphic dating of depositional sequences (Brown *et al.*, 1972; Zarra, 1989; Harris *et al.*, 1993; Harris and Laws, 1997). Subsurface lithofacies were only broadly identified and were not integrated with seismic data across much of the basin.

Paleocene

Paleocene sediments are over 100 m thick in the onshore subsurface, increasing to more than 200 m offshore (Spangler, 1950; Brown *et al.*, 1972; Zarra, 1989; Harris and Laws, 1994). They unconformably overlie Cretaceous sediments along the basin margin, but appear to be conformable downdip. They are mapped as the Beaufort Formation, which includes Lower Paleocene updip sand (Yaupon Beach Member; Harris and Laws, 1994) and downdip argillaceous lime mudstone (Jericho Run Member), and an Upper Paleocene sandy molluscan limestone (Mosely Creek Member; Fig. 2). These packages correspond with the Lower and Upper Paleocene sequences identified in the subsurface by Zarra (1989) and Harris *et al.* (1993).

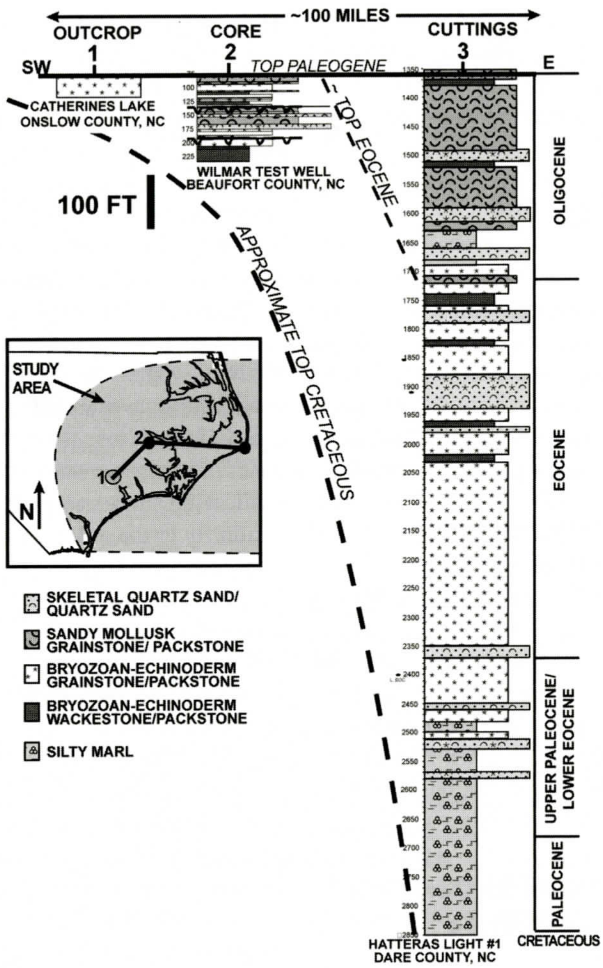

Figure 3. Comparison of lithologic datasets available from the North Carolina coastal plain, demonstrating the significant variation in sediment thickness between outcrops, continuous cores, and well cuttings from the onshore basin center. Note dramatic thickening of all ages of strata into the basin, and that this example is biased toward Middle Eocene strata; updip Paleocene and Oligocene sections are present elsewhere, but are less widespread across the coastal plain.

Eocene

Lower Eocene sediments are 0 to 20 m thick, and are confined to the subsurface (Brown *et al.*, 1972; Zarra, 1989). They were mapped as a single depositional sequence by Zarra (1989). Middle Eocene strata are mapped as Castle Hayne Limestone, which is dominated by bryozoan-echinoderm limestones. Eocene stratal thicknesses range from less than 15 m updip to over 200 m in the subsurface beneath the present coastline (Brown *et al.*, 1972; Zarra, 1989; Baum *et al.*, 1978; Ward *et al.*, 1978). Offshore, the combined Lower and Middle Eocene strata are over 300 m thick beneath the modern shelf, thickening to 400 m beneath the continental margin (Popenoe, 1985). Upper Eocene units of the New Bern Formation generally are 0 m to 10 m thick onshore, and consist of sandy molluscan packstones/grainstones and quartz sands (Fig. 2; Baum, 1977).

One uppermost Paleocene to Lower Eocene sequence was recognized by Zarra (1989) and Harris *et al.* (1993). A single Middle Eocene subsurface sequence was recognized by Zarra

(1989), but Harris *et al.* (1993) recognized four Middle Eocene sequences, plus one additional Upper Eocene sequence (Fig. 2). Three sequences were identified from this interval by Baum and Vail (1988).

Oligocene

Oligocene strata range from 0 m to over 100 m thick onshore, thickening basinward to over 400 m beneath the modern continental shelf. They include argillaceous lime mudstone (marl), fine –medium quartz sand, and sandy molluscan packstones/grainstones of the Lower Oligocene Lower River Bend Formation (Trent Formation of Baum et al. 1978), and the silty-sandy molluscan packstones/wackestones of the Upper Oligocene Upper River Bend Formation (Belgrade Formation of Zullo and Harris, 1987; Fig. 2; Baum et al., 1978;). One Lower Oligocene sequence and three Upper Oligocene sequences were recognized by Zarra (1989) and Harris *et al.* (1993; Fig. 2). The Oligocene units are unconformably overlain by Lower Miocene-Pliocene strata along the basin margin (Baum *et al.*, 1978; Zullo and Harris, 1987).

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Seismic dip lines show that the Paleogene shelf had a distinctive profile consisting of a shallow inner shelf, inner shelf break, deep shelf, and continental slope (Fig. 4). This dual-break geometry has been noted elsewhere on the U.S. Atlantic margin (cf. Miller *et al.*, 1998) and has a major influence on the distribution of facies across the basin. The wells studied penetrate only the inner shelf portion of this shelf profile, so the facies making up the seismic units offshore are inferred from deep water strata deposited updip during major shelf flooding events. Lithofacies were defined in the subsurface by examining sixteen hundred thin-sections of well-cuttings from 24 wells. Coffey and Read (2002) discuss the methodology for cuttings analysis used in this study.

The major lithofacies and their inferred depositional settings are described in Table 1 and depositional settings are interpreted below. Further discussion of facies properties and distribution can be found in Coffey (1999). Inability to differentiate complex heterogeneity observed in outcrop led to grouping of similar lithologies into facies assemblages, based on stacking patterns observed in outcrop and core (Fig. 4). The following facies assemblages are grossly arranged from shallow to deep:

Quartz Sand and Skeletal Fragment Quartz Sand facies described in Table 1 are shoreface to shallow shelf deposits, based on their nearshore, mollusk-dominated biotas, abundant terrigenous detritus, their positions adjacent to bases or tops of upward-deepening and upward-shallowing successions (respectively), and their similarity to the modern nearshore facies on the Carolina continental shelf (cf. Milliman *et al.*, 1968; Blackwelder *et al.*, 1982). The lack of sedimentary structures in the sands in outcrop probably was due to pervasive burrowing by bivalves, which are commonly present. This homogenization obliterated any aeolian or nearshore mechanical sedimentary structures.

Sandy Mollusk Fragment Grainstone/Packstone facies described in Table 1 formed by physical and biological fragmentation of mollusks and barnacles on the shoreface and nearshore shelf, the fragmented material being winnowed and transported by waves and currents, to accumulate as localized fragmented skeletal sands. Similar facies are common on the nearshore parts of warm temperate to subtropical shelves today (Collins, 1988; James *et al.*, 1994).

Sandy, Whole Mollusk Packstone/Grainstone facies shell beds described in Table 1 were formed by mollusk-dominated inner shelf assemblages (cf. Collins, 1988). Abundant whole shells suggest deposition in lower shoreface to mid-shelf settings of a wave-dominated shelf system, where sedimentation rates and lack of intense wave reworking inhibited biologic and physical fragmentation of valves. Interstitial spaces between the shells typically were filled by infiltrated terrigenous sand and silt probably introduced via longshore drift, along with lime mud produced by in-situ skeletal breakdown. Mud may have been deposited

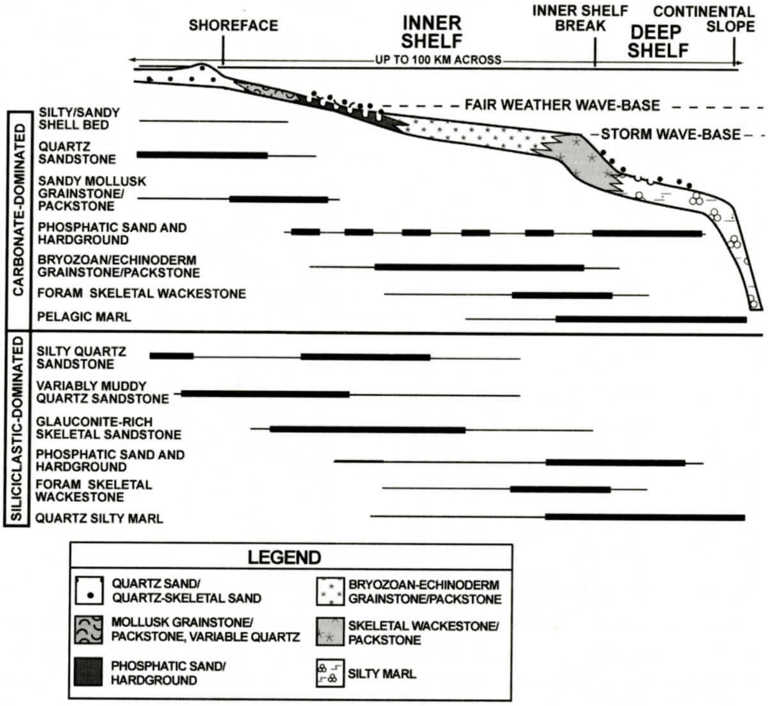

Figure 4. Generalized mixed carbonate/siliciclastic facies distribution across the Paleogene shelf. Note distinctive depositional profile with a low-relief shoreface, passing out onto a wave-swept region on the inner shelf, passing out into a sediment accreting region on the slightly deeper inner shelf (10 m to 50 m plus), an inner shelf break sloping gently (~1 degree) to a boundary current-influenced deep shelf at depths greater than 100 m deep, which terminates against the continental slope. The relative abundance of lithofacies within the general facies assemblage is noted by bars at base (bold indicates greater abundance).

during low energy periods, possibly under the influence of local seagrass cover typical of subtropical inner shelf areas today (cf. Wanless *et al.*, 1995).

Fine to Medium Quartz Sand/Silt described in Table 1 formed in low to moderate energy settings on the inner shelf that favored deposition of fines, together with tests of benthic and pelagic microorganisms. These facies probably formed seaward of higher energy shoreface sands, as on the Queensland shelf of eastern Australia (cf. Johnson and Searle, 1984). Fines were carried in from river systems during floods, then were moved out onto the shelf as muddy sediment plumes transported under the influence of longshore currents. When lacking open marine faunas, these strata also may have formed as local estuarine/lagoon fills.

Bryozoan-Echinoderm Grainstone/Packstone described in Table 1 likely formed in water depths from 30 m to 100 m, based on comparison with similar modern open shelf assemblages (Nelson *et al.*, 1988; Collins, 1988; James *et al.*, 2001). The open shelf setting is supported by diverse marine biotas (Fallow and Wheeler, 1963; Zullo and Harris, 1987; Baum, 1977) and evidence for sweeping by storm or swell waves, expressed as sand waves and cross-bedded units. A warm subtropical setting is suggested by the presence of large benthic foraminifera (cf. nummulitids and orbitoids), aragonitic bryozoans, and mollusk assemblages (Baum, 1977; Otte, 1981; Powell, 1981). Seasonal temperature variations may have been ameliorated by warm ancestral Gulf Stream currents.

Phosphatic Sand and Hardground described in Table 1 formed in a variety of shelf positions.

Table 1. Summary of Paleogene lithofacies observed.

Facies	Quartz sand/skeletal fragment quartz sand	Sandy mollusk-fragment grainstone/packstone	Sandy, whole-mollusk packstone/grainstone (shell beds)	Fine to medium quartz sand/silt	Bryozoan-echinoderm-grainstone/packstone	Phosphatic sand and hardground	Glauconitic sand	Fine skeletal packstone/wackestone	Carbonate mudstone/marl
Stratigraphic occurrence and thickness	Occur with shell beds, especially in Upper Eocene and Oligocene; 0.5 to 10 m thick, but rarely greater than 1 m in outcrop	Interlayered with shell beds and quartz sands; common in Oligocene interval; form stacked units; 1 to 5 m thick	Sheets, lenses, and small banks associated with quartz sands and skeletal quartz sands; 0.25 to 3 m thick; more common in Oligocene strata	Not present in outcrop; associated with sands in subsurface; 3 to 15 m thick; common in Upper Eocene and Oligocene strata in northeast	Dominant Middle Eocene facies; 2 to 15 m thick (locally stacked into 150 m thick buildup); less common in Upper Paleocene and Oligocene	Hardgrounds form semi-regional surfaces; may be overlain by oolitic phosphatic sands up to 0.5 m thick, except in thicker Upper Oligocene phosphorite accumulations of the northern basin (15 m)	Associated with planktic marls; more abundant in northern Albemarle basin (3-10 m thick)	Thin (3-5 m) units; commonly associated with marls	Thick sections (50 m) in Paleocene; In Eocene/Oligocene, relatively thin (2-10 m) in subsurface; thin to 3 m in outcrop over the arches
Color	Light gray	Light gray to light yellowish gray	Light gray to light yellowish gray	Dark yellowish to brown	White to very light gray	Yellowish brown to grayish black	Dark green	Light gray to light olive gray	Light olive gray
Bedding and sedimentary structures	Massive to crudely bedded	Massive, heavily burrowed; laterally discontinuous in outcrop	Massive/bioturbated	Massive in core	Some meter-scale sand waves in outcrop, commonly large-scale cross-bedded	Planar to irregular surfaces, with borings; common lags	Generally massive in core	Massive/bioturbated	Massive, or thin-bedded to laminated in outcrop
Constituents:	Highly-fragmented angular to rounded skeletal material and abundant rounded medium to coarse quartz sand	Abundant leached, fragmented and abraded mollusks and abundant rounded medium to coarse quartz sand; minor lime mud	Abundant leached whole mollusks and variable amounts of very fine to fine quartz sand and silt; lime mud matrix sparse to abundant	Common subrounded/angular fine quartz sand/silt; clay matrix; common fine skeletal fragments	Medium sand-gravel; bryozoans, echinoderms, clams, and forams; variable fine angular to subrounded medium quartz sand; sparse to abundant lime mud matrix	Minor skeletal material, commonly phosphatized; common rounded medium to coarse quartz sand	Medium to very coarse sand sized, spherical to ovoid glauconite pellets and rounded very fine to medium quartz sand; minor planktic and benthic forams; siliceous silt/clay present in stringers or as ovoid fecal pellets	Fine sand to gravel sized benthic skeletal debris; variable planktic biotas and very fine to fine subangular quartz sand in argillaceous lime mud matrix	Planktic tests and spicules variable amounts of angular quartz silt to very fine sand in a matrix of silt to clay-sized carbonate and terrigenous silt/clay; finely disseminated phosphate and oxides;
Biota	Clams, oysters, barnacles; minor echinoderms	Clams, oysters, some barnacles; minor echinoderms	Abundant clams and oysters; some gastropods	Diatoms, planktic and benthic forams; Some gastropods, bivalves, and echinoderms	Abundant bryozoa, echinoderms, brachiopods, moderate benthic and planktic forams; minor red algae, crab fragments, and ostracodes	Boring mollusks, encrusting organisms common (benthic foraminifera, thick-walled bryozoans)	Planktic and benthic foraminifera, minor sponge spicules, and pycnodontid oysters	Delicate bryozoans, echinoderms, and benthic forams; some planktic forams	Common planktic foraminifera, sponge spicules, radiolaria, calcareous nannoplankton, minor benthic foraminifera
Glauconite	Minor, very fine to fine sand size	Minor, fine to medium sand size	Minor, very fine to fine sand size	Minor, very fine sand size	Variable, fine to medium sand size	Common, medium to coarse sand size	Very abundant, medium to very coarse sand size	Variable, very fine to fine sand size	Abundant, very fine to fine sand size
Environment of Deposition	Barrier/shoreface/shallow shelf	Bay/shoreface/shallow inner shelf	Bay and shallow inner shelf	Low-moderate energy inner shelf	Storm-influenced deep inner shelf	Sediment starved/current-swept mid-deep shelf	Shallow (distal deltaic) to deep shelf	Deep shelf	Subwave base deep shelf

Sandy phosphatic facies formed on the high energy inner shelf, due to suppressed sedimentation by sweeping and abrasion of swell-waves (Emery, 1965; Milliman *et al.*, 1968; Collins, 1988; James *et al.*, 1994). In more deeply submerged settings, boundary currents may have swept the sediment surface, suppressing deposition, and allowing hardground pavement formation and encrustation. Pavements were eroded and redeposited onto the updip inner shelf during major transgressive events. Hence, major eustatic fluctuations may have reworked localized phosphate accumulations into regional, time-transgressive pavements across the inner shelf. Gyres spalled from the main boundary current likely localized upwelling to form thick, oolitic phosphate sand deposits (Prokopovich, 1955; Riggs, 1984). Some of the hardgrounds may have been modified by exposure during lowstands of sea-level, but many do not show evidence of emergence (Moran, 1989). Exposure-related phosphatic surfaces have been differentiated from submarine surfaces on the presence of crystal sand- or silt-infiltrated shell molds and depleted stable isotopes beneath the exposure surface (Baum and Vail, 1988).

Glauconitic Sand facies described in Table 1 developed in low energy open shelf settings with reduced sedimentation rates. Planktonic forams in some units suggest deeper shelf settings, but thicker, quartz sand-rich units that occur in updip positions likely formed on the shallow shelf. Modern shelves show wide range of water depths for glaucony formation (Cloud, 1955; Gorsline, 1963; James *et al.*, 1999). Sands likely formed beneath cool, normal salinity waters with elevated dissolved silica concentrations, in areas with abundant phyllosilicate clays and organic matter, and relatively reducing conditions, such as distal deltaic settings or areas of the shelf downdip from fine clastic point sources (Harder, 1980; Cloud, 1955).

Argillaceous Lime Mudstone/Marl described in Table 1 is the deepest water facies encountered in this study. Abundant fines and planktic fauna suggest deposition below swell wave base, probably in water depths greater than 100 m on an open shelf, although some strata may have formed at shallower depths in protected updip areas (cf. Collins, 1988; James, 1997; Marshall *et al.*, 1998). They formed by accumulation of planktonic tests, skeletal debris winnowed from upslope, and variable amounts of fine terrigenous siliciclastics carried across the shelf during major storms. Being largely below wave base, these deep shelf facies were not affected by surface wave energy, but offshore seismic data suggest they were subjected to significant episodes of reworking and incision by shore-parallel boundary currents. Fine Skeletal Packstone/Wackestone described in Table 1 formed predominantly in deep shelf settings. Modern analogs of these facies form below storm and swell wave base, often at depths of 100 m or more on open shelves (cf. Collins, 1988; James *et al.*, 1999). However, they may have been deposited at shallower depths in wave-protected areas of the Albemarle Basin, especially if structural highs created broad coastal promontories. Abundant lime mud, delicate neritic benthic organisms, and abundant planktonic foraminifera support a deep, open shelf depositional setting.

SEQUENCE STRATIGRAPHY

Regional cross-sections were constructed from the onshore well data using available seismic data and published biostratigraphic data to constrain correlations. Wells penetrate sections only on the inner shelf, so offshore data for the deep shelf is limited to seismic profiles. The Paleocene-Eocene cross sections were datumed at the top Eocene surface. Oligocene cross sections were hung from the top of the Oligocene. Age correlations between wells were based on biostratigraphic control published by Brown *et al.* (1972) and Zarra (1989), who subdivided the Paleogene subsurface into Lower and Upper Paleocene, Lower, Middle, and Upper Eocene, and Lower and Upper Oligocene intervals. Greater weight was placed on the more recent planktonic foraminiferal picks of Zarra (1989), with additional calcareous nannofossil control provided by Laws and Bralower (unpublished). Calcareous nannofossils were of limited use in constraining ages, due to considerable vertical mixing of fines with muds during drilling (Laws pers. comm., 1999). In addition, most of the grain-rich, updip lithologies encountered were not conducive to the preservation of these microfossils.

Biostratigraphic age picks were plotted onto interval transit time logs (inverse of sonic velocity) from five wells and then transposed onto regional seismic lines to tie correlations between wells. This was essential in areas showing broad, low angle clinoforms, which had not been previously recognized, because these subtle features were below the resolution of the biostratigraphic data. Offshore isopachs generated from seismic (Popenoe, 1985) were integrated with onshore data (Brown *et al.*, 1972; Harris and Laws, 1997) to construct basinwide isopach maps.

Given the problems inherent in well cuttings data (Coffey and Read, 2002), lithologic types present in each well sample interval were grouped into the following five facies associations prior to correlation between wells:

1. Shoreface-nearshore inner shelf association: quartz sandstone, mollusk-fragment quartz sandstone, and sandy whole- and fragmented-mollusk rudstone, grainstone and packstone,
2. Offshore, inner shelf association: bryozoan-echinoderm grainstone/packstone (mainly Eocene) and sandy barnacle echinoderm grainstone-packstone (Oligocene),
3. Wave- and current-swept shallow to deep shelf association: phosphatic sands/wackestone, and carbonate hardgrounds. These may occur on wave-abraded nearshore shelf (hardgrounds), and on deeply submerged inner shelf due to boundary currents and upwelling (hardgrounds and phosphatic units),
4. Deeper water shelf association: fine skeletal packstone/wackestone or fine to medium quartz sand/silt. These units are dominated by delicate benthonic and pelagic biotas, relative to the current-swept assemblage,
5. Sub-wave base, very deep shelf association: argillaceous lime mudstone.

All of the facies observed in the wells were deposited on the geomorphic inner shelf, but in a wide range of water depths, depending on the position of the shelf surface with respect to Paleogene relative sea-level. The dominant facies association recognized from each sample interval in the wells were used to draw the facies cross sections; correlations were constrained by seismic and biostratigraphic data. The open, wave dominated configuration of this passive margin resulted in laterally continuous, shore-parallel facies assemblage distribution, which facilitate correlation of strata and recognition of major eustatic fluctuations recorded by the strata. Regional correlations then were incorporated into a sequence stratigraphic framework (Vail *et al.*, 1977; Van Wagoner *et al.*, 1990; and Sarg, 1988).

Sequence boundaries were recognized on the cuttings logs by upward-shallowing trends of shelf carbonate facies into skeletal quartz sandstone cuttings fragments, with the sequence boundary being placed at the base of the interval showing a major increase in percentage of the shallowest-water lithofacies (Figs. 5-8). The percentage of quartz sand generally increases gradually upward to the sequence boundary, then reaches a maximum just above the boundary. There is little evidence of subaerial exposure associated with many sequence boundaries in this basin, which makes these surfaces difficult to recognize in outcrops, cores, and logs. Instead, they were defined by major seaward shifts in facies associations. In downdip wells lacking sandy intervals, sequence boundaries were placed near the tops of upward-shallowing trends, expressed by increasing percentages of inner shelf units above deep shelf facies. Phosphatic hardgrounds occur at many sequence boundaries in outcrop; however, downdip, they also occur on transgressive and maximum flooding surfaces. As these thin features make up only a small percentage of the well cuttings within a sample interval, they were not used as the primary criteria for differentiating bounding surfaces or systems tracts. In general, Paleocene and Eocene sequences consist of greater amounts of muddy to skeletal, open shelf carbonate material, while Oligocene sequences have significantly greater amounts of siliciclastic material and mollusk-dominated carbonate skeletal material (Figs. 5-8).

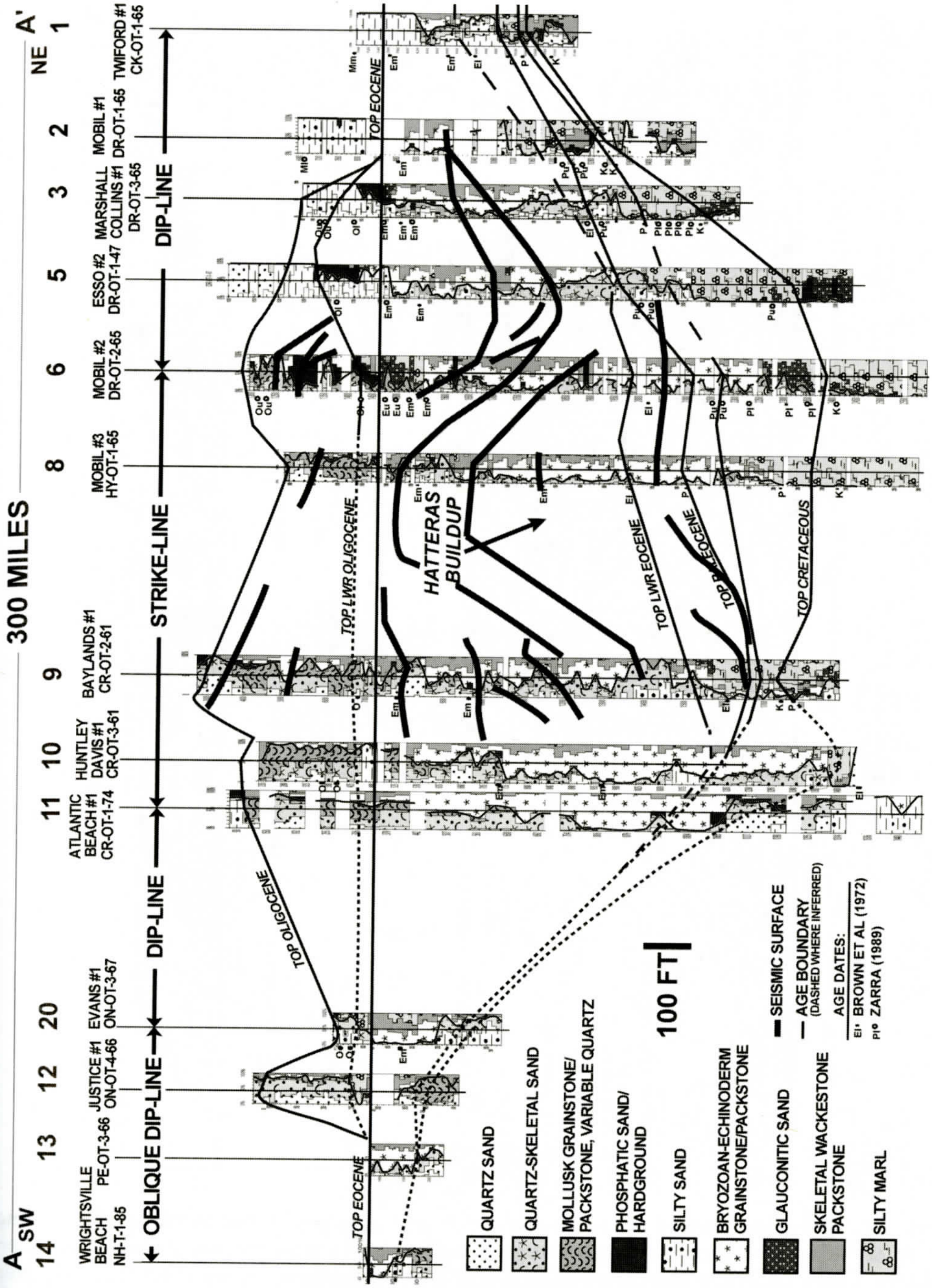

Figure 5. Raw well data "strike" cross-section across the Albemarle basin, showing biostratigraphic and seismic controls on correlation between wells (Datumed on Top Eocene). In each well, cuttings are plotted by percent rock type present in each sample interval (by facies increasing to the right); see Coffey and Read (2002) for further discussion of this method. Note seismic clinoform development in the central basin, indicating the development of the Hatteras Buildup of skeletal carbonates in the Lower-Middle Eocene. Location of the cross section is shown in Figure 1.

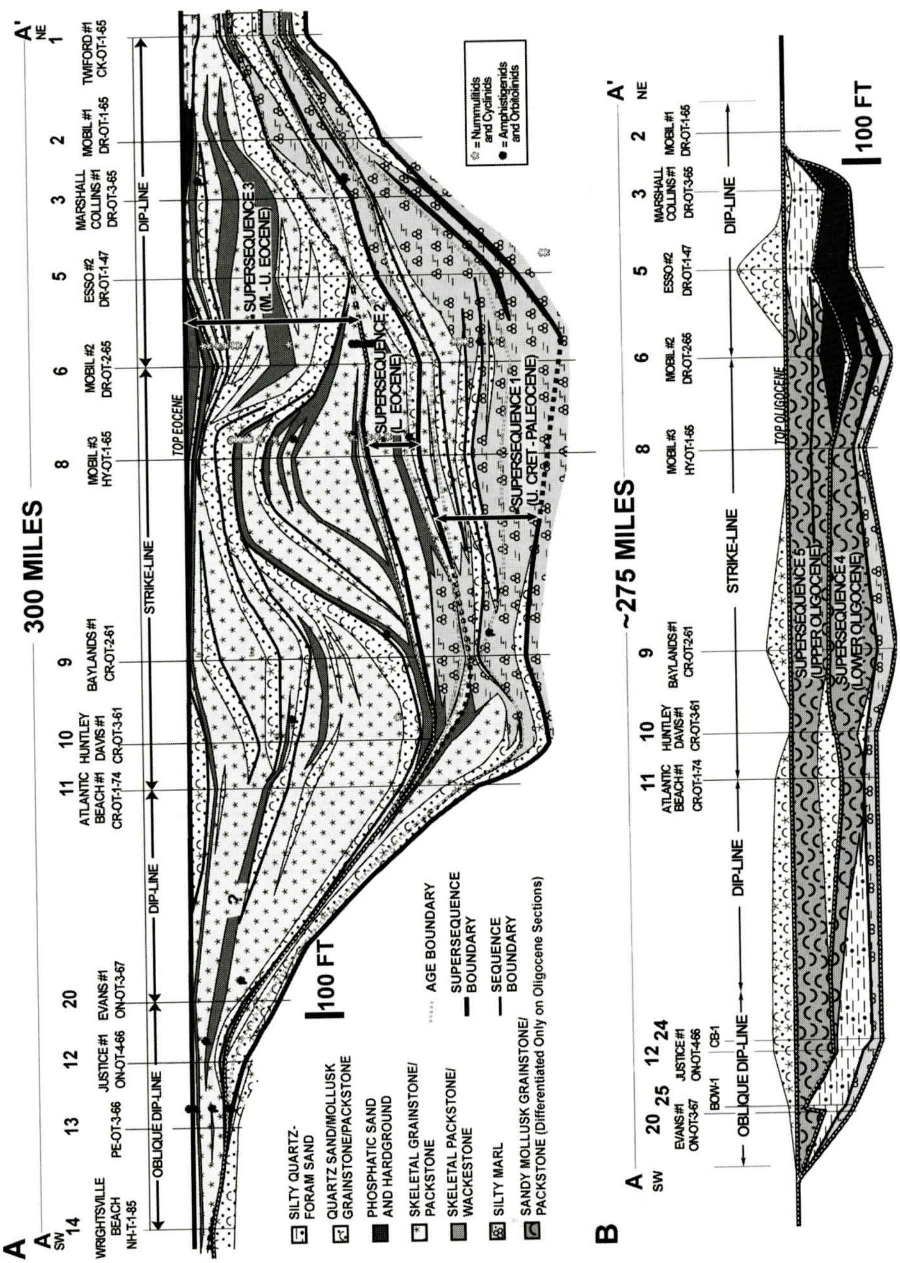

Figure 6. Interpretive "strike" cross-section from well data presented in Figure 5, showing inferred dominant lithologic units, correlations, and sequence stratigraphic surfaces based on the cuttings data. Interpretation constrained by regional biostratigraphic age control and seismic data. (A) Paleocene and Eocene cross section (Supersequences 1-3), showing multiples orders of sequence stratigraphic information revealed by cuttings data (Top Eocene datum); (B) Oligocene strike cross section (Supersequences 4-5), showing dominance of shallower water, quartz sand and mollusk-dominated facies assemblages (Top Oligocene datum). Note that wells 24 and 25 have been added to this section, which Harris et al. (2000) describe, and that this section does not extend as far along strike as Figure 6A. Also, note that quartz-mollusk-rich facies have been further broken apart in the Oligocene section, as they become more pronounced and indicative of sequence-scale variations.

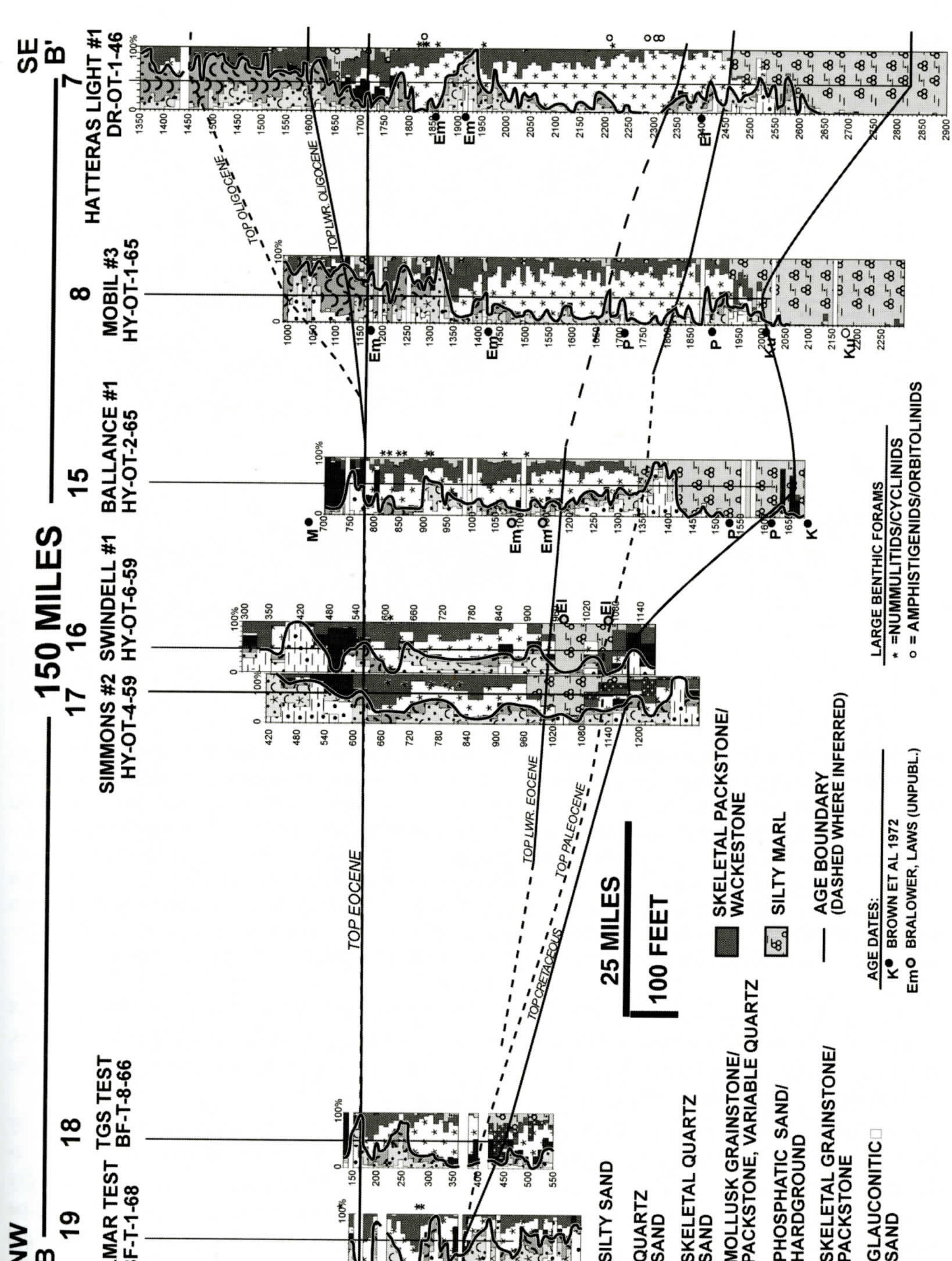

Figure 7. Raw well data dip cross section, showing age and limited seismic control on correlations between wells (Datumed on Top Eocene). Note absence of seismic correlation surfaces onshore, due to limited, low quality seismic data in updip locations. Location of the cross section is shown in Figure 1.

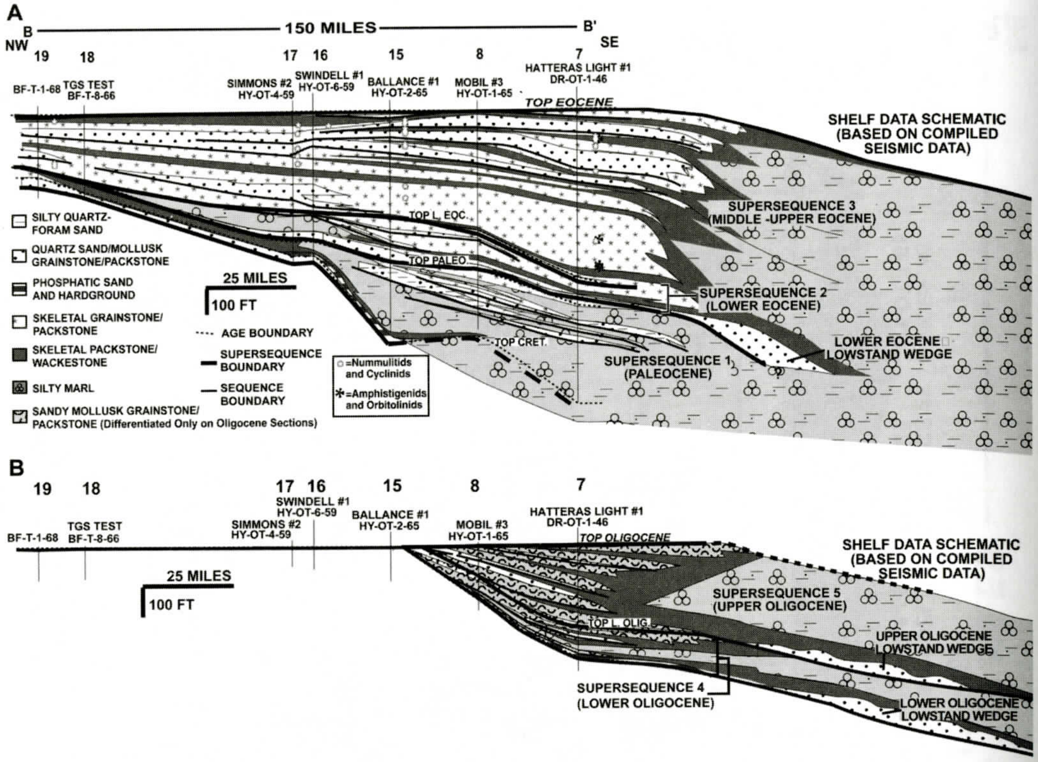

Figure 8. Interpretive dip cross-section B-B' from well data presented in Figure 7, showing inferred dominant lithologic units, correlations, and sequence stratigraphic surfaces based on the cuttings data. Interpretation constrained by regional biostratigraphic age control and seismic data. Schematic offshore projection is based on lowstand wedges and terminal shelf edges identified from shelf seismic data. (A) Paleocene and Eocene dip section, revealing large-scale supersequence and component sequence stacking patterns (Top Eocene datum). Wide-scale progradation in late Middle Eocene section (mid-Supersequence 3) corresponds with outcrop sections shown in Figure 9; (B) Oligocene dip section, showing extensively progradational stacking patterns in predominantly shallow shelf facies assemblages (Top Oligocene datum).

Transgressive systems tracts were defined where units showed an upward increase in proportion of deeper water facies (Figs. 5-8). The accompanying upsection decrease in the abundance of shallow water facies in the cuttings reflects progressive landward migration of facies during transgression.

Maximum flooding zones were placed at the bases of intervals in the wells characterized by the highest percentage of deepest water facies. In most cases, discreet flooding surfaces could not be identified in well cuttings, but were rather expressed by rapid significant shifts in facies assemblages. They typically underlie muddy carbonates and silty marls downdip, and skeletal carbonates updip. Flooding zones could not be identified in thin (less than 10 m) sequences, because they were beyond the resolution of the cuttings data.

Highstand systems tracts were recognized by up-section increase in shallow water, quartz-rich facies. They could be recognized only where a maximum flooding surface could be defined; otherwise, transgressive and highstand systems tracts were not subdivided (Figs. 5-8).

Supersequences

Five unconformity-bounded supersequences (Table 2) are recognized, most containing a

Table 2. Summary of supersequence observations from the Paleogene section, North Carolina.

Supersequence	Age Control	Distribution	Onshore Thickness	Dominant Composition	Seismic Expression	Stacking Patterns	Onshore Third Order Sequences	Outcrop Expression
Upper Oligocene (Supersequence 5)	P21-P22+	Limited to eastern basin; localized thicks onshore northwestern Onslow Bay	0-50 m; Thickest near siliciclastic point sources	Mollusk-dominated carbonates with abundant quartz sand	Locally well-developed clinoforms offshore; Strike parallel lobes on mid-shelf	LST: Local thick wedges offshore TST: Thin muddy carbonates HST: Aggradational to strongly progradational stacked sandy mollusk sequences	3+	Quartz sandy mollusk carbonates record prograding supersequence highstand
Lower Oligocene (Supersequence 4)	P19-P21	Widespread thin unit across eastern basin; thickens locally in southern basin	0-70 m; Generally less than 15 m	Silty sands coarsen up to mollusk-rich quartz sandy carbonates	Thin parallel reflectors updip; Progradational mid-shelf; Mounded deep shelf	LST: Offshore wedges on seismic TST: Regional silty marl with local basal phosphatic sand HST: Coarsening-up sandy mollusk grainstone; Fines away from Cape Hatteras	3	Basal silty marl marks supersequence MFS; Sandy, mollusk-rich carbonates record supersequence highstand
Middle-Upper Eocene (Supersequence 3)	P11-P16	Widespread across basin; thickest beneath Pamlico Sound Likely extends updip to near Fall Line	0-200 m; Thickest beneath Cape Hatteras	Bryozoan-echinoderm skeletal carbonate	Early: Regional downlap surface, then common clinoform development Offshore broadly mounded along strike	TST: Hatteras buildup of skeletal carbonate develops HST: Widespread progradation of upward-shallowing skeletal carbonate-quartz sand sequences	5+	Bryozoal carbonates record prograding supersequence highstand sequences Mollusk-rich Upper Eocene carbonates mark short-lived flooding event during supersequence highstand
Lower Eocene (Supersequence 2)	P8-P9	Confined to subsurface in central basin Highly thinned to absent across Onslow Block	0-40 m Thickest beneath Cape Hatteras	Bryozoan-echinoderm skeletal carbonate	Poorly imaged; Regional downlap surface	LST: Well-developed wedges offshore TST: Basal quartz sand; grades to bryozoan limestone HST: Upward-coarsening skeletal carbonate	1-2	Not Recognized in outcrop; Possibly preserved as thin bryozoal carbonates updip
Uppermost Cretaceous-Paleocene (Supersequence 1)	P1-P4	Limited across Onslow Block (local lobes offshore) Widespread across Albemarle Block	0-100 m; Thickest in east-central basin	Silty foram marls downdip Glauconitic sands updip	Thin, parallel reflectors onshore Broad, low angle clinoforms and local wedges offshore	LST: Wedges offshore TST: Condensed glauconite/phosphate sands/Hardground to silty marl HST: Quartz-mollusk sand and bryozoan carbonates	2-3	Glauconitic sands mark late supersequence transgression to early highstand

seismic-scale lowstand wedge along the inner shelf margin (Fig. 2). Each supersequence is expressed on the inner shelf as a grossly upward-deepening to upward-shallowing succession of component third order depositional sequences (Figs. 6, 8). Component sequences were more difficult to identify and map regionally using the well cuttings, because of their limited thickness, the poor resolution of the seismic and biostratigraphic framework, and problems inherent in the cuttings analysis (Coffey and Read, 2002). However, basinwide correlation of major sequences provides valuable insight into the updip stratigraphy in outcrop, where cuttings sample intervals became too large to resolve heavily eroded and thinned stratigraphy between outcrop exposures (Fig. 9).

Descriptions of the five supersequences identified in this study are provided in Table 2 and are discussed in greater detail in Coffey (1999). Supersequence 1 (Paleocene) is dominated downdip by argillaceous lime mud (marl), with abundant glauconitic sand updip (Figs. 6, 8). It gradually coarsens upward into skeletal carbonate as the supersequence highstand strata begin to prograde seaward (Fig. 8). Supersequence 2 (Lower Eocene) consists of marls and skeletal carbonates, which locally form a broad sediment spur, with limited siliciclastic input during the late highstand. The succession is capped by a Type 2 sequence boundary (Van Wagoner et al., 1990), which lacks evidence of sea-level fall off the inner shelf. Following this fall, widespread deposition of skeletal carbonates mark the Supersequence 3 (Middle-Upper Eocene) strata. These strata correspond with Middle Eocene skeletal carbonates observed in outcrop updip. However, a significant earlier transgressive sediment package in the basin has not been identified updip. Transgressive strata form a broad sediment spur (informally named the Hatteras buildup) beneath present-day Cape Hatteras (Fig. 6A). Supersequence highstand sediments extended from the modern outcrop belt into the basin as prograding sequences that filled accommodation space on the shelf, masking the signal of the earlier transgressive buildup on regional isopach maps. Increased siliciclastic material is characteristic of the Supersequence 3 highstand downdip, while thin, carbonate-dominated packages prevail updip (Fig. 9).

Controls on Sequence Development

Total subsidence rates for the onshore Paleogene sections average 1 cm/ky, roughly half of the Cretaceous subsidence rates, based on gross thickness variations between the two intervals in deep onshore wells. Overall, the accumulation rates for the Albemarle Basin are relatively low compared to accumulation rates calculated from much thicker sections in offshore wells elsewhere on the western Atlantic margin, where accommodation was not the limiting factor and subsidence was slightly higher (Steckler and Watts, 1982; Heller *et al.*, 1982). Variation in subsidence rates across the basin strongly controlled the thickness and to a lesser extent, the facies distribution of the Paleogene units. Thicker sediment packages on the Albemarle Block (Harris and Laws 1997) contain more siliciclastic units, favored thicker sediment packages, and focused siliciclastic sedimentation, relative to the much thinned, carbonate-dominated section of the Onslow block.

Supersequence 1 (latest Cretaceous to latest Paleocene)

Deposition of Supersequence 1 (Table 2) was initiated during latest Maastrichtian sea-level rise associated with transition into a global greenhouse climate and possible Antarctic glacial melting (Barerra *et al.*, 1987; Frakes *et al.*, 1994). Large amplitude (100m+) sea-level rise resulted in Upper Cretaceous near-shore facies to be overlain by deep water marls across much of the Albemarle Block (Fig. 6A). Eustatic rise probably was assisted by differential subsidence and consequent water loading, especially on the Albemarle Block. In the central, deeper part of the Albemarle Basin, Paleocene marls appear to form a correlative conformity on Cretaceous marls. The Supersequence 1 highstand (Thanetian) is more extensive updip, suggesting increased subsidence of the Albemarle Block in the Late Paleocene (Harris and Laws, 1997). In

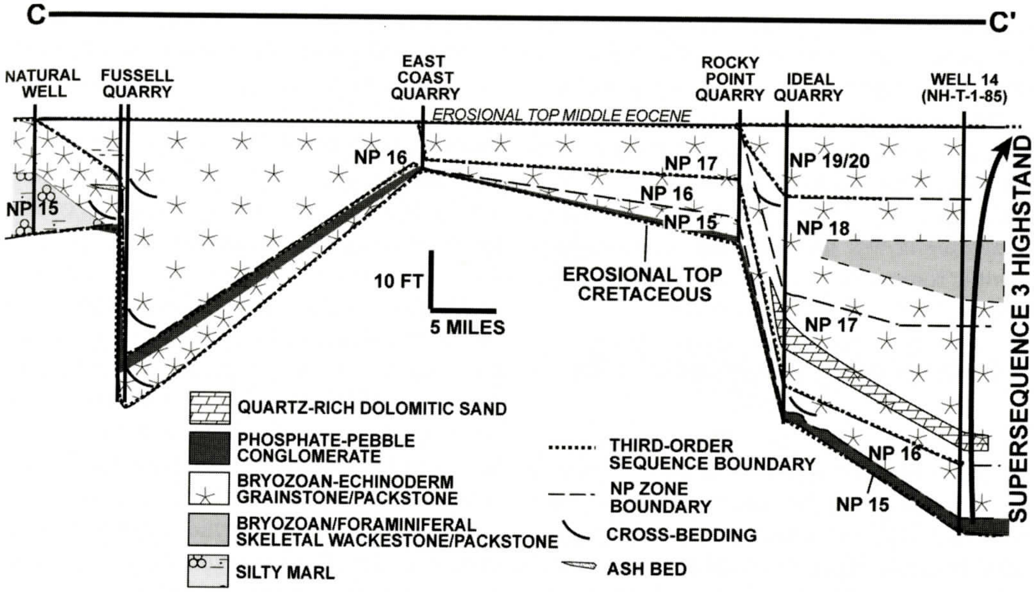

Figure 9. Highly thinned, updip dip cross-section C-C', showing general lithofacies trends and sequence stratigraphy of the prograding Supersequence 3 highstand from the Middle Eocene Castle Hayne Formation (limestone) on the Cape Fear arch (Onslow Block of Harris and Laws 1997). Lithologic data and age picks from updip outcrops are compiled from Worsley and Laws (1986) and Zullo and Harris (1987). Note highly variable package thicknesses and irregular erosional removal of section in updip areas of the basin, which combined with similar textural fabrics of updip sequences to complicate correlation between outcrops for years. Biostratigraphic evidence and regional cross-sections (Figure 6A) indicate that the updip section preserves only the highstand portions of sequences from the Supersequence 3 highstand. Location of cross section is shown in Figure 1.

contrast, the Onslow Block underwent limited subsidence, resulting in predominantly shallow shelf facies in the southern study area. Agreement in ages of the Paleocene sequences in North Carolina with the Haq *et al.* (1988) global eustatic curve led Harris and Laws (1997) to invoke a eustatic control, as did Miller *et al.* (1998) in New Jersey (Fig. 2).

Regional climatic warming throughout the Paleocene resulted in transition from wet temperate to moist subtropical climates on the Atlantic margin, in step with global warming trends (Nystrom *et al.*, 1991; Frakes *et al.*, 1994). The appearance of large benthic foraminifera in Upper Paleocene deep inner shelf facies support this warming trend (Figs. 5, 7). Late Paleocene progradation of the inner-shelf break, coupled with increased coarse siliciclastic input indicate sedimentation exceeded available accommodation on the inner shelf during the late highstand.

Supersequence 2 (Lower Eocene)

Deposition of Supersequence 2 (Table 2) followed a major fall (up to 100m) in relative sea-level, expressed downdip as a series of wedges on offshore seismic data, related to cooling after the global Paleocene-Eocene thermal maximum–induced flooding event (Bralower *et al.*, 2002). Shelf flooding along the downdip axis of the Albemarle basin resulted in deposition of thin, shallow water transgressive units on the inner shelf, followed by thin, but widespread deep shelf marls (Figs. 6A, 8A). Highstand deposition formed an upward shallowing succession with deposition of bryozoal sediments on the low relief Hatteras buildup near the inner shelf margin. Highstand deposition terminated near the end of the Early

Eocene, when thin, prograding sequences with siliciclastic caps were abruptly flooded by the thick shelf carbonate package of Supersequence 3. Global isotopic, faunal, and floral data indicate that the Cenozoic thermal maximum occurred in the Early Eocene (Miller *et al.*, 1987, 1998; Prothero, 1994; Berggren *et al.*, 1998), supported in this study area by abundant large benthic foraminifera (cf. nummulitids and orbitoids) in bryozoal shelf sediments.

Supersequence 3 (Middle-Upper Eocene)

Supersequence 3 is described in Table 2. A quartz sand unit in the eastern Albemarle basin records a low-magnitude (less than 50m) sea-level fall prior to deposition of Supersequence 3 (Fig. 6A). Sea-level fall resulted from latest Early Eocene global cooling, which continued into the Middle Eocene (McGowran *et al.*, 1997). Widespread Middle Eocene flooding of the entire present coastal plain area suggests that both the Onslow and Albemarle blocks may have undergone increased subsidence at this time, making this event more pronounced than the larger amplitude eustatic sea-level rise of Supersequence 2 (Harris and Laws, 1997). Thin, basal phosphatic conglomerates deposited on the southern basin margin (Onslow Block) reflect active ancestral Gulf Stream scouring and sediment-bypass, with earlier strata being highly thinned by erosion and limited accommodation space (Figs. 6A, 9). In the central basin, much of the inner shelf accommodation space was filled during transgression by the large Hatteras buildup composed of marginally subtropical echinoderm-bryozoan facies with scattered large benthic foraminifera (nummulitids and orbitoids; Fig 6A). A widespread, relatively thick quartz sand blanket across the Albemarle Block and mantling the Hatteras buildup reflects the onset of global cooling and aridification into the later Eocene (Figs. 6A, 8A; Miller *et al.*, 1987; McGowran *et al.*, 1997). Renewed flooding and warming in the latest Middle Eocene is marked by the return of widespread bryozoal carbonate deposition, which filled remaining topographic lows north and south of the Hatteras buildup to form a flat-topped shelf. A short-lived, small amplitude eustatic rise in the Late Eocene allowed deposition of intercalated mollusk shell beds and fine terrigenous silts and sands to the north of the Hatteras buildup on the Albemarle Block, where downwarping and compaction of fine sediments may have generated accommodation space (Fig 6A).

The later Eocene cooler climates, greater siliciclastic influx, and a change to a more flattened shelf geometry (accommodation limited) may have inhibited bryozoan-rich carbonate assemblages, compared to Middle Eocene strata. Timing of third-order sequences corresponds with cycles recognized by Miller *et al* (1998) on the New Jersey margin, which suggest a global control on relative sea-level changes, possibly tied to changes in global ice volume.

Supersequence 4 (Lower Oligocene)

Supersequence 4 is described in Table 2. Isotopic data and Antarctic dropstones indicate that an abrupt major global cooling in the Late Eocene marked the transition from global greenhouse to icehouse climates and culminated in the sea-level lowstand of the basal Oligocene (Miller *et al.*, 1987; Denison *et al.*, 1993; Prothero, 1994; Zachos *et al.*, 1994; McGowran *et al.*, 1997). In North Carolina, cooling resulted in pronounced development of Lower Oligocene lowstand deposits seaward of the offshore terminal Eocene inner-shelf margin. On the inner shelf, patchy quartz sands were deposited during third order lowstands and early transgressions. Return to warmer climates caused a large Early Oligocene sea-level rise, which drowned the North Carolina inner shelf and resulted in widespread deposition of marl across the inner shelf. Elevated sea-levels allowed significant ancestral Gulf Stream incision across the deep shelf and possible initiation of localized upwelling current via gyres, resulting in deposition of phosphatic units north of Cape Hatteras (cf. Riggs, 1984; Popenoe, 1985; Fig. 6B).

The molluscan faunas within the overall shallowing upward inner shelf succession indicate that local climate remained relatively warm, perhaps in part reflecting warming by ancestral Gulf Stream waters (Baum, 1977; Rossbach and Carter, 1991). However, warm water faunas characteristic of Eocene warm water carbonates are notably absent. The three third-order sequences evident on offshore seismic (Snyder *et al.*, 1994) and in a few of the onshore wells, may corresponds with three Early Oligocene events from New Jersey described by Kominz and Pekar (2001). However, the absence of age control prevents correlation of these events as eustasy-driven features.

Supersequence 5 (Upper Oligocene)

Supersequence 5 is described in Table 2. Major global cooling resulted in a significant sea-level fall, and caused localized deposition of Supersequence 5 lowstand sediment wedges on and at the foot of the Lower Oligocene (Supersequence 4) terminal inner-shelf break. The subsequent warming-induced rise flooded the North Carolina shelf, initiating widespread deposition of inner shelf sands and sandy mollusk carbonates (Figs. 6B, 8B). Gradual, long-term eustatic sea-level fall maintained shallow water, agitated settings during highstand progradation of the inner shelf. Areas with accommodation space not filled by Supersequence 4 deposition had water depths sufficient to allow muddy oolitic phosphates and silty-fine sands to accumulate. Upper Oligocene oolitic phosphate sands, like their predecessors, probably were associated with gyres spun off the ancestral Gulf Stream north of the shelf promontory at Cape Hatteras, while the silty sands in the northern study area were distal to the extensive deltas developed to the north in Virginia (Mixon *et al.*, 1989; Poag, 1992). Elsewhere, accommodation space was quickly filled by siliciclastic sediment influx, combined with biogenic, mollusk-dominated, cool-water carbonates during gradual sea-level fall. This resulted in extensive progradation of the inner shelf break and the formation of broad, seaward-dipping clinoforms.

Some workers have interpreted low diversity mollusk faunas with few warm water species as indicators of relatively cool inner shelf waters (Rossbach and Carter, 1991). Three to four inner shelf third-order sequences evident in seismic data (Snyder *et al.*, 1994) and locally in well cutting logs, may correspond with sequences identified by Kominz and Pekar (2001) on the New Jersey shelf, but lack of age control limits direct correlation of these features to eustatic curves.

OUTCROP EXPRESSION OF SEQUENCES

The regional cross sections across the Albemarle basin provide a regional sequence stratigraphic context for features observed in updip exposures. Limited age control prevents direct correlation of many subsurface events with outcrop surfaces, but stacking patterns observed in wells across the basin demonstrate how outcrops tie into the regional basin framework.

Eocene outcrops record the updip limits of prograding third-order sequences deposited during the Supersequence 3 highstand. Supersequence 2 strata have not been recognized in outcrop. The outcrop expression of Supersequence 3 transgressive strata may have been eroded by the onshore migration of the ancestral Gulf Stream scour during this time of significantly elevated sea-level. If true, phosphate-rich conglomerates of the New Hanover Member (when directly above Cretaceous strata) may preserve a record of the updip expression of Supersequence 2 and early Supersequence 3 transgressive strata within component reworked clasts. Progradational geometries associated with Supersequence 3 highstand outcrops likely account for apparent age discrepancies between closely-spaced outcrops of similar lithologic units (Fig. 9). Paleocene outcrops were not included in this study, but their generally glauconitic sand composition fits within the regional subsurface stratigraphic framework of Supersequence 1. Variably silty sands were deposited in a shallow shelf-distal deltaic setting during the Supersequence 1 late transgression to early highstand. Similar glauconitic sands are encountered in the subsurface Paleocene section near the base of the supersequence along the

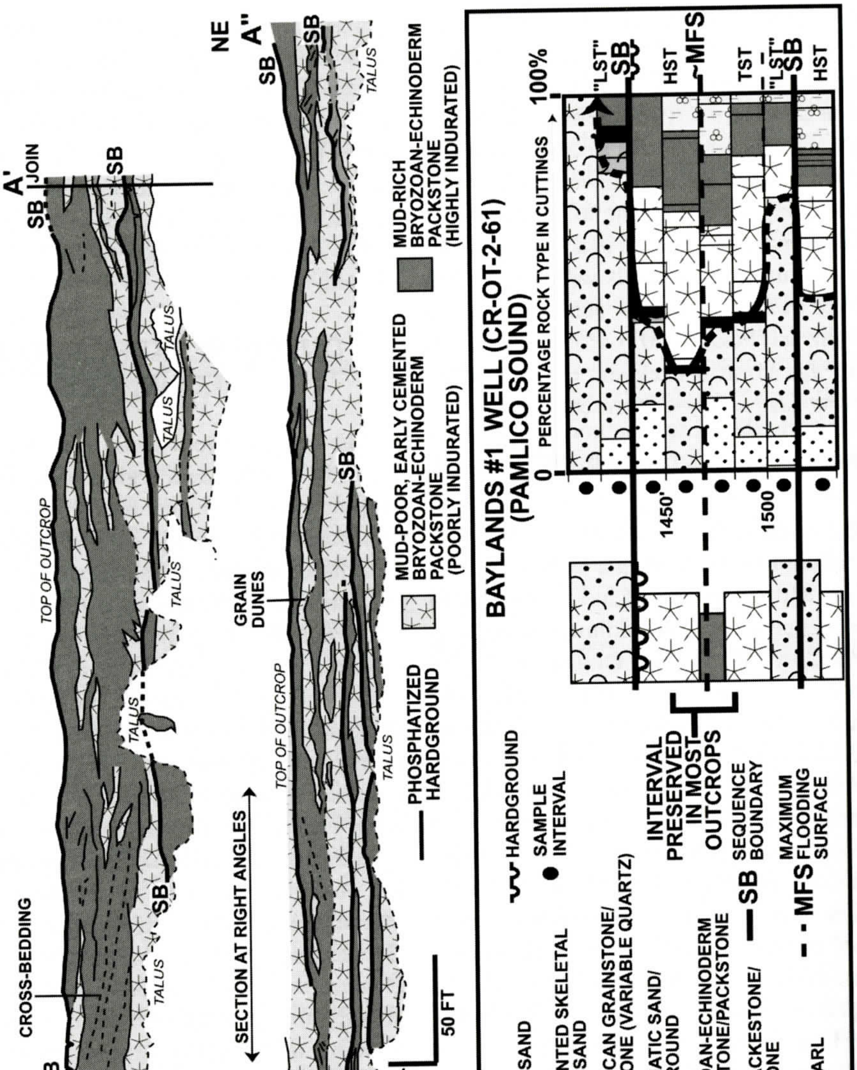

Figure 10. (A) Digitized photopan of a quarry face from the Martin-Marietta Catherines Lake quarry (taken 1998), showing complex lateral variations and stacking patterns from bryozoan-echinoderm-dominated skeletal carbonates from Middle Eocene exposures of the Castle Hayne Limestone. Subtle variations in grain size/content and diagenetic histories record the transgressive to highstand record in this highly-thinned, updip setting. Cross-bedding and east-southeast-oriented dune forms indicate deposition during ebb stages of storms in this mid-shelf skeletal carbonate unit. (B) Comparison of these stacking patterns with sequences recognized in well cuttings (bottom right) from the Baylands #1 well (Pamlico Sound, Carteret County) demonstrate the value of well cuttings in preserving a more complete stratigraphic record from the thicker basin section. Note the presence of quartz sands during lowstand-early transgression in well cuttings sequences. Differentiation of transgressive versus highstand strata in cuttings, as suggested by stratal variations in outcrop can only be made in thick sequences with close sample spacing in well cuttings.

margins of the basin depocenter (Fig. 6A), where they define the supersequence transgressive surface. Downdip, glauconitic facies grade into widespread argillaceous lime muds (marls). Greater abundance of glauconite to the north reflects increased siliciclastic influx from the Chesapeake region, as well as transition to more temperate conditions.

Most Eocene outcrops record upward-fining successions and decrease in cementation. Strata were deposited during the late transgressive to early highstand stages of third-order sequences and closely resemble textural trends observed in third-order sequences from downdip well cuttings (Fig. 10). However, downdip sequences often preserve a record of lowstand to early transgressive siliciclastic sedimentation, which is rarely expressed updip (Fig. 10B). Instead, updip sections often have a basal phosphatic condensed interval that corresponds with the sequence boundary, transgressive surface, and possibly part of the preceding late highstand (Figs. 9, 10). As such, only a limited amount of time from each third-order sequence is recorded in outcrop sections. Condensed sections likely developed as the wave-swept, inner shelf migrated seaward during the late highstand of the preceding sequence. They were moderately cemented, thus allowing preferential preservation during subsequent subaerial exposure. As sea-level rose during the next transgression, these beveled surfaces provided a hard substrate for reinitiation of encrusting carbonate biotas when the shelf flooded to depths sufficient to limit wave abrasion. In downdip wells, phosphatic material and coarse siliciclastic material are associated with transgressive surfaces, sequence boundaries, and highstand strata, but do not consistently form at a single time in the depositional sequence.

East-oriented cross-bedding and dunes observed in updip Middle Eocene outcrops indicate that much of the sediment deposition occurred during periods of large swell waves or major storms, with dunes forming during ebb flows (Fig. 10A). Grain-rich units are more commonly cross-bedded and likely formed in higher energy conditions during third-order transgression. Increased carbonate mud and greater bioturbation in upper parts of sequences indicate lower energy conditions, likely below the influence of fair-weather wave base, during sequence highstands (Figs. 9, 10).

Mollusk-dominated assemblages in Upper Eocene outcrops resemble transgressive strata from Eocene third-order sequences in downdip wells. Timing of deposition updip corresponds with a thin, large amplitude flooding event within the late Supersequence 3 highstand expressed downdip as a thin mud-rich carbonate interval. The third-order flooding event appears to correspond temporally with a short-lived, but significant warming event recognized in the Southern ocean (Khirthar restoration of McGowran et al., 1997). This rapid flooding event may explain the Upper Eocene package occurrence within the larger-scale, progradational Middle to Upper Eocene succession.

Oligocene strata in outcrop closely resemble materials observed in well cuttings, but the downdip wells preserve much thicker third-order sequences (Fig. 11). Outcrops record the regional Supersequence 4 transgression to maximum flood as a thin silty marl (Lower River Bend or Trent Formation), which corresponds with a similar marl that extends across much of the subsurface basin (Fig. 6B). Most outcrops, however, expose the Supersequence 4 and 5 highstand strata. These strata contain well consolidated, mollusk packstone-grainstone intervals, and are thus more resistant to erosion. Outcropping units were deposited in shoreface to shallow inner shelf settings, often proximal to ancestral fluvial point sources. Deposition of inner shelf facies within the main outcrop belt, possibly combined with more widespread deposition of variably sandy mollusk-dominated facies on the flattened Oligocene shelf and cooler climatic conditions, resulted in more widespread mollusk-dominated facies in Oligocene strata.

Sequence boundaries commonly underlie quartz sands in both outcrop and subsurface sections, sometimes corresponding with a phosphatic hardground (Fig. 11A). Transgressive strata are dominated by quartz sands, with skeletal material increasing toward the maximum flood. Downdip sequences often have thin,

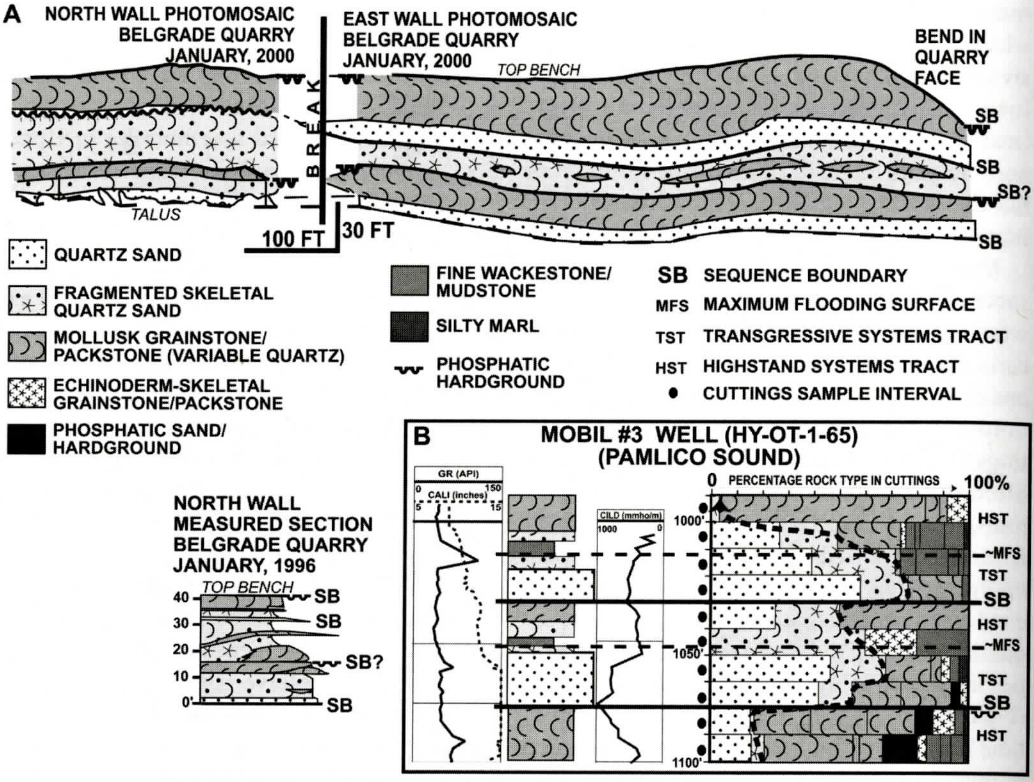

Figure 11. (A) Digitized photopan of a quarry face from the Martin-Marietta Belgrade quarry (taken 1999), showing lateral variations and stacking patterns from quartz sand and variably sandy mollusk-dominated skeletal carbonates from Upper Oligocene exposures of the Belgrade Formation. Note that sequence boundaries correspond with the bases of quartz sands, often associated with planar phosphatized hardgrounds or sands, and that complex lateral facies variations exist at the outcrop scale. (B) Comparison of outcrop stacking patterns with well-cuttings data (bottom right) from the Mobil #3 well (Pamlico Sound, Carteret County) demonstrate the consistent stratal expression of depositional sequences in the much thicker basin section. Note the more pronounced evidence of maximum flooding in the cuttings expressed by the presence of fine wackestones and silty marl cuttings fragments and the gradual increase of mollusk-dominated limestones during sequence highstands. Observation of complex facies variations in outcrop, coupled with limited biostratigraphic control (largely a function of unfavorable lithologies for sample preservation) makes correlation of sequences in outcrop with subsurface events more problematic than in the Eocene section.

mud-rich, phosphatic to marly carbonate fragments in cuttings that mark the late transgressive systems tract to maximum flood (Fig. 11B). Updip preservation of these thin flooding intervals is unlikely, given their limited expression in thicker, downdip wells. Highstand strata are dominated by coarse, variably sandy mollusk grainstone-packstone units in outcrop (consolidated bench forming units; Fig. 11A). Mollusk-dominated carbonates also significantly increase in abundance during third-order highstands in downdip wells (Fig. 11B). However, they often are difficult to differentiate from skeletal sands in cuttings, due to the small sample size of cuttings fragments. Significant lateral variation in facies observed in some Oligocene outcrop intervals present similar problems in identifying components of sequences in well cuttings, but comparison of stacking patterns in multiple wells helps to differentiate significant facies variations within a sequence stratigraphic framework (Figs. 5, 7).

CONCLUSIONS

Data from thin-sectioned well-cuttings, wireline logs, biostratigraphic, and seismic data were used to construct a sequence stratigraphic framework for the 0-500 m thick, subsurface Paleogene shelf succession in the Albemarle Basin of North Carolina. Regional observations of the subsurface stratigraphy help to explain the depositional setting and sequence stratigraphic context of thin outcropping strata in updip areas of the basin. Limited sedimentation rates on this passive margin following Upper Cretaceous drowning gave rise to a distinctive dual-break shelf geometry, which is typical of the southeastern U.S. Atlantic margin even today. The inner shelf was characterized by quartz sand and sandy mollusk facies inshore, passing seaward into a broad, wave-swept, sediment-starved abraded shelf, and then into storm-influenced bryozoan-echinoderm carbonates to depths of several tens of meters. Deeper water, fine-grained carbonates and marls were deposited on the inner-shelf only during major highstands in relative sea-level.

Long-term shelf subsidence rates were low, but major crustal blocks beneath the basin appeared to have undergone a complex history of differential subsidence that modified the effects of eustatic sea-level changes across the coastal plain. Arches or structural blocks bordering the basin (Onslow Block and Norfolk arch) acted as positive elements, localizing shallow shelf deposition during low magnitude sea-level highstands, while the more rapidly subsiding intervening Albemarle Block developed a thick, more open marine section. The strong eustatic signal documented by Miller et al. (1998) from the Paleogene of the New Jersey coastal plain agrees with the general amplitude and timing of stratal development from North Carolina, supporting eustasy as the dominant control on deposition.

Widespread deep water conditions followed drowning of the inner shelf during the Paleocene, resulting in deposition of updip glauconitic sands and thick, downdip shale and marl. Following the terminal-Paleocene lowstand, Eocene flooding of the inner shelf initiated shelf deposition dominated by bryozoal limestones that locally developed into the large inner shelf Hatteras buildup. Widespread quartz sands that developed during high frequency sea-level falls, punctuate the carbonate-dominated succession. Following Late Eocene cooling and onset of global icehouse climates, Oligocene accommodation space was greatly decreased, except during initial deep shelf flooding. Reduced accommodation, combined with overall cool global climate and low sea-level, favored widespread deposition of quartz sand and sandy molluscan facies of the two Oligocene supersequences.

Global climate was a major influence on supersequence development. Major cooling events and associated sea-level fall in the latest Cretaceous, end of the Eocene, medial Oligocene, and end Oligocene generated supersequence boundaries and transitions to cooler water, sand prone facies, while a significant Middle Eocene cooling event generated a widespread sand unit throughout the region. Major warming events and associated sea-level highstands, were associated with large scale transgression of the shelf and widespread warm water subtropical carbonate deposition with conspicuous bryozoal carbonates and a large Eocene carbonate buildup. The ancestral Gulf Stream eroded and remobilized sediment on the deep shelf during post-Paleocene highstands, and even extended onto the inner shelf during the Middle Eocene supersequence highstand; it scoured the upper continental slope during supersequence lowstands.

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SOUTHEASTERN GEOLOGY
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WILMINGTON HARBOR DEEPENING, CAPE FEAR RIVER, SOUTHEASTERN NORTH CAROLINA, GEOTECHNICAL CONSIDERATIONS

W. BURLEIGH HARRIS

Department of Earth Sciences
University of North Carolina at Wilmington
Wilmington, North Carolina 28403

TONG HAW

U.S. Army Corps of Engineers
Nashville District
P.O. Box 1070
Nashville, TN 37202-1070

ABSTRACT

The U.S. Army Corps of Engineers (USACE) is deepening the Wilmington ship channel between mile -6.7 in Long Bay and mile 2.9 (Cape Fear River) to -44.0-ft mean lower low water (MLLW) or -45.0-ft MLLW (where rock is encountered), and between mile 2.9 and mile 27.2 (at Wilmington) to -42.0-ft (MLLW) or -43.0-ft MLLW (where rock is encountered). Rock engineering properties were determined in order to formulate a construction design and to produce plans and specifications for bidding and construction. About 200, 2-in (NW) and 4-in (4-in x 5 1/2-in) core holes were drilled and 250 miles of seismic "boomer" data collected. Examination of selected data indicates that the stratigraphy controls the occurrence of rock, while sediment type, joint density, unconformity occurrence, and bed thickness control rock strength. Where thick, well-lithified, Cretaceous or Tertiary limestone (Rocky Point Member of the Peedee Formation, Bald Head Shoals Formation, or Castle Hayne Limestone) subcrop the river within the dredging prism, rock elevations in the channel are high. In these areas, contractors may choose to drill and blast to deepen the channel; however, this method poses greater potential damage to the environment. Where unlithified Tertiary and Cretaceous sand (Peedee Formation, Island Creek Member of the Peedee Formation, Yaupon Beach Formation, River Bend Formation) subcrop the river within the dredging prism, rock elevations are low. In these areas, rock-cutter-head type dredge or dipper dredge, can be used to achieve deepening to the permitted depth. These techniques mitigate damage to the environment as compared to blasting.

INTRODUCTION

Wilmington Harbor, a Federal navigation project maintained by the U.S. Army Corps of Engineers (USACE), extends from the Atlantic Ocean to the Port of Wilmington, a length of about 35 miles along the Cape Fear and Northeast Cape Fear Rivers in southeastern North Carolina (Fig. 1). Although the Cape Fear River has been used for several hundred years for shipping, in 1949 the State of North Carolina approved the issue of $7.5 million in bonds for construction and improvement of the seaports of Wilmington and Morehead City. In 1952, terminals equipped to handle oceangoing vessels were completed. Prior to 1958, Wilmington Harbor ocean bar channels in Baldhead Shoals, Long Bay were -35-ft deep by 400-ft wide and the main river channel from Southport to Cape Fear Memorial Bridge -34-ft deep by 400-ft wide. In 1962 Congress authorized further deepening of Wilmington Harbor ocean bar channels to -40-ft Mean Low Water (MLW) by 500-ft wide, and the river channel between Southport and the Cape Fear Memorial Bridge to -38-ft MLW by 400-ft wide. In 1996 Con-

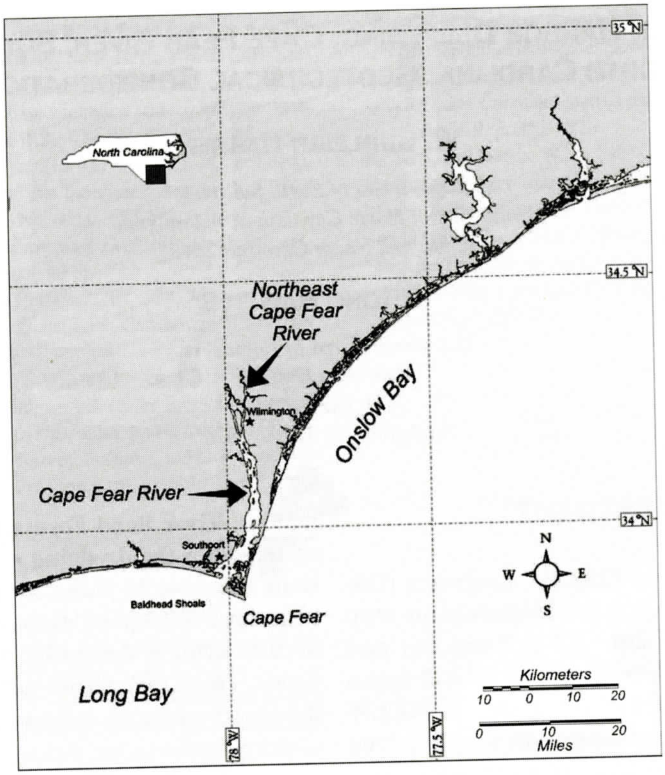

Figure 1. Southeastern North Carolina showing the location of the Cape Fear and Northeast Cape Fear Rivers.

gress (Wilmington Harbor, N.C.-96 Act) authorized deepening and widening the ocean bar channels (Baldhead Shoals) to -44-ft MLLW (Mean Lower Low Water), the river channel between Southport and the Cape Fear Memorial Bridge to -42-ft MLLW, and the reach above the Cape Fear Memorial Bridge to -38-ft MLLW. This authorization resulted from the current widths and depths not being adequate for vessels 800 ft to 950 ft in length with 32- to 38-ft drafts. MLLW datum was introduced between 1962 and 1996 and results in a 0.6-ft difference in the upper reaches of the project.

Deepening of the channel bars (Ocean Bar, Long Bay) and the rivers (Cape Fear, Northeast Cape Fear) has resulted in the drilling of about 200, 2-in (NW) and 4-in (4-in x 5 ½-in) core holes in some cases to 100 ft in depth and acquisition of about 250 miles (400 km) of seismic "boomer" data. Core samples have provided detailed information on the geotechnical properties of rocks to be encountered within the proposed dredging prism of the rivers and offshore channel in Long Bay (Zapata Engineering, 1999). Seismic reflection data provided limited information on the distribution of units and depth to Top of Rock; consequently the USACE has placed more reliance on boring data. Boring data has been used to develop and map the geologic framework of Long Bay and the tidally influenced areas of the Cape Fear and Northeast Cape Fear Rivers. Harris and Haw (2000) presented a preliminary analysis of the geotechnical considerations considered in channel deepening.

This paper presents information on how the geology of southeastern North Carolina influences and controls techniques chosen to deepen the Cape Fear River between Southport and Wilmington. The realigned Ocean Bar Channel in Long Bay and the channel in the Northeast Cape Fear River are not discussed in this paper; rather, the emphasis is on the Cape Fear River channel south of the Cape Fear Memorial

Bridge. The main focus of the paper is to present geotechnical data that differentiates dredgeable material from material that requires blasting. A primary construction consideration linking geology and engineering properties is related to the anticipated method used to widen and deepen the channel. Where rock was predicted to occur within the dredging prism, anticipated rock engineering properties impacted the method used, for example, dredging versus blasting. The determination of whether rock can be dredged with a rock cutter head or requires drilling and blasting depends on physical properties indicated by the unconfined compressive strength, thickness, lateral extent, and joint or fracture frequency (RQD). Specific site characteristics used to develop the idea that the geology controls the method chosen to deepen the channel include: 1) stratigraphy, 2) unit distribution, 3) rock type and induration, 4) porosity, 5) the relationship between unit and geotechnical properties (unconfined compressive stress, rock quality designation, etc.), and 6) impact of unconformities on unit hardness. Throughout this paper, channel reaches are used to refer to specific areas along the Cape Fear River; the reaches are identified along the river in Figure 2.

An environmental concern facing the USACE in deepening Wilmington Harbor was the potential destruction of endangered or protected species. Some environmental groups and regulatory agencies did not favor blasting as a construction method and threatened to stop project construction if these species were killed. It was essential for the USACE to let a contract where the contractor minimized blasting or its collateral damages to the environment and maximized dredging to achieve the designed harbor depth.

PREVIOUS WILMINGTON HARBOR PROJECTS

Previous deepening events in Wilmington Harbor that contributed to the knowledge of the geology and its engineering significance include a 1964 project to deepen the channel to a -40-ft depth, 1993, Baldhead Shoal Channel dredging to achieve an authorized depth of -40-ft depth, and a 1998 Blast Effects Mitigation Test to judge the efficiency of air curtains to attenuate blast pressures.

In the late 1960's USACE began deepening the Cape Fear River portion of Wilmington Harbor to a depth of -34 ft by dredging. Rock could not be removed by dredging in the areas of Keg Island and Big Island (Fig. 2), and the USACE terminated this contract and contracted with another group who utilized blasting. In litigation arising from this deepening project, the former dredging contractor's geologic consultant concluded that the rock was harder, particularly in areas of unconformities, than represented by the government.

In the early 1990's Baldhead Shoal Channel was deepened to achieve a previously approved project depth of -40 ft. The USACE contracted a rock cutter-head dredge, and studied the project dredging to determine if the entire harbor was capable of being dredged rather than requiring blasting. The USACE concluded that some of the rock could be dredged, but rock associated with unconformities would probably require blasting for removal.

In 1998, the use of air curtains to mitigate blast wave pressures was tested. Analyses of test results concluded that deploying air curtains did not provide a high enough level of effectiveness to warrant its application. Blast wave pressure could be sufficiently controlled by the use of stemming in the blast holes, proper quantity and use of explosives, and use of shock tubing instead of detonation cord to initiate the blasts. The subsurface geologic investigation for blasting for the air curtain test and the excavation of the blasted rock confirmed that the tested rock was better cemented adjacent to unconformities. The thickness of the well-cemented rock varied and in places was underlain by loosely consolidated sediments.

GEOLOGY

The Cape Fear arch, centered in North Carolina, is the primary structural feature in the southeastern Atlantic Coastal Plain Province (Fig. 3). The axis trends northwest-southeast

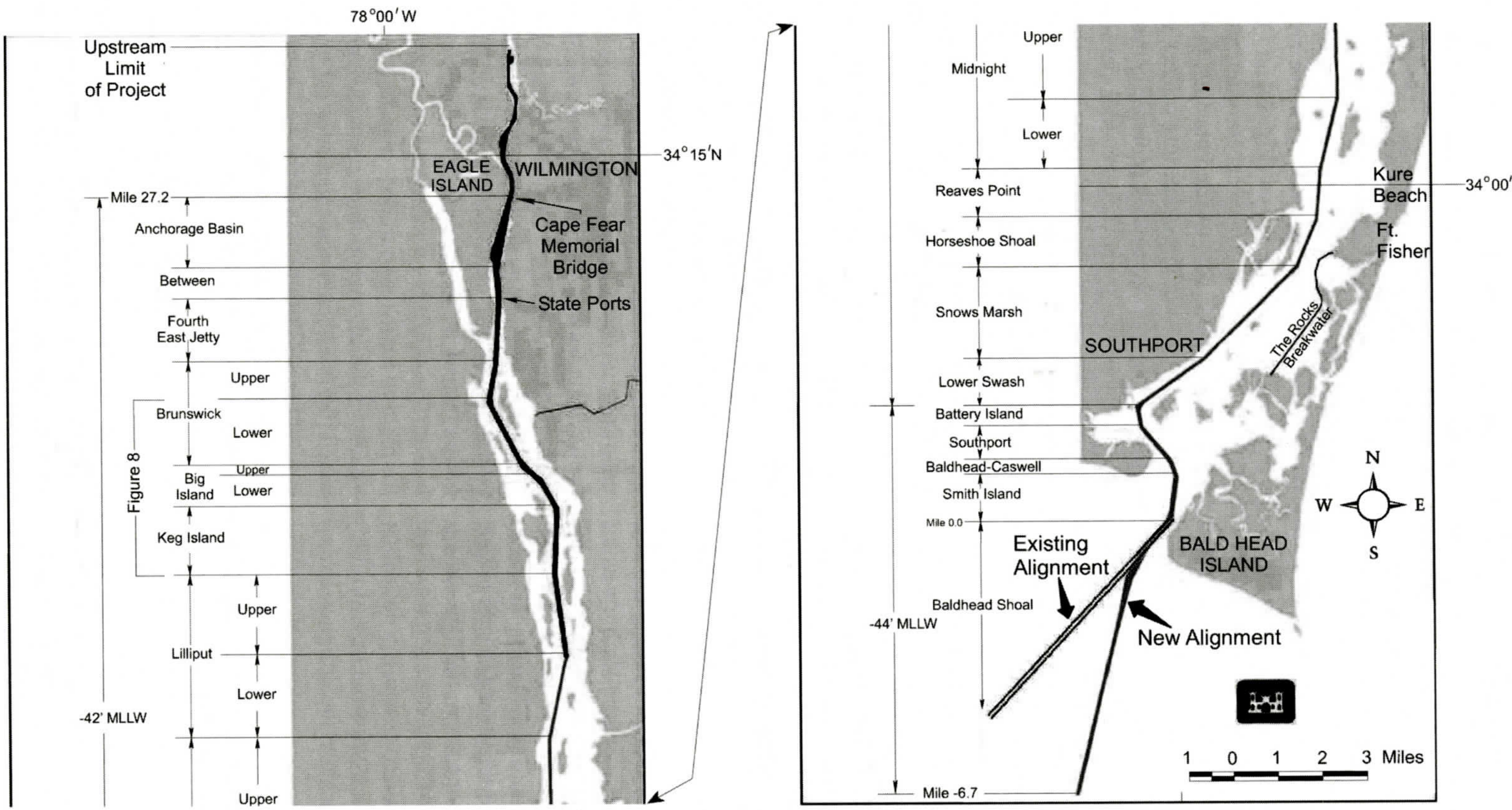

Figure 2. Details of the Cape Fear River illustrating river mileage and U.S. Army Corps of Engineers (USACE) designated areas (reaches). Note that the Existing Alignment of the channel in Long Bay is also referred to as the ocean bar channel.

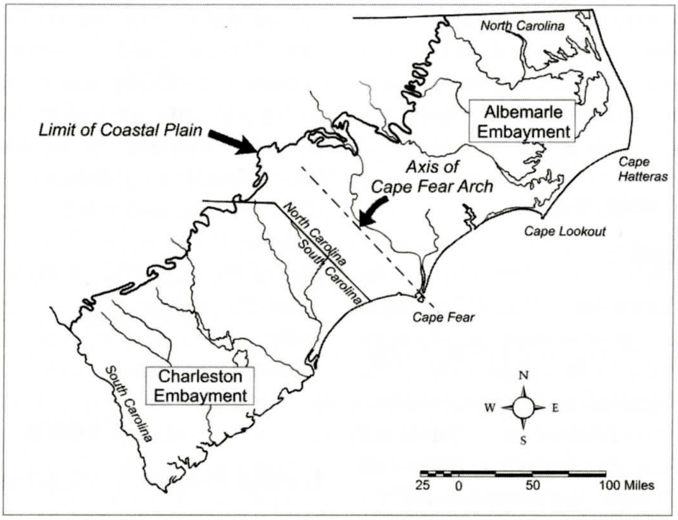

Figure 3. Generalized Atlantic Coastal Plain map of North and South Carolina showing major basins and highs. Placement of the axis of the Cape Fear arch is after Harris and Laws (1997).

and lies north of the South Carolina-North Carolina State line between the Albemarle Embayment to the north and the Charleston Embayment to the south.

The Cape Fear River flows along the approximate axis of the Cape Fear arch between Wilmington and Baldhead Shoals (Figs. 1, 2). The channel cuts through the Quaternary into sedi-

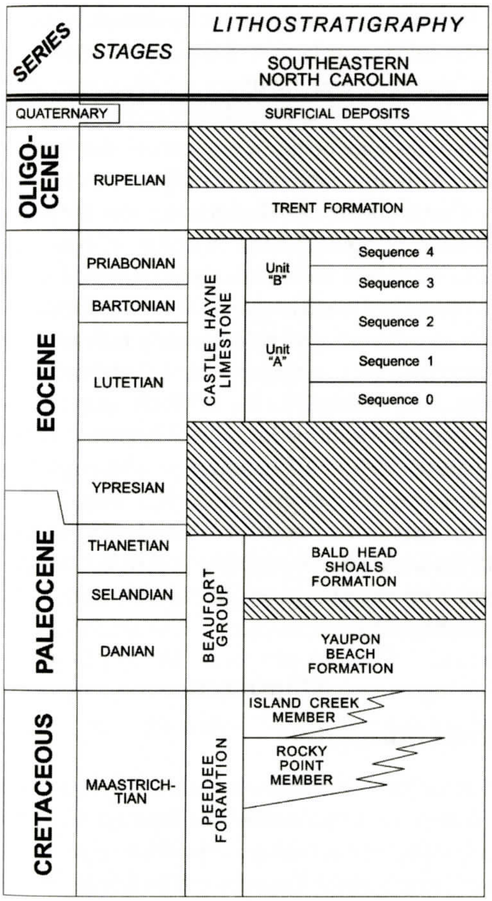

Figure 4. Stratigraphic column of units that occur within the southeastern part of the North Carolina Coastal Plain. Descriptions and spatial distributions of the Rocky Point and Island Creek Members of the Peedee Formation are provided by Harris (1978) and Dockal and others (1998), respectively. Sohl and Owens (1992) also recognized the Island Creek lithology but did place a formal lithostratigraphic name on the unit. Harris and Laws (1994) designated the Beaufort Group recognizing these two formations in southeastern North Carolina. Zullo and Harris (1987) subdivided the Castle Hayne Limestone into sequences and provided lithologic criteria to distinguish unit A from unit B. The Trent Formation is the oldest Oligocene unit recognized in North Carolina (Worsley and Turco, 1979; Zarra, 1989; Rossback and Carter, 1991). Units occurring within the dredging prism of the Cape Fear River that must be removed include the Peedee Formation, the Rocky Point Member of the Peedee Formation, the Bald Head Shoals Formation, the Castle Hayne Limestone and the Trent Formation.

ments and rocks ranging in age from Cretaceous to Oligocene (Fig. 4), with older sediments and rocks updip and younger sediments and rocks downdip. Pre-Quaternary units recognized are discussed below.

Cretaceous

Peedee Formation

The Peedee Formation is Late Cretaceous and consists of dark gray to green, argillaceous, calcareous very fine to fine quartz sand. Two members are recognized at the top of the unit, the Rocky Point and Island Creek. The Rocky Point Member disconformably(?) overlies sediments of the typical Peedee Formation and disconformably underlies either the Island Creek Member of the Peedee, the Paleocene Beaufort Group or the Eocene Castle Hayne Limestone. The Rocky Point Member consists of moderately to well-lithified sandy limestone or friable quartz sand (Harris, 1978). It underlies most of the area of the river but occurs within the dredging prism in the Keg Island-Big Island area and south of Cape Fear Memorial Bridge in the Anchorage Basin (Fig. 2).

The Island Creek Member is an olive gray, poorly indurated, very fine to fine grained, argillaceous dolomitic sand that overlies the Rocky Point Member. It is only recognized along the Northeast Cape Fear River, north of the Isabell Holmes Bridge in Wilmington, and in the northern part of New Hanover County (Dockal and others, 1998) (Fig. 1).

Paleocene

Beaufort Group

Sediments of Paleocene age in North Carolina are referred to the Beaufort Group (Harris and Laws, 1994). Four formations are recognized but only two occur in the southeastern part of the state, the older Yaupon Beach and the younger Bald Head Shoals Formations (Fig. 4). The Yaupon Beach Formation consists of olive green to gray, glauconitic, very fine to fine-grained argillaceous quartz sand and is only recognized in core holes along Ocean Bar Channel in Long Bay (Fig. 1).

The Bald Head Shoals Formation disconformably overlies the Yaupon Beach Formation and disconformably underlies the Eocene Castle Hayne Limestone (Fig. 4). It occurs along the entire length of the Ocean Bar Channel but is best developed and thickest near the mouth of the Cape Fear River. It has also been identified in cores in the Snows Marsh area in the lower part of the Cape Fear River (Fig. 2). The Bald Head Shoals Formation is a moderately to well indurated, sandy, argillaceous, fossiliferous limestone.

Eocene

Castle Hayne Limestone

The Castle Hayne Limestone occurs throughout eastern North Carolina and consists of various limestone types. Generally, the base of the unit is a phosphate pebble conglomerate; the middle is poorly to well-indurated fossiliferous limestone and the upper is soft, unconsolidated limestone. However, these general lithologies may occur in any part of the formation. Although several unconformities divide the Castle Hayne into distinctive parts, the parts are difficult to recognize in cores. The occurrence of minor sand-sized quartz mixed with limestone in cores along the Cape Fear River allows the unit to be divided grossly into a lower part (A) and to an upper part (B), respectively (Fig. 4) (Zullo and Harris, 1987). A well-developed unconformity with several meters of relief separates A and B in outcrop. Although the Castle Hayne Limestone underlies much of the Cape Fear River south of Wilmington, it only occurs within the dredging prism in the Big Island-Keg Island area and the Baldhead Shoals area (Fig. 2).

Oligocene

Trent Formation

The Trent Formation is the oldest Oligocene unit exposed in the North Carolina Coastal Plain (Fig. 4). Although it is primarily recognized north of the Cape Fear River, it is identified in cores offshore Kure Beach in Onslow Bay, and in the Cape Fear River (Snyder and others, 1994; Harris and others, 2000). The unit off Kure Beach consists of sandy foraminiferal silt and silty clay and dolosilt. This same unit is recognized in three cores from the lower part of the Cape Fear River within the dredging prism in the Snows Marsh area (Fig. 2), but only a few feet are present.

Quaternary

Undifferentiated Surficials

Unfossiliferous sand overlies the older fossiliferous units and is generally light gray to yellow, medium to fine-grained with trace quantities of clay, gravel and peat. In some case, dark organic-rich sand occurs. These deposits are variable in thickness but usually are less than a few feet thick and represent various ages. Included in the Surficial deposits are modern sediments that occur in the Cape Fear River channel.

EXPLORATION PROGRAM

Borings

Beginning in 1987, test borings were used to examine the sediment and substrate of the Cape Fear and Northeast Cape Fear Rivers and the Ocean Bar Channel in Long Bay. Since 1993, 233 soil and rock borings and 234 wash probes have been made; however, as this paper concentrates on the Cape Fear River, only soil and rock borings drilled between 1993-1998 located in the Cape Fear River channel were examined (Appendix 1). Locations of wash probes are not given but are available upon request. Soil borings have been made by splitspoon and shelby tube boring methods. One hundred and forty-eight 2-in (NW) and 4-in (4 x 5-1/2-in) core borings, in some cases to 100 ft in length, have been completed since 1989 in Wilmington Harbor.

When rock was encountered in the harbor deepening project, core borings were necessary to determine the quality and quantity of rock to be removed during channel deepening and construction. Interpretation of the geology from core borings helped establish geological trends such as direction and dip of rock, unconformities, and areal distribution of geological formations. General physical characteristics of the material to be removed were also determined based on knowledge of the geological formations encountered. Cores were generally drilled in areas where wash-probes and seismic suggested that rock occurred within the dredging prism. All cores are stored at a USACE storage facility in Wilmington.

Splitspoon Boring

Representative soil samples were collected by splitspoon sampler from selected locations and samples were stored in sealed jars. Failure to drive the splitspoon more than a foot of depth with one hundred blows was determined to represent refusal. The point of refusal of the splitspoon sampler defines Top of Rock.

Shelby Tube Boring

Shelby tube soil sampling consisted of using drill rig hydraulics to push a 3- or 4-in diameter metal tube approximately 2 to 3 ft into the material being investigated. The interval of material sampled by Shelby tube method was usually determined from splitspoon borings. Shelby tube samples were extruded from the sample tube and tested for soil strength characteristics as they related to stability questions.

Core Boring

Core borings were usually drilled in conjunction with other borings. Splitspoon sampling was conducted through overburden to the Top of Rock, casing set, and the remainder of the site was cored to a predetermined depth. Two core diameters were used for the investigation of Wilmington Harbor. Some 4-in diameter core was drilled to obtain better core recovery when the rock was soft, fractured, friable, or contained interbedded soft zones. One- to two-in core borings were utilized in poorly consolidated, fractured, or interbedded rock.

Wash Probes

Wash probes were generally used to identify areas where rock occurred within the dredging prism but without having to increase core hole density. Wash probes were made by jetting water through an open-end splitspoon sampler, fishtail drill bits, roller rock bits, or opened end metal pipe to a predetermined depth or until the probe could no longer penetrate the material being investigated. When side-wall friction of the material in the hole being probed prevented the probe from penetrating deeper, the hole was abandoned without determining the Top of Rock. When the probe encountered material that did not allow penetration (a solid ringing sound was apparent when the probe was bounced on the material) and it was judged by the drilling inspector to be *in situ* naturally occurring material (bedrock), the point of refusal was defined as Assumed Top of Rock. Borings were usually drilled or probed to approximately eight ft below the design-dredging prism to encompass the subsurface that may require subdrilling for blasting. To determine the subsurface top of rock in the Ocean Bar Channel realignment, probes were taken to approximately -70 ft MLLW or to probe refusal, whichever occurred first.

Seismic

Several seismic (boomer) surveys were conducted in the Cape Fear River and Atlantic Ocean parts of Wilmington Harbor to help determine the areal extent of the Top of Rock. Although original seismic surveys were localized where individual projects were authorized, two seismic surveys were later conducted a few years apart approximately the length of Wilmington Harbor and southeast of the existing Ocean Bar Channel (Fig. 2). Comparison of Top of Rock determined from seismic to Top of Rock determined from core borings revealed that the seismic survey was not reliable under conditions where signals were attenuated by sediment or gaseous conditions. In those instances no interpretations could be made, and in other instances, picks of Top of Rock were not sufficiently close to the borehole-determined Top of Rock to be considered reliable. Seismic data were capable of revealing generalized subsurface geologic trends that were correlated to core hole data. As seismic reflection data provided limited information on the distribution of units and the depth to Top of Rock, the USACE placed more reliance on borings for unit and rock presence. No seismic lines are illustrated in this paper; selected profiles are available in a report prepared by C and C Technologies (1997).

ROCK ENGINEERING PROPERTIES AND CHANNEL CONSIDERATIONS

Rock engineering properties determined were the degree of cementation, unconfined compressive strength, joint frequency, texture, fabric, distribution and thickness, and the degree and influence of weathering on the strength of the material. Factors assessed to determine the dredgeability of the rock for a given channel design are discussed below and are illustrated in Figures 5-7. Although lateral variability in these factors occurs because of variations in stratigraphy, they are considered as a whole to be representative within each stratigraphic unit.

Unconfined Compressive Strength

Percent Core Recovery

Unconfined compressive stress (UCS) tests have been used to assess rock excavation technique. This parameter is commonly used in the dredging industry more than triaxial compressive or direct shear tests to assess rock strength. Eighty-seven samples were selected from 50 WH98 core holes for tests of unconfined compressive strength. In addition, unconfined compressive strength tests are reported for 31 WH93 and five WH94 core samples. Cores, formations and peak load failures are keyed to the principal units that occur in the dredging prism in Figure 5. Compressive stress tests for identified units were performed by Law Engineering and Environmental Services, Raleigh, N.C., on samples taken from 1998 core holes.

Percent core recovery (PCR) or rock intact is another parameter used to assess rock strength. Depending upon rock type and the quality of the drilling, the lower the percentage of core recovered usually indicates the rock has low strength.

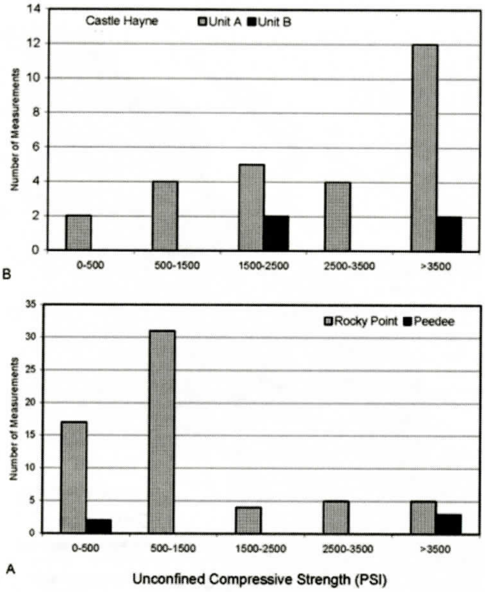

Figure 5. Unconfined Compressive Stress (PSI) of Peedee Formation, Rocky Point Member, and Castle Hayne Limestone, Wilmington Channel.

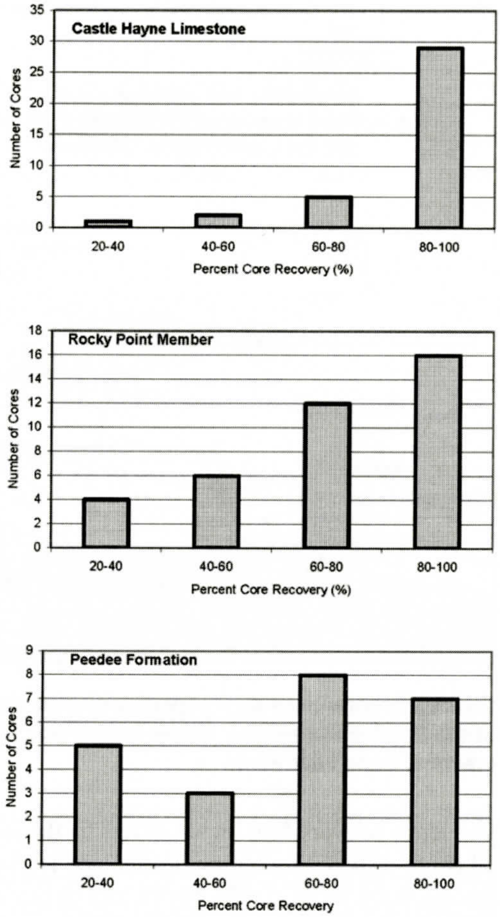

Figure 6. Comparison of Percent Core Recovery, Peedee Formation, Rocky Point Member and Castle Hayne Limestone, Wilmington Channel

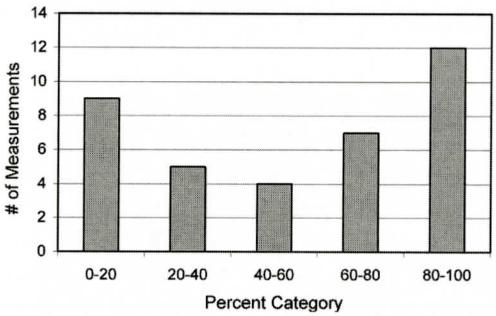

Figure 7. Rock Quality Designation (RQD) in Dredging Prism (-43 ft) for cores in Wilmington Channel. See text for discussion of RQD determination.

The concept is that rocks of low strength or high fracture frequency are easily lost during the drilling process whereas rocks of high strength or low fracture frequency are more easily recovered. Percent core recovery is determined by dividing the total amount of core recovered by the total depth cored (core length that should have been recovered in the drilling process). As an example, drilling fluid commonly washes away friable sand or poorly consolidated parts of the Peedee Formation. Poor drilling skills, practices, and equipment may induce artificially high core losses in some competent rocks; therefore, judgment is required in using Percent Core Recovery as an indicator of rock strength (Fig. 6).

Rock Quality Designation (RQD)

Deere and Deere (1963) reported on using the Rock Quality Designation (RQD) as an indicator of rock competency. RQD is determined by dividing the accumulative length of core that has no discontinuities occurring in a

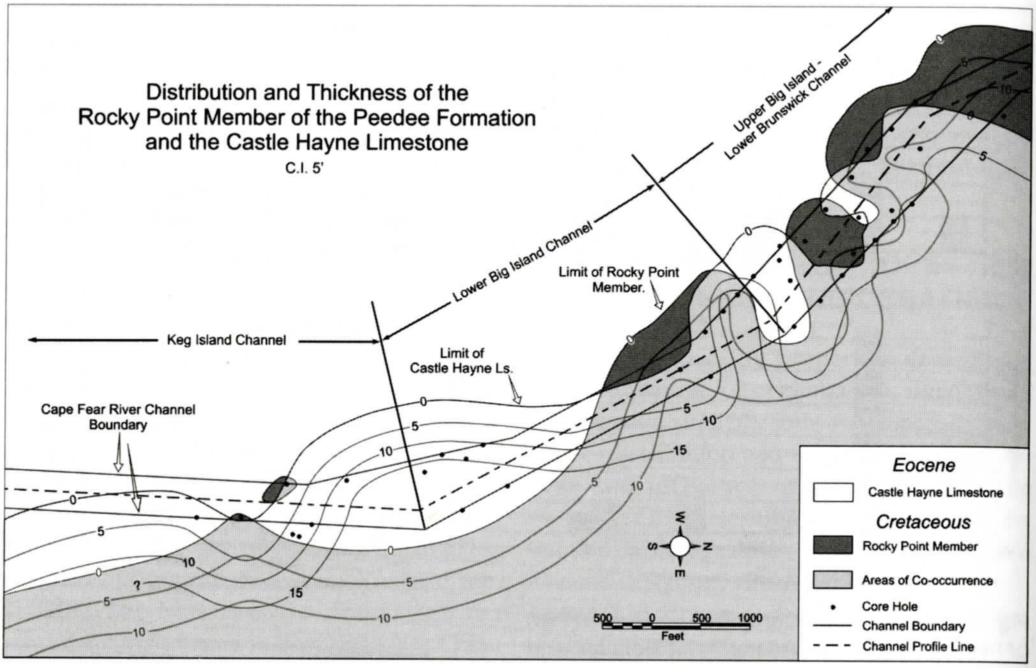

Figure 8. Distribution and thickness of the Castle Hayne Limestone and the Rocky Point Member of the Peedee Formation, Lower Brunswick, Upper Big Island, Lower Big Island and Keg Island reaches, Cape Fear River.

frequency of every four inches or less by the total depth drilled. Discontinuities include joints, breaks along weak planes, faults, and cavities. RQD is expressed as a percentage with low percentages indicating numerous discontinuities and less competent rock; thus low RQDs contribute to the ease at which rock can be dredged. Higher percentages of RQDs indicate fewer discontinuities and greater rock competence. RQD values for cores that occur within the dredging prism are illustrated in Figure 7.

Rock Thickness

Rock thickness and lateral extent are fundamental factors that affect dredgeability. Thin bedded, spatially restricted very hard rock may be dredgeable, but thick-bedded rock with low to moderately low strength extending over a large area, may not be economically removed by dredging. The mechanical breaking and suctioning by a rock cutter-head dredge of low to moderately low strength rock may be slower than drilling, blasting, and mucking by a bucket or dipper stick dredge. Figure 8 illustrates the distribution and thickness of the Rocky Point Member and Castle Hayne Limestone in the Keg Island, Lower Big Island Channel and Upper Big Island-Lower Brunswick Channel reaches of Cape Fear River. Figure 9 is a cross-section from Keg Island to Lower Brunswick along the center of the Cape Fear River that is illustrated in Figure 8.

RESULTS

Distribution and Thickness of Units

Geologic mapping in Wilmington Harbor provides information on the distribution and thickness of rocks that occur in the dredging prism. Units in the dredging prism that contain rock include the Peedee Formation, the Rocky Point Member of the Peedee Formation, the Bald Head Shoals Formation, the Castle Hayne Limestone and the Trent Formation (Fig. 4).

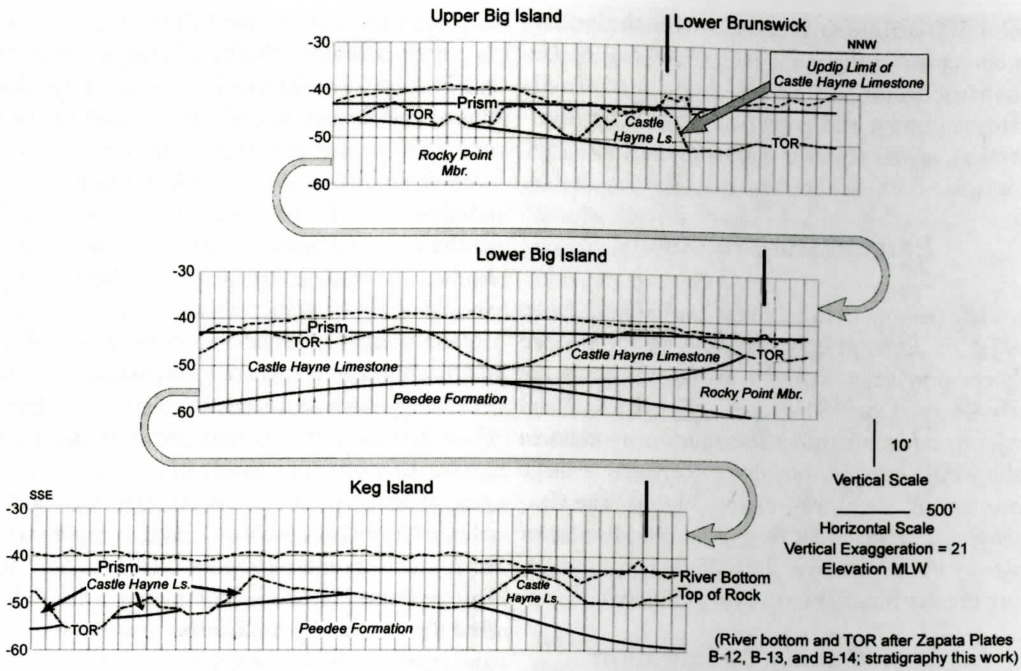

Figure 9. Cape Fear River channel profiles, Lower Brunswick, Upper Big Island, Lower Big Island and Keg Island reaches, Cape Fear River (see Figure 2). Line of profiles is shown as Pilot Centerline on Figure 8.

However, only the Rocky Point Member and the Castle Hayne Limestone pose major problems to the determination of dredgeability because of their location relative to the channel and lithologic characteristics.

Rocky Point thickness varies along the river channel. It occurs in the dredging prism in the Anchorage Basin, Between Channel and the upper part of Fourth East Jetty Channel (Fig. 2) where it reaches a thickness of over 21 ft. In Lower Brunswick, Upper Big Island and Lower Big Island it is thinner, about 10 ft, and is generally overlain by the Castle Hayne Limestone (Figs. 8, 9).

The Bald Head Shoals Formation occurs mainly in the Ocean Bar area just south of the Cape Fear River in Long Bay ranging in thickness from less than 3 ft to greater than 22 ft. It has also been identified in Snows Marsh in the southern part of the Cape Fear River (Fig. 2) with a maximum thickness of greater than 5 ft; however, the base has not been penetrated.

The Castle Hayne Limestone crops out in the Keg Island, Lower Big Island and Upper Big Island areas of the Cape Fear River (Figs. 8, 9). Although most core holes do no penetrate the entire unit, it can be characterized as being over 10-ft thick. Further south along the river the Castle Hayne Limestone is also exposed in the upper part of Lower Lilliput channel and the lower part of Upper Lilliput channel; it is also over 10-ft thick in this area. Between Snows Marsh and Battery Island channels the Castle Hayne Limestone also occurs at several locations and reaches a thickness of almost 20 ft (Fig. 8).

Unconfined Compressive Strengths

Unconfined compressive stress tests of rocks were determined from the Peedee Formation, the Rocky Point Member and the Castle Hayne Limestone (Fig. 5). Unconfined compressive strengths of Peedee rocks are biomodal with all measurements occurring in either the 0-500 psi or the >3500 psi range. Unconfined compressive strengths of the Rocky Point Member vary greatly but cluster in two classes, the 0-500 psi and 500-1500 psi intervals with the greater number occurring in the later class (Fig. 5). Unconfined compressive strengths of Castle Hayne units A and B also have a broader distribution; however, most cluster in the 1500-2500 psi and >3500 psi classes (Fig. 5).

Percent Core Recovery

The percent core recovery varied in all units (Fig. 6). Percent core recovery of the Peedee Formation is bimodal with a large number in the 20-40% and the >60% ranges. The Rocky Point Member has a similar distribution by class in the >60% ranges, but does not show a large number in the 20-40% range (Fig. 6). The Castle Hayne is different from either the Peedee or Rocky Point with over 78% of the cores providing greater than 80% recovery (Fig. 6).

Rock Quality Designation

Although this parameter offers considerable insight into the method of excavation that may be necessary, it was found that in most cases few fractures, bedding planes or cavities were present in cores. Figure 7 illustrates RQD numbers in 20% classes for all cores within the dredging prism where macroscopic core examination provided visual estimates.

DISCUSSION AND CONCLUSIONS

The Cape Fear River Channel between Wilmington and Battery Island crosses several lithostratigraphic units ranging in age from Cretaceous through Holocene. Units vary in hardness based on original sediment type, degree of lithification and position relative to unconformities. Well-lithified material occurs within the dredging prism of the river (-50 ft. MLLW) at various localities and is mainly related to the unit present, thickness and distribution, rock strength, and percent core recovery.

The oldest unit that underlies the river channel is the Cretaceous Peedee Formation. It underlies the entire river but only occurs in the dredging prism from the Fourth East Jetty Channel through Upper Lilliput Channel (Fig. 2). South of Upper Lilliput Channel, it generally occurs below the dredging prism overlain by the Eocene Castle Hayne Limestone or younger units. The Peedee Formation is usually poorly consolidated but at a couple of core sites it is well-lithified and has a high compressive strength (Fig. 5). However, zones of hard rock in the Peedee Formation are thin and spatially limited and removal by rock-cutter-head dredge should easily be accomplished.

The Rocky Point Member of the Peedee Formation has a greater spatial distribution than the Peedee Formation (Anchorage Basin to upper Fourth East Jetty channel and Keg Island to Lower Brunswick channel) (Fig. 2), and its degree of lithification is also variable. Most samples of the Rocky Point have compressive strengths less than 1500 lbs psi (Fig. 5). The Rocky Point Member is commonly better lithified directly below the overlying unconformity and becomes less lithified with increasing distance below. Based on these factors, removal of the Rocky Point Member may require blasting in addition to removal by rock cutter-head dredge.

The Castle Hayne Limestone has the greatest unconfined compressive strengths of the three units (Fig. 5); however, its thickness and spatial distribution in the dredging prism is less. Therefore, taken alone, it presents little problems for removal. However, in the Keg Island to Upper Big Island parts of the channel, the Castle Hayne Limestone overlies the Rocky Point Member and both occur in the dredging prism. Taken together, this relationship creates problems in removal because of the additional thickness of competent rock and its greater spatial distribution. In addition, the occurrence of unconformities at the top and within the Castle Hayne Limestone exacerbates the effect of rock competency because of the greater degree of cementation that often occurs below the uncomformities. However, this effect appears to be less pronounced and more highly variable for the Castle Hayne Limestone than for the Rocky Point Member.

Laboratory tests indicate that well-cemented rock has higher unconfined compressive strength than rock less well-cemented (Fig. 5).

Well-cemented rock within this study area usually occurs in the vicinity of geological contacts characterized by erosion or nondeposition. Other researchers have found that rock is usually better cemented below unconformities (McLaurin and Harris, 2001). Where unconformities are identified in the construction prism and have sufficient lateral extent, blasting may be required for rock removal. The thickness and lateral extent of well-cemented rock varies and also controls to some degree the method selected for channel deepening. In some areas of Wilmington Harbor the well-cemented rock is underlain by that part of the Peedee Formation, which has the physical properties of soil. In these areas it is believed that the rock cutter head dredge could cut through the well cemented rock, undermining it so that it would break up and fall. If an area below the design prism is created it may be possible for harder rock to be contained and stored below the design construction elevation prism. Depending on operation considerations a contractor may use a rock-cutter-head dredge to remove all possible material, carefully mapping the areas it could not dredge, and later return to drill and blast those areas.

Criteria for Cutter-Head Dredgeable Rock

Delineation of channel geology is necessary in order to determine practical and economical construction methods. Where rock was interpreted to occur within the channel prism, physical characteristics were used to assess rock dredgeability. Physical characteristics of the rock assessed were its unconfined compressive strength (UCS), percentage of core recovery per boring, percent Rock Quality Designation (RQD), and estimated thickness and lateral extent.

Tentative quantitative values for dredgeable rock were assigned based on unconfined compressive strength, percent core recovery, rock quality designation (RQD), and rock thickness. These values are tentative and must be considered collectively when evaluating rock for dredgeability. As dredging industry values are not established, these values were derived using judgment and experience from previous dredging in Baldhead Shoal Channel. The values are: (1) rock with UCS of 4300 psi or less; (2) percentage core recovery of 47% or less; (3) Rock Quality Designation of 30% or less; and (4) thickness, approximately less than 2 or 3-feet; length, approximately less than 500 feet, and; width, approximately less than 400 feet. These parameters represent a summary of work done by Haw for the final Feasibility Report and Environmental Impact Statement (U.S. Army Corps of Engineers, 1996). Based on these parameters, Table 1 suggests the conditions under which rock can be dredged in the Cape Fear River. The values are approximate and depend upon other factors such as discontinuities, bedding, type and condition of dredging equipment, and thickness of rock beds of high, unconfined compressive strength.

Table 1. Suggested parameters for determination of dredgeability for rock along the Cape Fear River.

Unconfined Compressive Strength	Thickness	Length	Width
<500	<6'	<500'	<400'
500-1500	<3'	<250'	<400'
1500-2500	<1.5'	<100'	<400'
2500-3500	<1'	<50'	<400'
3500-4300	<0.5'	<50'	<100'

Construction

One of the first major Wilmington Harbor contract awards involving rock removal was announced on August 24, 2000. Great Lakes Dredge and Dock Company (GLDDC) was the successful bidder for a contract covering Lower Brunswick Channel to Keg Island (first of five Cape Fear River contracts). GLDDC mobilized the drill boat Apache, bucket (dipper stick) dredge New York, and cutter-head (suction or hydraulic) dredges Illinois and Texas to accomplish the work. Initially, GLDDC used the Illinois to remove as much overburden sediment as possible and began drilling and blasting with the Apache and mucking with the New York in areas where USACE Top of Rock maps suggested sufficient rock to implement such a plan. After initial success with drilling and blasting, GLDDC encountered areas where blasting was not applicable. These areas were where the thickness of rock thinned and may have been underlain by loosely consolidated sediments of the Peedee Formation. In these cases the dredge Texas was utilized, and to keep the drill boat Apache from remaining idle, it was used to probe areas where drilling and blasting was probably required. Contractually, material to be removed was designated unclassified, therefore, the volume of blasted rock and dredged rock was not specifically recorded.

Analysis of construction records are necessary to judge whether the USACE's geotechnical findings and geologic interpretation were consistent with the contractor's performance in the deepening of Wilmington Harbor. This information should be available for evaluation as other reaches of Wilmington Harbor are now complete. Completion of phase 1 of the contract by GLDDC five months ahead of schedule may indicate that the USCOE's findings were relevant and accurate.

SUMMARY

Plans to deepen Wilmington Harbor have necessitated a detailed geologic, engineering and environmental analysis of the river from Baldhead Shoals to Wilmington. To provide information on potential problems, about 200, 2-in (NW) and 4-in (4-in x 5 1/2-in) core holes were drilled and about 250 miles of seismic "boomer" data collected. Examination of the data indicates that the Cretaceous Rocky Point Member, the Paleocene Bald Head Shoals Formation, and Units A and B of the Castle Hayne Limestone occur along much of the river channel, and their presence in the dredging prism has important repercussions for channel engineering and design. Although these rocks and their associated unconformities are irregular and dip below the design elevation in most channel reaches, they occur within the dredging prism in other channel reaches. When they occur within the projected channel prism they frequently create higher rock elevations, and consequently, may control the selected method of channel deepening. In addition, when unconformities between units occur within the channel prism, units below the unconformities are harder, better cemented and have higher unconfined compressive stress. Where hard, laterally extensive and thick rock occurs within the dredging prism, contractors may choose to drill and blast to deepen the channel; however, this method has greater potential to damage the environment.

Where unlithified sand of the Peedee Formation, the Island Creek Member of the Peedee Formation, the Paleocene Yaupon Beach Formation and the Oligocene Trent Formation occur along the river, rock elevations are low. In these areas, rock-cutter-head type dredge can be used to achieve deepening to the permitted depth. These techniques mitigate damage to the environment as compared to blasting.

Although the Environmental Impact Statement identified several areas of potential concern (threatened and endangered species, loss of tidal marsh, loss of primary nursery areas, salinity intrusion into surface and ground waters, increased tidal ranges, etc.) mitigation measures included in the project compensate for these losses, or no significant adverse impact is expected. This project indicates that geologic/geotechnical investigations are essential in understanding the most economic methods of channel deepening with the least environmental impact.

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APPENDIX.

Core borings located by latitude and longitude and river reaches (see Figure 2).

BORE HOLE	LATITUDE	LONGITUDE	REACH	BORE HOLE	LATITUDE	LONGITUDE	REACH
WH93-02	341626.450	775656.507	North of Cape Fear Memorial Bridge	WH98-23	341305.413	775712.336	Anchorage Basin
WH93-09	341336.342	775711.277	Anchorage Basin	WH98-25	341259.325	775712.997	Anchorage Basin
WH93-11	341320.309	775711.010	Anchorage Basin	WH98-27	341249.509	775720.599	Anchorage Basin
WH93-21	341240.270	775733.950	Anchorage Basin	WH98-3*	341632.222	775701.308	North of Cape Fear Memorial Bridge
WH93-45	341055.200	775726.020	Fourth East Jetty	WH98-30	341238.398	775732.897	Anchorage Basin
WH93-56	340940.540	775744.290	Lower/Upper Brunswick	WH98-31	341225.941	775725.684	Anchorage Basin
WH93-60	340859.420	775714.020	Lower Brunswick	WH98-32	341222.736	775722.379	Anchorage Basin
WH93-64A	340714.120	775606.710	Keg Island	WH98-34	341213.137	775723.096	Between Channel
WH93-67	340505.270	775603.960	Upper Lilliput	WH98-35	341212.373	775729.606	Between Channel
WH93-68	340429.660	775603.020	Lower Lilliput	WH98-4*	341628.858	775702.352	North of Cape Fear Memorial Bridge
WH93-69	340315.120	775622.070	Lower Lilliput	WH98-42	341106.989	775724.254	Fourth East Jetty
WH93-73	340202.290	775622.520	Upper Midnight	WH98-49	340939.380	775732.835	Lower Brunswick
WH94-01	340821.039	775652.799	Upper Big Island	WH98-56	340823.483	775656.174	Lower Brunswick
WH94-02	340831.370	775654.300	Upper Big Island	WH98-57	340823.916	775650.303	Upper Big Island
WH94-03	340816.920	775646.920	Upper Big Island	WH98-58	340818.564	775650.312	Upper Big Island
WH94-04	340821.020	775642.790	Upper Big Island	WH98-60	340823.065	775643.533	Upper Big Island
WH94-05	340817.080	775637.550	Upper Big Island	WH98-61	340817.668	775641.829	Upper Big Island
WH94-06	340725.450	775610.060	Keg Island	WH98-62A	340819.286	775639.025	Upper Big Island
WH94-07	340733.380	775610.990	Lower Big Island	WH98-63A	340815.994	775634.868	Upper Big Island
WH94-08	340737.590	775612.690	Lower Big Island	WH98-64	340812.194	775639.116	Upper Big Island
WH94-09	340439.450	775601.160	Lower Lilliput	WH98-65A	340809.666	775638.482	Upper Big Island
WH94-10	340432.470	775555.970	Lower Lilliput	WH98-66A	340810.648	775634.317	Upper Big Island
WH94-19	340908.200	775722.810	Lower Midnight	WH98-67	340806.924	775634.889	Upper Big Island
WH94-20A	340635.860	775607.170	Lower Midnight	WH98-68A	340813.485	775631.902	Upper Big Island
WH94-22	340506.150	775559.870	Lower Midnight	WH98-69A	340810.974	775628.734	Upper Big Island
WH94-25	335625.440	775835.350	Snow Marsh	WH98-70	340803.681	775630.671	Lower Big Island
WH94-26	335524.300	775955.550	Lower Swash	WH98-71	340801.848	775628.090	Lower Big Island
WH94-27	335449.660	780055.290	Lower Swash	WH98-72	340802.393	775622.610	Lower Big Island
WH94-28	335429.460	780114.410	Battery Island	WH98-73	340759.334	775623.506	Lower Big Island
WH98-1	341629.484	775655.692	North of Cape Fear Memorial Bridge	WH98-75	340739.301	775614.366	Lower Big Island
WH98-121	335603.585	775903.355	Snow Marsh	WH98-76	340741.789	775609.362	Lower Big Island
WH98-126	335438.307	780117.656	Battery Island	WH98-77A	340735.116	775613.171	Lower Big Island
WH98-127	340821.167	775641.440	Upper Big Island	WH98-78	340737.182	775606.400	Lower Big Island
WH98-128	340805.271	775632.626	Upper Big Island	WH98-81	340721.904	775604.778	Keg Island
WH98-132	340814.315	775642.919	Upper Big Island	WH98-81A	340721.953	775604.694	Keg Island
WH98-16	341332.533	775705.095	Anchorage Basin	WH98-81B	340721.972	775604.658	Keg Island
WH98-18	341324.242	775710.644	Anchorage Basin	WH98-82	340719.356	775609.687	Keg Island
WH98-19	341320.304	775715.041	Anchorage Basin	WH98-83	340710.209	775605.630	Keg Island
WH98-2	341623.281	775655.822	North of Cape Fear Memorial Bridge	WH98-86	340450.493	775556.590	Upper Lilliput
WH98-20	341316.712	775712.586	Anchorage Basin	WH98-87A	340445.627	775601.170	Upper Lilliput
WH98-21	341315.434	775716.901	Anchorage Basin	WH98-88A	340440.961	775601.504	Upper Lilliput
WH98-22	341309.191	775720.219	Anchorage Basin				