Environmental Coastal Geology: Cape Lookout to Cape Fear, NC

Editor:
William J. Cleary

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Environmental Coastal Geology: Cape Lookout to Cape Fear, NC

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FOREWORD AND ACKNOWLEDGMENTS

The level of understanding of the North Carolina coastal systems has increased markedly over the last decade. The papers in this guidebook provide an overview of the environments, processes, underlying geology and man's interaction with the coastal processes. The assemblage of papers provides the participant a comprehensive account of ongoing research and perspectives on the environmental geology and processes that shape the shorelines within the Onslow Bay compartment.

I am grateful for the advice and counsel of all those who contributed to this guidebook and fieldtrip. First I would like to thank the authors of the papers. Peer reviews were instrumental in improving the content, focus and clarity of the papers. I would also like to thank the individuals who will contribute to the description of each fieldtrip stop and the subsequent discussions.

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I would also like to acknowledge the financial support provided by Dr. James F. Merritt of UNCW's Center for Marine Science Research and Dr. Jo Ann Seiple, Dean of the College of Arts and Sciences. Butch Goodson of Jackson Beverage provided the refreshments for the opening reception. This guidebook is UNCW's Center for Marine Science Research contribution #147.

Bill Cleary

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AN OVERVIEW OF THE MARINE TERTIARY AND QUATERNARY DEPOSITS BETWEEN CAPE FEAR AND CAPE LOOKOUT, NORTH CAROLINA

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ABSTRACT

Tertiary and Quaternary marine sediments in the North Carolina Coastal Plain are distributed on two crustal blocks, the Onslow and the Albemarle. Differential uplift and subsidence of these blocks about the Neuse Hinge has controlled patterns of relative coastal onlap, sediment distribution, and the positions of late Tertiary and Quaternary scarps and terraces.

Paleocene sediments (Beaufort Group) are restricted principally to the southern part of the Onslow Block and north of the Neuse Hinge. Eocene sediments (Castle Hayne Limestone and New Bern Formation) represent the most widely distributed early Tertiary unit in North Carolina, and are found over most of the Onslow Block. Oligocene sediments (Trent, Belgrade and Silverdale Formations) are locally distributed north of the New River, north of the Neuse Hinge and in Onslow Bay. The Miocene Pungo River Formation is mainly developed north and east of the White Oak River and Neuse Hinge, respectively. The Pliocene Duplin Formation represents the most extensive marine onlap during the late Tertiary, and occurs as outliers over much of the Onslow Block. The Pliocene Chowan River and Bear Bluff Formations are developed north of the Neuse Hinge and in the Cape Fear area, respectively. The lower and middle Pleistocene Waccamaw/James City Formations, and Socastee/Flanner Beach Formations are mainly developed on the southern part of the Onslow Block and north of the White Oak River. (Plio-Pleistocene distribution is related to formation and ~ development of the Hanover-Surry Scarp, Bogue-Suffolk Scarp and the Alligator Bay Scarp.

INTRODUCTION

This paper presents a summary of the Tertiary and Quaternary marine stratigraphy and discusses the associated scarps and terraces. In-depth discussions of North Carolina early Tertiary stratigraphy are presented by Harris and Zullo (1991), Harris *et at.* (1993), Harris and Laws (1994; in press), Laws (1992), and Zullo and Harris (1987). Miocene stratigraphy for the area is discussed by Snyder *et at.* (1991). Pliocene and Pleistocene stratigraphy is discussed by Ward *et at.* (1991) and Soller and Mills (1991). Dockal (this volume) discusses upper Pleistocene units on the Cape Fear Arch.

The area along the North Carolina-South Carolina state line (approximate axis of the Cape Fear Arch) and the White Oak/Neuse Rivers (Neuse Hinge) is referred to as the Onslow Block (Harris and Laws, in press). To the north of the Neuse Hinge is the Albemarle Block. Differential uplift and subsidence of these blocks has controlled the stratal geometries and patterns of relative coastal onlap on each block, the distribution of Coastal Plain units, and the positions of late Tertiary and Quaternary scarps and associated terraces.

TERTIARY

Tertiary units on the Onslow Block are assigned to the Tejas Megacycle of Haq *et at.* (1987), and are represented by the Paleocene Beaufort Group, the Eocene Castle Hayne Limestone and New Bern Formation, and the Oligocene Trent, Belgrade and Silverdale Formations [Fig. 1). In this paper, the terminology of Baum *et at.* [1978) as modified by Zullo and Harris (1987) and Harris and Laws (1994) is followed.

Paleocene

The Paleocene Beaufort Group represents two depositional sequences (Fig. 1). The oldest sequence, the TA 1.2, is represented by the Yaupon Beach Formation of Danian age. The youngest sequence, TA2.1 , is represented by the Bald Head Shoals Formation of Thanetian age.

Danian (Figure 2a)

The Yaupon Beach Formation is recognized only on the southern part of the Onslow Block on the axis of the Cape Fear Arch (Harris and Laws, 1994). It consists of olive green to gray, very fine to fine-grained slightly argillaceous bioturbated quartz sand. A moderately to well preserved, low diversity nannofossil assemblage including lower Danian taxa *Cruciplacolithus prim us,* C. *tenuis, Ericsonia cava, Biscutum* spp. and *Neochiastozygus* sp., and Cretaceous survivor species *Placozygus sigmoides, Markalium in versus* and *Cyclogelosphaera reinhardtiis* present. This assemblage, in the absence of *Chiasmolithus danicus,* correlates to the lower Danian *Cruciplacolithus tenuis* Zone (NP2 or CP1 b).

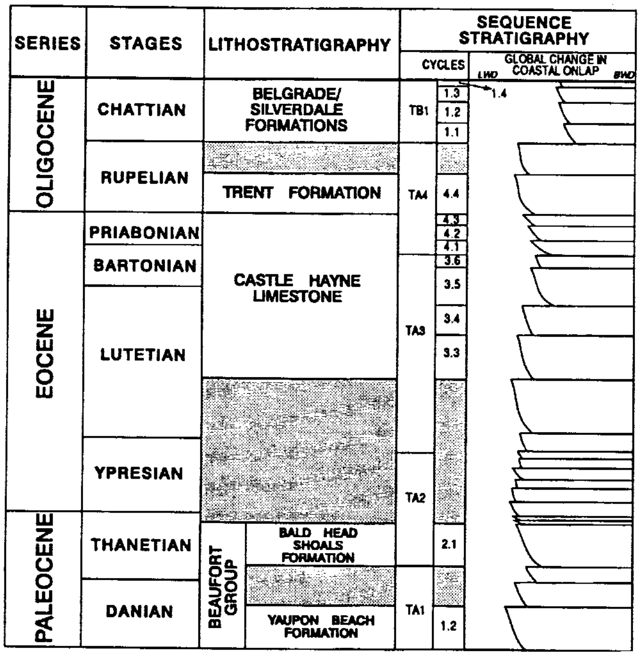


Figure 1. Generalized early Tertiary lithostratigraphy and sequence stratigraphy on the Onslow Block, North Carolina, modified from Harris *et al.* (1993) and Harris and Laws (1994, in press).

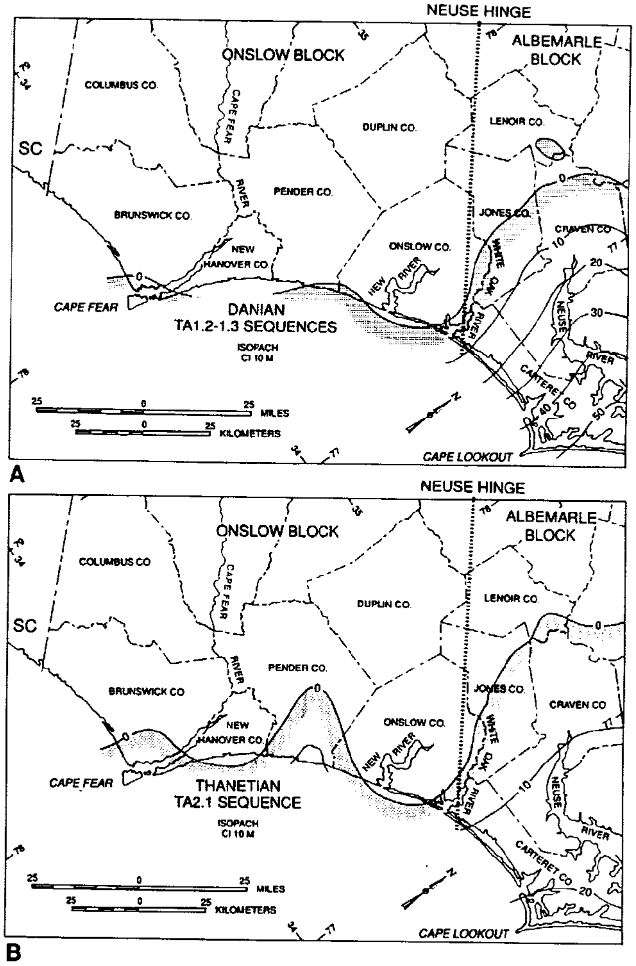


Figure 2. A. Isopach of Danian sediments on the Onslow Block between the axis of the Cape Fear Arch and the Neuse Hinge (modified from Harris and Laws, in press). B. Isopach of Thanetian sediments on the Onslow Block between the axis of Cape Fear Arch and the Neuse Hinge (modified from Harris and Laws, in press).

Thanetian (Figure 2b)

The Bald Head Shoals Formation is also restricted to the southern part of the Onslow Block; however, Thanetian aged sediments are recognized at several localities in Pender County. The Bald Head Shoals Formation consists of almost 7 m of sandy, molluscan-mold mudstone, wackestone to packstone, and contains very sparse calcareous nannofossils and foraminifers, but abundant gastropods (turritelline) and pelecypods. Three mollusks that are age-diagnostic in the Gulf Coastal Plain are identified; the gastropod *Mesalia biplicata* Bowles, and the pelecypods *Barbatia* (Cucullaearca*) cuculloides* and *Acanthocardia (Schedocardia) tuomeyi.* Units that contain these mollusks in the Gulf Coastal Plain are considered Thanetian in age (Mancini and Tew, 1988). The occurrence of the benthic foraminiferal species *Cibicides neelyi, Eponides lotus, Anomalinoides umboniferus,* and *Cibicidina* sp. support a Thanetian age.

Eocene

Five Lutetian to Priabonian depositional sequences occur on the Onslow block from Brunswick to Carteret Counties. They are represented by the Castle Hayne Limestone and the New Bern Formation (Fig. 1).

Lutetian-Bartonian (Figure 3a)

Three Lutetian and Bartonian depositional sequences (TA3.3, TA3.4, and TA3.5/3.6) are recognized and assigned to the Castle Hayne Limestone. Where indurated, these sequences consist dominantly of sandy, bryozoan and molluscan biomicrudite and biosparrudite, and locally phosphate pebble conglomerate. Where unindurated, they consist of bryozoan sand, which is often glauconitic.

Priabonian (Figure 3b)

Two younger sequences are recognized and assigned to the Castle Hayne Limestone. The older (TA4.1) straddles the Bartonian- Priabonian boundary with the surface of maximum flooding approximating the stage boundary. Transgressive deposits are interpreted below this surface to be Lutetian/Bartonian; highstand deposits above this surface are interpreted to be Priabonian in age. The high stand part of the sequence is the thickest and best developed, therefore, it

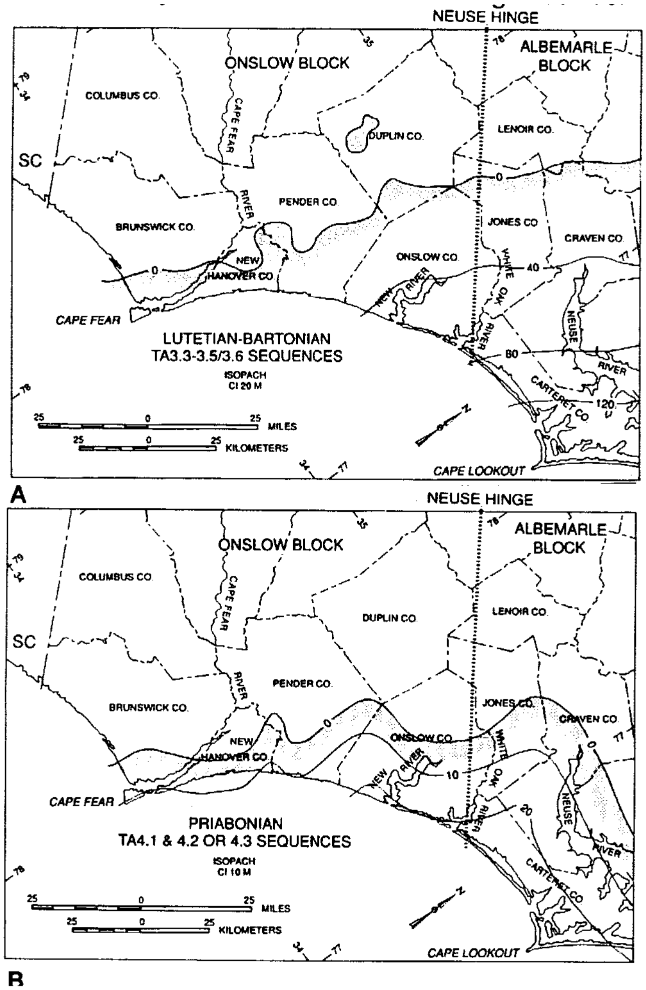


Figure 3. A. Isopach of Lutetian and Bartonian sediments on the Onslow Block between the axis of the Cape Fear Arch and the Neuse Hinge. Note that outliers occur on the Onslow Block (modified from Harris and Laws, in press). B. Isopach of Priabonian sediments on the Onslow Block between the axis of the Cape Fear Arch and the Neuse Hinge (modified from Harris and Laws, in press).

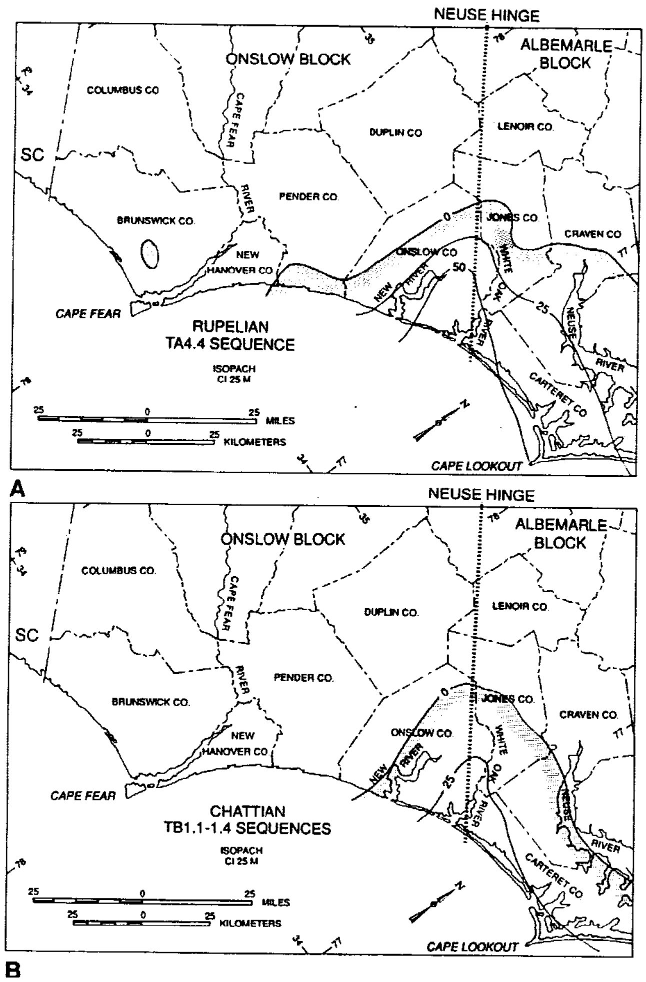


Figure 4. A. Isopach of Reupelian sediments on the Onslow Block between the axis of the Cape Fear Arch and the Neuse Hinge (modified from Harris and Laws, in press). B. Isopach of Chattian sediments on the Onslow Block between the axis of the Cape Fear Arch and the Neuse Hinge (modified from Harris and Laws, in press).

is included in this section for discussion. The younger sequence (TA4.2 or TA4.3) is exclusively Priabonian in age and has a more restricted spatial distribution. Both sequences consist predominantly of. bryozoan, sponge and molluscan biomicrite and biomicrudite except along the northern part of the Onslow Block. Along the Neuse Hinge, the New Bern Formation that represents either the TA4.2 or TA4.3 sequence consists of sandy pelecypod-mold biosparite and biosparrudite.

Oligocene/Early Miocene

One Rupelian, several? Chattian and one Aquitanian sequence are recognized between Brunswick and Carteret Counties (Fig. 1). The Rupelian sequence (TA4.4) is represented by the Trent Formation of Baum *et al.* (1978), the Chattian sequences (TB1.1-1.4) by the Belgrade/Silverdale Formations, and the Aquitanian part of sequence TB 1 .4 by the *Crassostrea* channel deposits of Baum *et al.* (1978) and Zullo and Harris (1987).

Rupelian (Figure 4a)

The Trent Formation is confined to the area between the New and Neuse Rivers. In the vicinity of the Neuse Hinge it consists of three ascending lithofacies; sandy echinoid biosparite, sandy pelecypod-mold biomicrudite and barnacle, pelecypod-mold biosparrudite. To the south near Jacksonville it consists of sandy foraminiferal silt and silty clay. This sequence is assigned to the TA4.4 cycle based on the occurrence of the barnacle *Lophobalanus kellumi* and the pectinid

Chlamys trentensis (Zullo and Harris, 1987), mollusks that have early Vicksburgian (Rupelian) affinities (Rossbach and Carter, 1991), foraminifers indicative of the *Globergerina ampliapertura* Zone (P19/20) (Zarra, 1989), and calcareous nannofossils indicative of zones NP21-22 (Worsley and Turco, 1979).

Chattian-Aquitanian (Figure 4b

The Chattian Belgrade and Silverdale Formations are restricted to quarries and core holes from about the New River in Onslow County northward through eastern Jones, Craven and Carteret Counties. Chattian sequences are also well developed in Onslow Bay (Snyder *et al.,* 1991). The Aquitanian *Crassostrea* channel deposits are only found within a few kilometers north and south of the White Oak River. The Belgrade Formation consists of about 8 m of sandy, pelecypod-mold biomicrudite with minor interbeds of quartz sand. The Silverdale Formation consists of about 3 m of mollusk- rich quartz sand, which is occasionally lithified and moldic. It occurs downdip (eastward) of the Belgrade Formation and is considered equivalent in age. Calcareous nannofossils (Laws and Worsley, 1986; Laws, 1992; Parker and Laws, 1991), planktonic Foraminifera (Zarra, 1989), and megafauna indicate that the Belgrade and Silverdale Formations span planktonic foraminiferal zones P21 and P22 (Zullo and Harris, 1987). The Belgrade and Silverdale Formations were suggested by Zullo and Harris (1987) to represent four depositional sequences ranging in age from Chattian to Aquitanian (TB1. 1-lower part of 1.4). The Aquitanian *Crassostrea* channel deposits were interpreted by Zullo and Harris (1987) to represent the highstand of the TB1.4 sequence.

Miocene

Miocene sediments onlap the emerged Coastal Plain along a north-south line that approximates the White Oak River and are referred to the Pungo River Formation (Snyder *et al.,* 1991) (Figs. 5 and 6). The Pungo River Formation is best developed on the Albemarle Block and in Onslow Bay. Based on seismic analysis, Miocene sediments are interpreted to represent three unconformity bounded packages identified as the Frying Pan, Onslow Bay and Bogue Banks Sequences. Lithofacies of the Frying Pan Sequence include muddy, quartzitic phosphatic sand; organic-rich, phosphatic mud; and molluscan-barnacle shell gravels interbedded with quartz sand or foraminiferal quartz sand (Riggs and Mallette, 1990). The Onslow Bay Sequence consists of calcareous muds and biogenic sands and gravels with varying amounts of siliciclastic sand and chert (Riggs and Mallette, 1990). The Bogue Banks Sequence consists mainly of siliciclastic muds and sands; the sands usually contain minor phosphate and the muds usually contain abundant silt-sized dolomite (Riggs and Mallette, 1990). Based on study of planktonic foraminifers, calcareous nannofossils, diatoms and radiolarians, the three Miocene depositional sequences were dated by Snyder *et al.* (1991) as Burdigalian (Frying Pan Sequence), Langhian (Onslow Bay Sequence), and Serravallian (Bogue Banks Sequence).

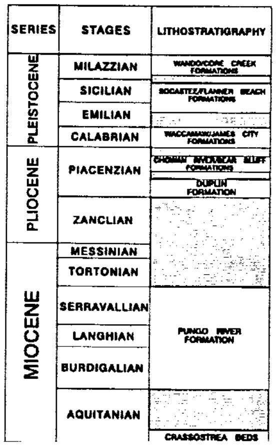


Figure 5. Late Tertiary and Quaternary lithostratigraphy of the Onslow Block.

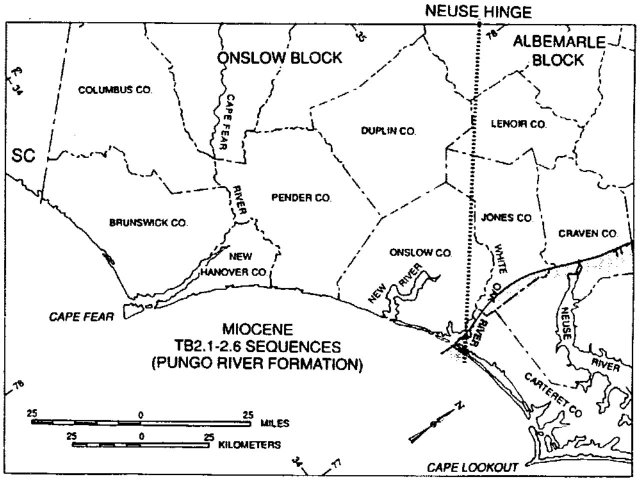
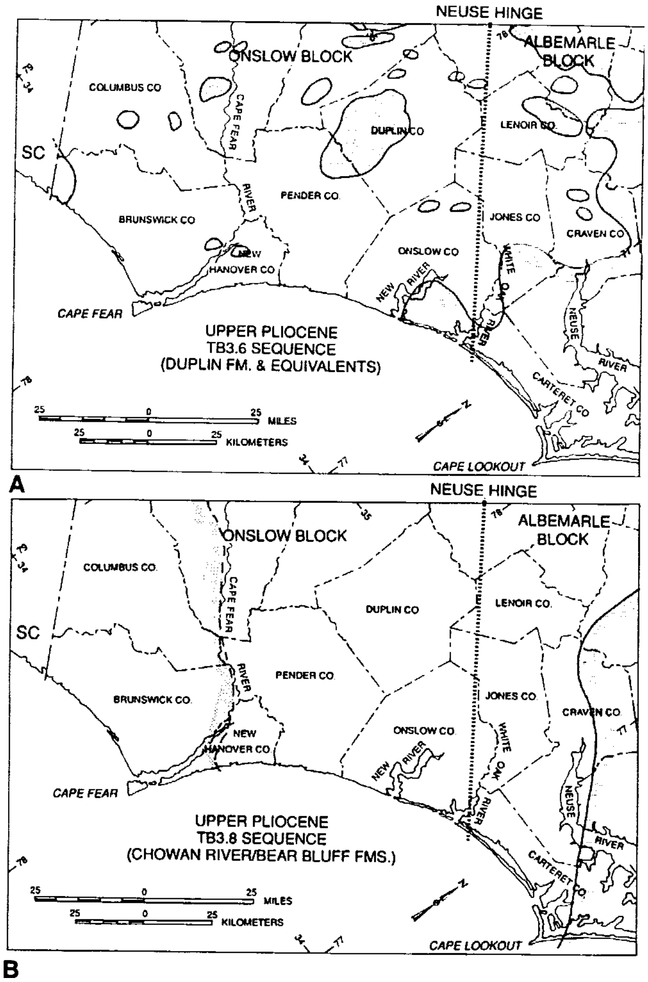


Figure 6. Distribution of Miocene sediments on the Onslow Block (modified from Brown *et al.* 1974, and Snyder *et al.,* 1991)

Pliocene

Pliocene units in North Carolina are referred to as the Duplin/Yorktown Formations and the Bear Bluff/ Chowan River Formations (Figs. 5, 7a and 7b). The Yorktown Formation is usually used for lower and lower upper Pliocene sediments that occur north of the Neuse Hinge on the Albemarle Block (Ward *et al.,* 1991). The Duplin Formation is used for age equivalent sediments that occur south of the Neuse Hinge on the Onslow Block. The Chowan River Formation is



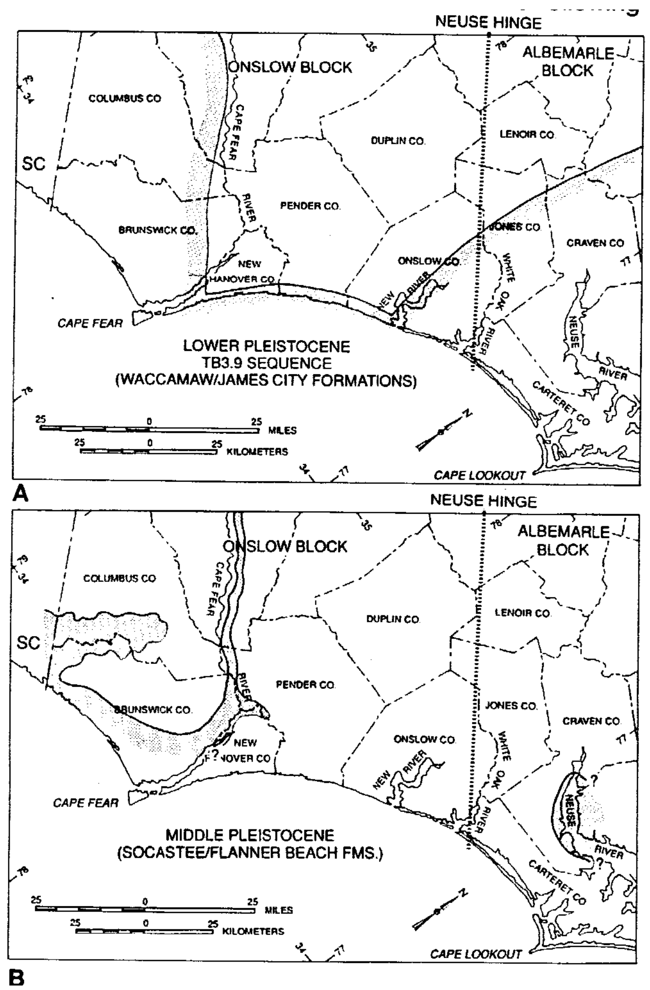


Figure 7. A. Distribution of the Pliocene Duplin Formation and equivalents (TB3.6 Sequence) on the Onslow Block. Sequence designation is after Zullo and Harris (1992). B. Distribution of the Pliocene Chowan River/Bear Bluff Formations (TB3.8 Sequence) on the Onslow Block (modified from Ward *et al.,* 1991). Sequence designation is after Zullo and Harris (1992).

Figure 8. A. Distribution of lower Pleistocene Waccamaw/ James City Formations (TB3.9 Sequence) on the Onslow Block (modified from Owens, 1989; Ward *et al.,* 1991). Sequence designation is after Zullo and Harris (1992). B. Distribution of the middle Pleistocene Socastee/Flanner Beach Formations on the Onslow Block (modified from Mixon and Pilkey, 1976; Owens, 1989; Ward *et al.,* 1991).

also used for latest Pliocene sediments that occur on the Albemarle Block, and the Bear Bluff for age equivalent sediments on the Onslow Block. The Duplin Formation consists of sand, sandy and silty clay, and very shelly sand commonly overlying a basal phosphate pebble conglomerate. North of the Neuse Hinge the Rushmere and Mogarts Beach Members of the Yorktown Formation (=Duplin Formation) are continuous; however, to south on the Onslow Block, the Duplin is preserved as outliers. The thickest section of the Duplin Formation also occurs to the south where almost 5 m are found in Bladen County (Ward *et al.,* 1991). However, most outliers on the Onslow Block contain less than 2 m of the Duplin Formation.

The upper Pliocene Chowan River Formation is only used in North Carolina north of the Neuse Hinge; to the south, the Bear Bluff Formation of DuBar *et al.* (1974) is recognized. The Bear Bluff Formation is known mainly from the area south of the Cape Fear River, and may occur adjacent to the Intracoastal Waterway below the Waccamaw Formation on the central Onslow Block. The Bear Bluff Formation consists of calcareous sandstone, sandy limestone, subarkosic sand, and calcareous silt and has a maximum observed thickness that exceeds 33 m (DuBar *et al.,* 1974).

QUATERNARY

Pleistocene {Figures 8a and 8b)

Pleistocene geology along the seaward side of the Onslow Block south of the Neuse River is poorly known.

Mixon and Pilkey (1976) mapped the geology of the Cape Lookout area (Carteret-Craven Counties), Owens (1989) mapped the Florence, South Carolina, and North Carolina, 10 x 20 Quadrangle (Brunswick and western New Hanover Counties), and Dockal (this volume) is currently examining the area of southern New Hanover and Brunswick Counties. However, no detailed geologic mapping of Pleistocene units has been completed on the Onslow Block south of New River. The following discussion is mainly of those areas marking the southern and northern parts of the Onslow Block.

The Waccamaw/James City Formations are used for early Pleistocene sediments of similar lithology that occur on the southern and northern parts of the Onslow Block, respectively (Figs. 5 and 8a). The Waccamaw Formation occurs over most of the area south of the Cape Fear River, particularly in low areas developed on older units (i.e., the Peedee Formation), and north of the Cape Fear River in small pits and dredge spoils just west of the Intracoastal Waterway. It has also been identified in Burnt Mill Creek in New Hanover County and probably occurs at other lower elevation localities that are associated with the margins of the Onslow Block. The Waccamaw Formation consists of poorly to moderately well sorted fossiliferous fine to coarse sand which grades upward into unfossiliferous sediments (Owens, 1989). A local thin conglomerate of phosphate and quartz pebbles occurs at the base of the unit. Sediments that contain typical Waccamaw fossils range in thickness to almost 7 m (DuBar *et al.,* 1974) in Brunswick County.

The James City Formation of DuBar and Solliday (1963) is recognized along the Neuse River below New Bern. It extends to the north onto the Albemarle Block almost to Virginia, and to the south to the New River (Blackwelder, 1981). Several small pits west of the Intracoastal Waterway between the New and Cape Fear Rivers indicate that the unit extends to the southeast eventually becoming the Waccamaw Formation (Ward *et al.,* 1991). Although Ward *et al.* (1991) indicate that the Waccamaw/James City Formations extend west of the Hanover Scarp, I know of no lower Pleistocene marine sediments on the central Onslow Block north of the Cape Fear River. The James City Formation is an unconsolidated shelly argillaceous sand and sandy clay (DuBar and Solliday, 1963). Although the unit is considered to be early Pleistocene in age (Ward *et al.,* 1991), Campbell (1993) suggested that it is late Pliocene based on oxygen isotopes.

Numerous lithostratigraphic names have been applied to middle and upper Pleistocene units between the Cape Fear and Neuse Rivers (Fig. 5). Middle Pleistocene units are referred to the Socastee/ Canepatch and Flanner Beach Formations (Soller and Mills, 1991). The Socastee Formation, the major coastal Pleistocene unit in the Cape Fear region, consists of basal coarse sand, fine gravel and reworked shells to 1 m in thickness, and interbedded sand and clay. The sand and clay are commonly peaty and contain upright tree trunks (Owens, 1989). The Socastee ranges up to 5 m in thickness (DuBar *et al.,* 1974) in the northern coastal area of South Carolina. Its extent between the Cape Fear and Neuse Rivers is unknown; however, if present, it is probably restricted to the seaward edge of the Onslow Block (Fig. 8b). The Canepatch Formation, named for exposures in the Myrtle Beach, South Carolina area by DuBar (1971), was restricted to one subsurface locality along the Intracoastal Waterway by Owens (1989). Therefore, the name is not used in this paper. The Socastee Formation is middle Pleistocene in age based on isotopic dates (McCartan *et al.,* 1982).

In the Neuse River area, the Socastee Formation is correlated to the Flanner Beach Formation of DuBar and Solliday (1963). The Flanner Beach Formation consists of unconsolidated clay, sandy clay, argillaceous sand, and peaty sand and clay, which reach almost 12 m in thickness; molluscan fossils are common in the lower part (DuBar and Solliday, 1963). Although the Flanner Beach Formation was restricted to exclude some of the originally defined parts of the unit by Mixon and Pilkey (1976), the unit occurs seaward of north-trending elements of the Suffolk Scarp. The Flanner Beach Formation is also considered to be middle Pleistocene in age; its distribution is shown in Figure 8b.

Late Pleistocene units are poorly described and are assigned numerous lithostratigraphic names. Dockal (this volume) discusses upper Pleistocene stratigraphy in the Cape Fear region.

SCARPS AND PLAINS ON THE ONSLOW BLOCK

Several scarps and associated terraces (plains) are recognized on the Onslow Block between Cape Fear and Cape

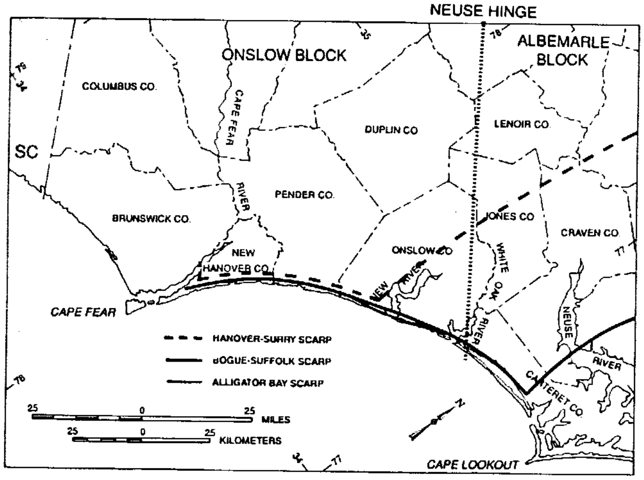


Figure 9. Relation of scarps and terraces to major structural features associated with the Onslow Block (modified from Zullo and Harris, 1979; and Harris and Laws, in press).

Lookout (Fig. 9). Zullo and Harris (1979) recognized three scarps that formed the seaward borders of tilted plains in the area: the Hanover Scarp, the Bogue-Suffolk Scarp, and the Alligator Bay Scarp. The Hanover Scarp originated at an interpreted cape in central New Hanover County north of the Cape Fear River. To the south, Zullo and Harris (1979) suggested that the scarp paralleled the north side of the Cape Fear River for several kilometers eventually becoming the Surry Scarp 80 km inland of the coastal margin. Although Flint (1940) recognized the Surry Scarp inland on the Onslow Block, Zullo and Harris traced the Hanover Scarp northeastward to just south of the New River where it turned abruptly to the north eventually merging inland along the Neuse Hinge with the Surry Scarp. Soller and Mills {1991) followed the identification and location of the Surry Scarp as mapped by Flint {1940), and did not recognize the Hanover Scarp. The plain delimited on the Onslow Block by the Orangeburg Scarp and the Hanover-Surry Scarp is identified as the Duplin Plain {Zullo and Harris, 1979). Sediments of Duplin age represent the youngest marine formation underlying the area. Zullo and Harris {1979) indicated that Duplin Plain was at an elevation of more than 12 m in central New Hanover County and over a distance of 60 km gradually increased to about 21 m on the west side of the New River.

The Bogue-Suffolk Scarp is located seaward of the Hanover Scarp and essentially delimits the modern mainland coast on the Onslow Block. Mixon and Pilkey {1976) mapped the Bogue Scarp north of the New River, and indicated that in central Carteret County, it abruptly turned north and became part of elements associated with the Suffolk Scarp. The plain delimited by the Hanover Scarp and the Bogue-Suffolk Scarp is called the Waccamaw/Canepatch Plain {Zullo and Harris, 1979) and ranges in elevation from about 7.5 m in central New Hanover County to over 10.5 m just north of the New River. Waccamaw and James City Formation sediments represent the youngest marine sediments underlying the plain. Zullo and Harris {1979) also proposed the Alligator Bay Scarp for a linear feature that occurred seaward of the Bogue Scarp between Spicer and Alligator Bays, Onslow County. The plain bounded by Bogue Scarp and the Alligator Bay Scarp rose from sea level 12 km south of New River to about 4.5 mat New River and was designated the Socastee Plain. North of New River Inlet, the Alligator Bay Scarp may merge with the Bogue Scarp, forming the western limit of the Core Creek Sand.

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THE COQUINAS OF THE NEUSE FORMATION, NEW HANOVER COUNTY, NORTH CAROLINA

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ABSTRACT

The coquinas of the Neuse Formation in southern New Hanover County, North Carolina, represent only a small portion of a depositional suite, which formed in the high-energy environment of a Late Pleistocene shoreface at a time corresponding to oxygen isotope stage 3 or 75 to 55 ka BP. The fauna associated with the coquina indicates climatic conditions that are i indistinguishable from the present climate. The coquinas are the product of post-depositional diagenesis of carbonate shell bearing shoreface sands where dissolution, cementation, and calcification of aragonite occurred at or near the paleo-water table. A later dissolution episode of the carbonate fraction of the coquina and associated strata by oxygenated meteoric waters resulted in the formation of an unlithified, generally reddish, non-fossiliferous sand which generally blankets the area. I

INTRODUCTION

The coquina found on the beach in the area of Fort Fisher in New Hanover County, North Carolina, represents one of the very few naturally occurring rock out croppings in the Coastal Plain Province of the Carolinas. The coquina is not laterally extensive nor is it of significant thickness, but it occurs as sporadic isolated patches in a north to south arcuate band over an area roughly 15 km long by 2 km wide (Figure 1}. This paper presents a synopsis of the stratigraphic nomenclature applied to the coquina and then presents a detailed petrologic description and interpretation of the conditions of deposition and diagenesis of the coquina.

The published record of coquinas in southeastern North Carolina and especially New Hanover County is sparse although the area has been visited frequently by geoscientists for over 200 years. The first published record is in Stephenson's (1912} description of the Pamlico Formation under "Detailed Sections" where he notes the presence of coquina rock at "Old Fort Fisher" and at a site “one mile southeast of Carolina Beach wharf." Stephenson's report, however, only provides a brief list of some of the fauna collected by a Dr. Vaughan and provides a photograph of the outcrop on the beach at Fort Fisher. U. S. Army engineers, during the course of a beach erosion study in 1931 made 14 "wash borings" at the Fort Fisher site (House Document 204, 72 ND Congress, 1 st Session). These provide some insight into the lateral variability of the strata though the records lack detailed lithologic descriptions. Richards (1936), in describing the fauna of the Pamlico Formation, mentioned the exposures at Snows Cut and Fort Fisher and provided a comprehensive list of the fauna. Wells (1944) provided the first detailed description of the Pleistocene strata in the Carolina Beach-Fort Fisher area. He divided the strata into five units: Galveston Sand, Pine Sand, Castalia Sand, Kure Sand, and Cape Fear Coquina. This is apparently the first in print usage of the term .'Cape Fear Coquina." Fallow and Wheeler (1969) in their definition of the Neuse Formation noted several locations of coquina in the Carolina Beach area. They designated the coquina as representing the .'Coquina facies" of the Neuse

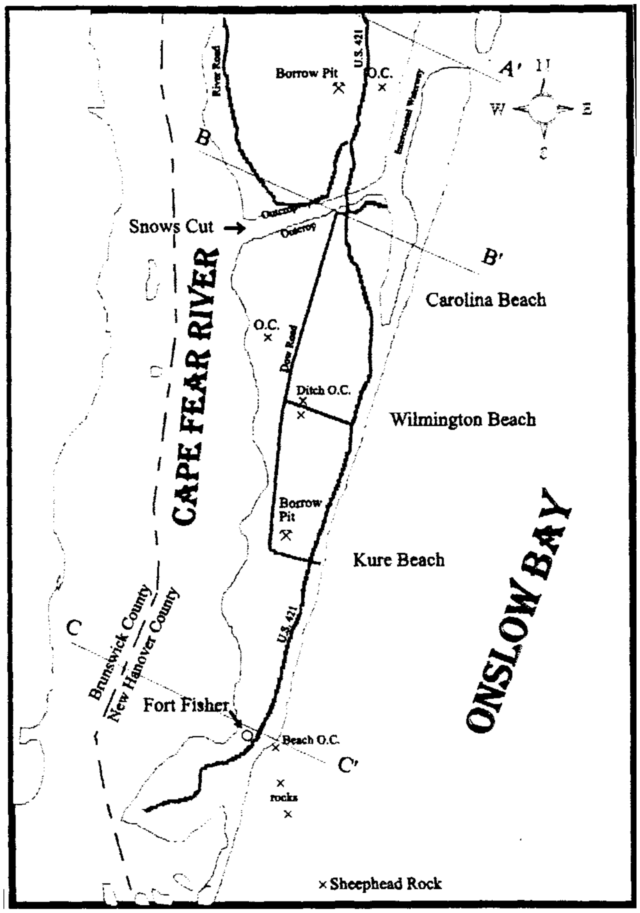


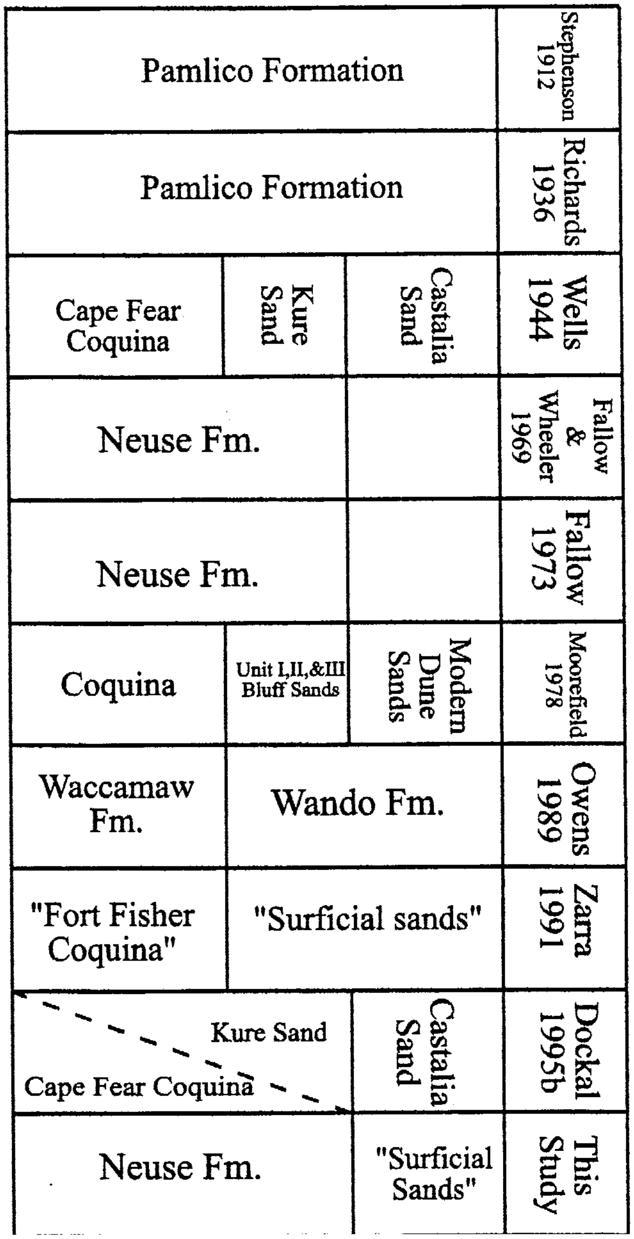
Figure 1. Map of the study area showing the occurrences of coquina both on shore and off shore in southern New Hanover County, North Carolina. A-A’, B-B’, and C-C’ indicate the locations of profiles illustrated on Figure 7.

Formation and they designated the section on the north side of Snows Cut as a reference section for the proposed Neuse Formation. Fallow (1973) later considered the coquina to be the "High-energy Facies" of the Neuse Formation. Moorefield (1978 was the first to recognize and describe submerged coquina outcrops in the area. He noted that the submerged outcrops, though identical to those on the land surface, were encrusted with algae, barnacles, colonies of the bivalve *Mytilus,* serpulid worms, bryozoans and the coral *Astrangia.* Moorefield reported that these submerged outcrops were undergoing biological erosion especially by the rock- boring bivalve *Lithophaga.* The U. S. Army Corps of Engineers (1982), during the course of a design study for beach stabilization, made a number of split spoon borings at the Fort Fisher Historic site. Some of these penetrated to the underlying Castle Hayne Limestone (Eocene). The records of these borings in combination with the 1931 records provide a good view of the lateral variance in lithology over a very limited geographic area. Prosser (1993) attempted to ascertain the age of the coquina by using the Uranium series method on *Mercenaria* shells collected at Snows Cut. Dockal (1992, 1995b) applied the radiocarbon method to shells of *Donax variabilis, Nassarius obsoleta,* and *Crassostrea virginica,* which were also collected at Snows Cut. Wehmiller and others (1988) and Wehmiller and others (1995) applied the amino acid racemization to specimens of *Mercenaria* from the coquina.

NOMENCLATURE REVIEW

The fossiliferous sands of Pleistocene age in New Hanover County and adjacent offshore areas are informally referred to today as the "Cape Fear Coquina," a term first used by Wells (1944) for the coquinas between Snows Cut and Fort Fisher. This term can not be used as a formal lithostratigraphic name because the name Cape Fear is already in use for Cretaceous strata located in the coastal plain of the Carolinas; the Cape Fear Formation.

The earliest workers within the southeastern Atlantic seaboard region applied the term Columbia Formation and later Columbia Group to all the Quaternary strata. Both terms have not been applied in the region for decades and were never used in reference to the strata encompassed by this study outside of Stephenson's (1912) usage of Pamlico Formation which was considered at that time to be a subdivision of the Columbia Group. Stephenson (1912) and later Richards (1936) definitely referred to the strata considered in this report as belonging to the Pamlico Formation; however later workers did not make use of the Pamlico name in a lithostratigraphic sense (Figure 2). Du Bar and Solliday (1963) argued not to use the term Pamlico Formation partly because the type area was a terrace plane, a geomorphic feature and therefore the unit did not represent a true lithostratigraphic unit. Du Bar and Solliday (1963) proposed the Fanner Beach Formation to replace the concept of the Pamlico as a lithostratigraphic unit. The name Fanner Beach has never been applied directly to the coquinas of the Cape Fear. Fallaw and Wheeler (1969) objected to usage of the Fanner Beach Formation because the name included an assemblage of "distinct lithologic units" or units of terrestrial origin and those of clearly marine character. Fallaw and Wheeler (1969) proposed the name Neuse Formation which was by definition to encompass just the "marine fossiliferous Pleistocene deposits in North Carolina." This they divided into four facies: "Fine-grained sand facies", Very fine-grained sand



Pamlico Formation			Stephenson 1912
Pamlico Formation			Richards 1936
Cape Fear Coquina	Kure Sand	Castalia Sand	Wells 1944
Neuse Fm.			Fallow & Wheeler 1969
Neuse Fm.			Fallow 1973
Coquina	Unit I,II,&III Bluff Sands	Modern Dune Sands	Moorefield 1978
Waccamaw Fm.	Wando Fm.		Owens 1989
"Fort Fisher Coquina"	"Surficial sands"		Zarra 1991
Kure Sand Cape Fear Coquina		Castalia Sand	Dockal 1995b
Neuse Fm.		"Surficial Sands"	This Study

Figure 2. Lithostratigraphic nomenclature that has been applied in the literature to the coquina and associated strata in southern New Hanover County.

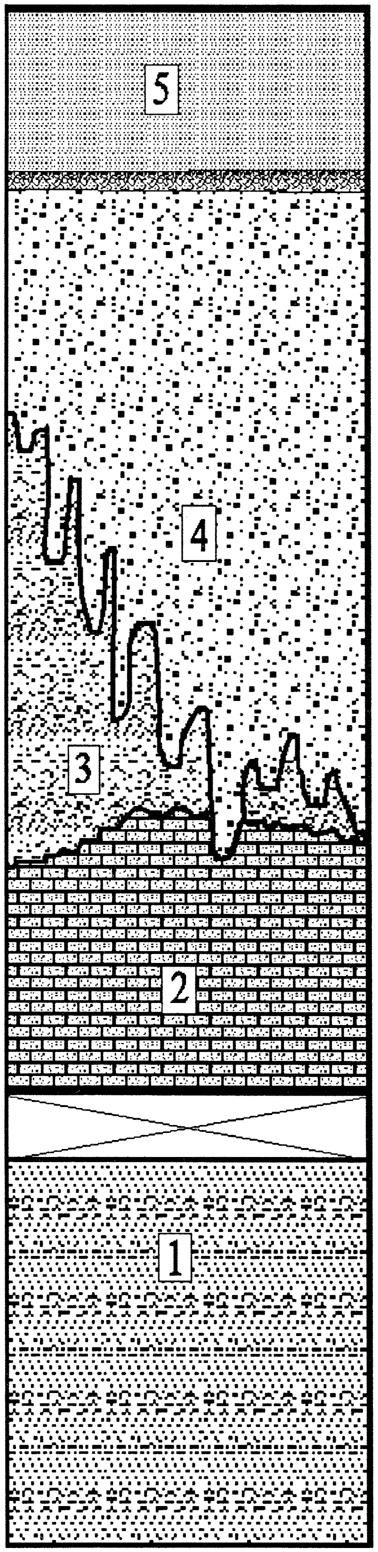
Table 1: Grain Size Analysis of Insoluable Residues

Number	Md	Mz	s	Sk	K	%in-soluable		Lithology Location
SCN-44	0.8	0.8	0.9	0.05	1.0	52.1%	coquina	Snows Cut, north side
SCN-47	0.8	0.7	1.3	-0.2	0.9	32.4%	coquina	Snows Cut, north side
SCN-63	0.0	0.1	1.4	0.0	1.0	44.8%	coquina	Snows Cut, north side
SCN-73	0.5	0.5	1.4	0.1	0.9	53.9%	coquina	Snows Cut, north side
SCN-67	0.6	0.7	1.0	0.0	1.0	37.2%	coquina	Snows Cut, north side
WilB-1	1.4	1.0	1.8	-0.4	1.1	50.4%	coquina	Wilmington Beach, O.C.
FF-56	1.5	1.3	1.1	-0.3	0.8	52.1%	coquina	Fort Fisher HS
SCN-22	1.2	1.1	0.9	-0.2	0.9	45.7%	shell hash	Snows Cut, north side
SCN-45	1.4	1.2	0.9	-0.3	1.1	46.5%	shell hash	Snows Cut, north side
SCN-46	1.3	1.1	0.9	-0.3	1.1	37.7%	shell hash	Snows Cut, north side
SCN-60	1.1	0.9	1.1	-0.3	1.1	34.0%	shell hash	Snows Cut, north side
SCN-61	0.4	0.3	1.3	-0.1	1.0	45.1%	shell hash	Snows Cut, north side
SCN-30	1.3	1.2	1.3	-0.3	0.8	100%	sand	Snows Cut, north side
SCN-41	1.5	1.4	0.9	-0.3	1.4	100%	sand	Snows Cut, north side
SCN-42	1.3	1.2	1.2	-0.2	1.2	100%	sand	Snows Cut, north side
SCN-50	0.0	0.0	1.2	0.0	1.2	100%	sand	Snows Cut, north side
SCN-52	0.6	0.5	1.1	-0.2	0.8	100%	sand	Snows Cut, north side
SCN-53	1.1	1.1	0.7	-0.1	0.9	100%	sand	Snows Cut, north side
SCN-59	1.4	1.2	0.9	-0.4	1.1	100%	sand	Snows Cut, north side
SCN-62	1.0	0.9	1.0	-0.2	0.9	100%	sand	Snows Cut, north side
SCN-40	2.8	2.7	0.5	-0.1	0.9	100%	fine sand	Snows Cut, north side
SCN-51	2.0	2.0	0.5	0.0	0.7	100%	fine sand	Snows Cut, north side
SCN-55	2.8	2.8	0.6	0.0	0.9	100%	fine sand	Snows Cut, north side

Approximately 100 grams of sample acidized in 10% HCl and then dry sieved. Parameters after Folk (1980): Md = Median in f units; Mz = Graphic Mean in f units; s = Inclusive Graphic Standard Deviantion in f units; Sk_G = Graphic Skewness; K_G = Graphic Kurtosis

facies", Sand-silt-clay facies", and "Coquina facies." The outcrop on the north side of Snows Cut was designated as a reference section for their Neuse Formation. Du Bar and others (1974) proposed the name Socastee Formation for a group of related strata near Myrtle Beach, South Carolina. They indicate that the Socastee is found within the Wilmington, North Carolina area but did not specify where. The description of the Socastee is very similar to that of the strata reported here and to that of the Neuse Formation. It is believed here that the Socastee Formation is in synonymy with the Neuse Formation, differing only in the state in which each are found. The name Neuse Formation therefore has priority over the name Socastee Formation when being applied to North Carolina strata.

Owens (1989) applied the name Wando Formation to the sands at Snows Cut and Waccamaw Formation to the coquina. Use of the term Wando is valid for the surficial unlithified sands which overlie the coquina; but application of the term Waccamaw to the coquina is wrong. The Waccamaw Formation occurs at a depth of -10 meters (-35 feet) below mean sea level and below the coquina exposures throughout the area as indicated by drilling at Fort Fisher by the U. S. Army Corps of Engineers (1982). Zarra (1991) referred to the coquina as the "Fort Fisher Coquina" but made no attempt to formerly define the name. Dockal (1995b) applied the informal name "Cape Fear Coquina" and divided it into three subdivisions or lithofacies of diagenetic origin; "shell hash lithofacies", sandy limestone lithofacies", and "Kure sand." The later being equivalent to Wells (1944) use of the term "Kure Sand" and the other two being equivalent to his "Cape Fear Coquina." Dockal's incorporation of the "Kure sand" into the Cape Fear Coquina was based upon the interpretation that it represented the insoluble residue left after the leaching of the carbonate shells and cements of the coquina; a view also suggested by Fallaw and Wheeler (1969). It is recommended here that the name Cape Fear Coquina be suppressed and that name Neuse Formation be applied both to the coquinas as originally intended by Fallow



Stratigraphic Section, Snows Cut, North Side

5. Sand; medium grained, moderately sorted, near symmetrical to coarse skewed, mesokurtic to leptokurtic, quartz sand. At the top is a weakly developed soil. THICKNESS 1 m.

Unconformity

Paleosol; reddish brown to black, medium to coarse grained, poorly sorted, moderate to well indurated, very ferruginous, quartz sand. Forms a horizontal planar, laterally persistent marker horizon that is moderately resistant to erosion. THICKNESS 0.1 to 0.5 m.

4. Sand; medium to coarse grained, moderately to poorly sorted, near symmetrical to coarse skewed, platykurtic to leptokurtic, weakly indurated, ferruginous sublitharenite. Sedimentary structures generally lacking with the exception of at least one lens shaped pocket with weakly marked cross bedding and burrows at the base toward the east end of the outcrop. Top of unit is a rapid color change with increasing iron oxide cement. Layer is laterally persistent throughout the area. THICKNESS 2 to 3 m

3. Shell hash; 60% shell debris and 40% siliciclastic grains, weak grain size sorting, weakly marked trough and tabular planar cross stratification, and a strongly developed sense of shell imbrication with the shells assuming a concave down orientation. The majority of the shells are fragmented and well rounded. Mercenaria, Busycon, and Rangia are abundant. Non indurated. Top is a sudden change to sand with the contact being a very undulatory surface of at least one meter relief where the overlying sand literally interfingers with the shell hash. Currently very limited extent only found at the west end north side of the canal. THICKNESS 0.0 to 1.5 m

2. Limestone; fine to very coarsely grained, weakly sorted, cross bedded; arenaceous, fossiliferous (Mercenaria, Busycon, and Rangia); poorly cemented, very friable and porous. Grades rapidly into overlying unit with decrease in cementation; Contact forms a slightly undulatory surface that cuts across marker horizons of coarser shell material which extend from limestone into overlying shell hash. Unit pinches out laterally and not found at the east end of the canal. Base not exposed. THICKNESS 0.0 to 1.5 m

Covered

1. Sand; gray to greenish gray; very fine to coarse grained interbedded, moderately to well sorted, abundant rounded carbonate bioclasts in the coarser fractions; finer beds are moderately argillaceous and slightly calcareous; unindurated. Contact with overlying beds is nowhere exposed but from bore hole records the contact is a gradational change either in color or degree of induration or both. THICKNESS 5 to 10 m.

Figure 3. Stratigraphic section from the North Side of Snows Cut. Unit 1 is below sea level and is inferred from drilling data. Mean low is roughly at the base of Unit 2.

and Wheeler (1969) and also to the strata in the area that are depositionally related to the coquina as described below.

DESCRIPTION OF THE COQUINAS AND RELATED BEDS

The best exposure of the coquina and associated strata is to be found on the north bank of Snows Cut west of the US 421 bridge (Figure 1) (Site 24 of Carter and others, 1988). The coquina at Snows Cut ranges from a medium to very coarsely grained fossiliferous sand to an arenaceous fossiliferous limestone; the siliciclastic fraction ranges from 32% to 54% of the mass (Table 1). The dominant grains are subangular to rounded monocrystalline quartz and well rounded molluscan shell fragments. These are weakly to moderately cemented with blocky calcite. Molds after various aragonitic bioclasts are abundant but aragonitic shells and shell fragments are still in abundance as well as shells of calcitized aragonite. Grain size, though moderately to well sorted throughout, is not constant (Table 1). There are coarser zones which contain whole molluscan shells, especially *Mercenaria, Busycon, Crassostrea,* and *Rangia.* These zones are up to 0.5 meters thick and traceable across the whole outcrop. Shells are generally concave down and imbricate suggesting a southerly transport direction. Trough cross-stratification, though weakly marked, also indicates a southerly transport direction. The coquina at the west end of the north bank of Snows Cut has a maximum thickness of 1 .5 meters and pinches rapidly eastward and westward. Those on the south bank are over 2 meters thick but generally present a poorer exposure.

The coquina at Snows Cut is overlain by an unlithified arenaceous shell hash or marl (Figure 3). Dominant grains are like that of the coquina; monocrystalline quartz and rounded shell fragments with the siliciclastic fraction representing 34% to 46% of the mass (Table 1). Grain size distributions of the siliciclastic fraction are comparable to those of the coquina (Table 1). Scattered throughout are well-preserved molluscan shells, but none are in growth position, none are articulated, and most but not all exhibit some degree of abrasion (Dockal 1995b). Like the coquina there is a weak sense of imbrication and cross-stratification. Cement is absent except for a minor amount of pendant cement within some of the shelter pores and meniscus calcite cement near the base of the arenaceous shell hash.

The contact with the underlying coquina is a rapid gradation in the degree and type of cementation. Dockal (1995b) interpreted this to have resulted from diagenesis near the paleo-water table. The shell hash proper with its pendent cements lying within the vadose lone, the coquina with its blocky calcite cement lying within the phreatic lone, and the boundary area with the meniscus cement represent the capillary fringe just above the water table.

Overlying the shell hash and the coquina where the shell hash is absent is a medium to coarse grained, moderately to poorly sorted, near symmetrical to coarse skewed, platykurtic to leptokurtic sand (Table 1 }. The sand is nonindurated to moderately indurated with ferruginous cement. The color of the sand ranges from a pale yellow to black. Sedimentary structures are generally absent but one can observe zones where larger grains, granules and pebbles occur within the still poorly sorted sand. These when tracked laterally pass into the coarser shell bearing zones of the shell hash or coquina. On the north side of Snows Cut and about halfway between the main coquina outcrop and the US 421 bridge a lens of finer and better sorted sand occurs within this sand layer (Table 1, samples SCN-40, 51, 55}. This lense has weakly marked trough cross-stratification and some burrows. The boundary between these two sand types is very indistinct suggesting that the finer sand my have been a lower energy phase with less carbonate bioclasts. At the eastern end of Snows Cut several dark brown to black horizons can be seen within the sand layer. These appear to be only zones of enrichment of iron oxides and have no relation to a sedimentary structure or to fossil soil horizons.

The contact between the sand and the underlying shell hash or coquina is a very distinct and undulatory surface where the overlying sand appears to literally interfinger in a vertical sense with the underlying shell hash or coquina. The sand forms cylindrical bodies 0.2 to 0.4 meters in diameter which project into the underlying material a meter or more. Dockal (1995b} described these as "fingers" and Moorefield (1978} referred to them as "potholes." They represent a geochemical front along which carbonated material dissolved. The sand, which sits above this surface, is the insoluble residue left over after dissolution of all the carbonate from the shell hash or coquina. The sand has the same grain types and grain size distribution as that of the insoluble residues from the shell hash and coquina (Table 1 }.

At the top of this sand layer is a well-marked nearly horizontal lying paleosol. Overlying this is finer grained sand that is moderately to well sorted. This sand is directly related to some of the Holocene dunes in the immediate area such as Sugar Loaf within Carolina Beach State Park just to the south of Snows Cut. Overlying this are spoils from the construction of the canal.

What underlies the sand and where present, the coquina at Snows Cut is not as well understood. Recent drilling by the U.. S. Army Corps of Engineers just east of the bridge revealed 610 7 meters of gray green sands with abraded shell debris and bands of shells and greenish gray silty sand sitting below the ferruginous sand (Ben Lackey, personal communication 1996). This material appears to be little different outside of color from the main sand noted above and the unlithified shell hash.

The coquina and associated beds at Fort Fisher (Figure 1) are very similar to those of Snows Cut. The cross stratification of the coquina is easier to see but this is more a reflec-

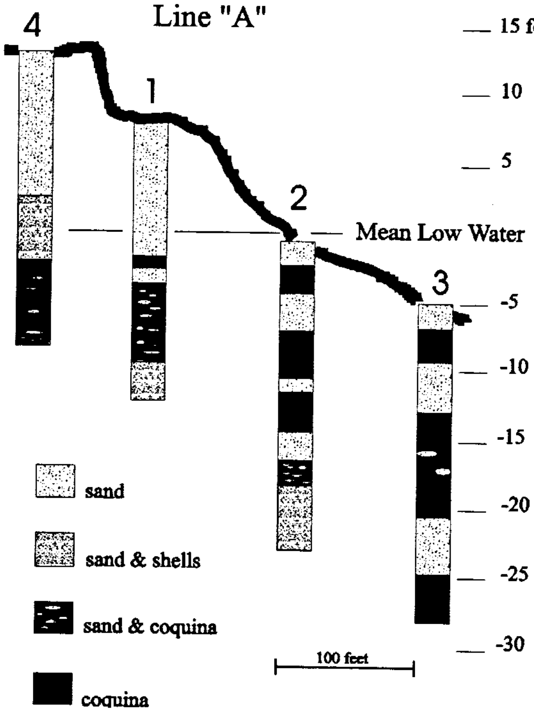


Figure 4. Wash boring logs of Line "A" from the beach face at Fort Fisher Historic Site. (Modified from House Document No. 204, 72 nd. Congress, 1 st. Session, Plate VII).

tion of outcrop type and not a true lithologic difference with that of Snows Cut. The cross- stratification at Fort Fisher has been described in detail by Fallow and Wheeler (1969), Fallow (1973), and Mansfield (1978). Mansfield (1978) found three sets of directions indicating paleocurrent flows of S65°W, S23°E and S22°W. As at Snows Cut the coquina is not laterally extensive. In comparison between the 1931 borings, the 1982 borings, and the present outcrop it appears that the main body of coquina was to the east of the present beach and has since 1931 largely eroded away. The 1931 study indicated that the coquina was as much as "9 feet thick" in places and extended continuously from boring to boring north to south (Figure 4). U.S. Army Corps of Engineers (1982) reports that "The coquina is irregular in thickness and elevation" and that "it is also discontinuous " The shell hash observed overlying the coquina at Snows Cut has not been observed in recent times at Fort Fisher however the 1931 study indicates a similar lithology being present. The ferrugenous sand that dominated the Snows Cut outcrop is present as well as the paleosol at the top of the sand. Well's (1944) description of this area notes several sand and associated paleosols. However these appear now to be no different that the color banding noted at Snows Cut in the main sand layer. Underlying the coquina is a plastic greenish- gray silt which contains sand filled burrows. The 1982 Corps of Engineers borings indicate 10 meters (32 feet) of gray to green sand similar to that found at Snows Cut underlie the coquina and associated ferruginous sand. The change from the ferrugenous dark brown to buff sands to the gray green sand type "is irregular with elevation from boring to boring varying as much as 5 feet and ranging from zero to -10 m.s.l." U.S. Army Corps of Engineers (1982).

The coquina occurs at other scattered localities throughout the area from just north of Snows Cut to Fort Fisher and adjacent off shore waters (Figure 1). Lithology of the coquina is always the same and in the on shore areas it is always associated with the ferruginous sand. The coquina, the shell hash, and the surrounding sands, which lie below the paleosol, are all considered here to be of the same original depositional layer. There present difference in lithology being due entirely to post-depositional diagenesis. The initial sediment was probably much like the shell hash seen at Snows Cut or the finer sand noted also at Snows Cut and from the Corps of Engineers borings. The coquina is simply cemented shell hash where the cementation formed at or near the paleo-watertable. The ferrugenous sand is the insoluble residue left from the later dissolution of all carbonate material from the shell hash, coquina, or finer sand. The reddish coloration represents the zone of oxidation of the sediments which is probably modern or Holocene. This passes downward to the greenish gray colored sediments found in the borings which are situated in a reducing geochemical environment.

Lithoclasts found in the coquina, shell hash, and sands are the same. These range in size from granules to cobbles and vary in lithology ranging from metamorphic rock fragments derived from Piedmont source areas to sedimentary rock fragments of Coastal Plain sources. Most are well rounded and half have a discoidal shape which would be characteristic of a pebble that has been within the surf environment for some time. Of the sedimentary rock fragments most probably were derived from sandstone in the Pee Dee Formation (Cretaceous) which would have been exposed a few tens of kilometers northwest of the area near Wilmington. One lithoclast contained the oyster *Conradostrea lawrencei* which would have been derived from the Waccamaw Formation (Pliocene/ Pleistocene). The Waccamaw occurs in the subsurface in the area about 11 meters (35 feet) below the top of the coquina and probably was exposed within a few kilometers northwest of the area. Of particular interests are lithoclasts of coquina found within the coquina. These range up to 15 cm in diameter, are somewhat rounded, spherical, and identical in all aspects of lithology to the main body of coquina. This indicates that the area has or had more than one body of coquina and further points out that the coquina and associated beds contain material reworked from older beds.

Mollusks which are commonly found in the coquina and shell hash include: *Anadara brasiliana, Crassostrea virginica, Dionocardium robustum, Donax variabilis, Mercenaria mercenaria, Rangia cuneata, Tagelus plebius, Busycon con-*

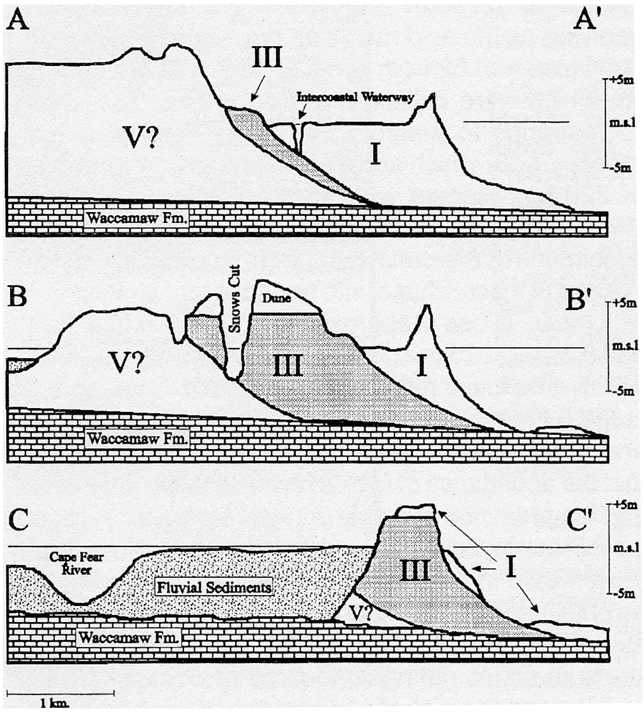


Figure 5. Modern latitude ranges for the molluscan fauna from the Neuse Formation of Snows Cut, New Hanover County, North Carolina (34°× 3’14” N; 77°× 54’23” W).

trarium, and *Nassarius obsoletus.* Other identified mollusks are listed in Figure 5 and Richards (1936), Fallaw (1973), and (Dockal 1995b). The foraminifera fauna is dominated by *Ouinqueloculina* and *Hanzawaia* (Fallaw, 1973) The two corals present are, *Septastraea crassa* which is quite common though always greatly abraded and *Siderastrea radians* which is rare but always well preserved, lacking abrasion, and encrusting other bioclasts. The barnacle *Balanus improvisus* has been described from the strata (Zullo and Miller, 1986). Flat echinoid fragments are common and an occasional whole specimens of the sand dollar, *Millita* sp., are found. Small fish teeth and crab claws are readily found in the finer fractions and shell fillings. Mammalian bones and teeth are infrequently encountered. These include mastodon (Richards, 1936), bison (Wilmington Star News, February 4,1995), camel and deer.

AGE OF THE COQUINAS AND RELATED STRATA

The age of the coquina has generally been considered to be Late Pleistocene (Fallaw and Wheeler, 1969). The coquina contains *Anadara brasiliana* (Lamarck), a mollusks which is characteristic of Blackwelder's (1981) upper Pleistocene and Holocene Yongesian Substage of the Longian Molluscan Stage. The present near sea level topographic position of these deposits suggest deposition in association with a sea level high stand above the altitude of the present sea level but below that of the high stand associated with the nearby 7-meter (25 foot) terrace. The Yongesian Substage designation for the coquina, its geomorphic position east or seaward of what is possibly the Suffolk Terrace, and the elevation of the strata relative to sea level suggests assignment to Stage 5 of the oxygen isotope base sea level curve of Chappel and Shackleton (1986). Wehmiller and others (1988), applying amino acid racemization, found a mean D/L Leu value of 0.52 from two specimens of *Mercenaria* sp. which were collected at Snows Cut. This value corresponds to amino zone Illd of Wehmiller and others (1988) which apparently has an age in excess of 220 ka.. Recent work by Wehmiller and others (1995) notes the additional amino acid analysis of 16 specimens of *Mercenaria* sp. from Snows Cut. The AI I values of these "cluster into two apparent aminozones with mean values of approximately 0.46+/-0.025 (n=4) and 0.34+/-0.025 (n= 12)" (Wehmiller and others, 1995, p.331). The lower ratio corresponds to oxygen isotope stage 5 the higher ration to stages 7 to 9 (Wehmiller and others, 1995, figure 2). Dockal (1995b) argued that the abundance of fossils reworked from older units and the presence of purple colored *Mercenaria,* which elsewhere in the region have lower A/l values than 0.34, would imply that even lower A/l values should be obtainable from the Snows Cut strata and therefore they should represent an age younger than stage 5. Uranium series dating conducted by Prosser (1993) on *Mercenaria* sp. shells from the shell hash at Snows Cut indicate an age of 62 ka BP. Radiocarbon evaluation of a variety of shells from the same site and stratum at Snows Cut found an apparent age of 24 to 29 ka BP (Dockal 1992, 1995b). However, as Dockal (1995a) pointed out radiocarbon assays giving this range of apparent age may have been affected by an extreme enhancement of the cosmic ray flux and thus may represent an age closer to 60 ka BP. Without additional and improved geochronologic work it is probably safest to assume that the coquina and related strata at Snows Cut and Fort Fisher were deposited before the most recent glaciation, isotope stage 2, yet sometime after isotope stage 5. This would best correspond to a slight warming period and sea level high stand belonging to isotope stage 3 or 75 to 55 ka BP.

ENVIRONMENT OF DEPOSITION

The molluscan fauna suggest deposition under climatic conditions similar to that found today along the southeastern Atlantic seaboard between 34 and 36 degrees north latitude (Figure 5). Fallaw (1973) considered the molluscan fauna of the Neuse Formation as a whole to indicate climate conditions similar to those of today but with slightly higher water temperatures than present. Part of the evidence of this was the presence of *Cardita floridana, Pyramidella crenulata,* and *Cantharus cancellarius.* The present northern limit of the range of the former is Florida and the later two is South

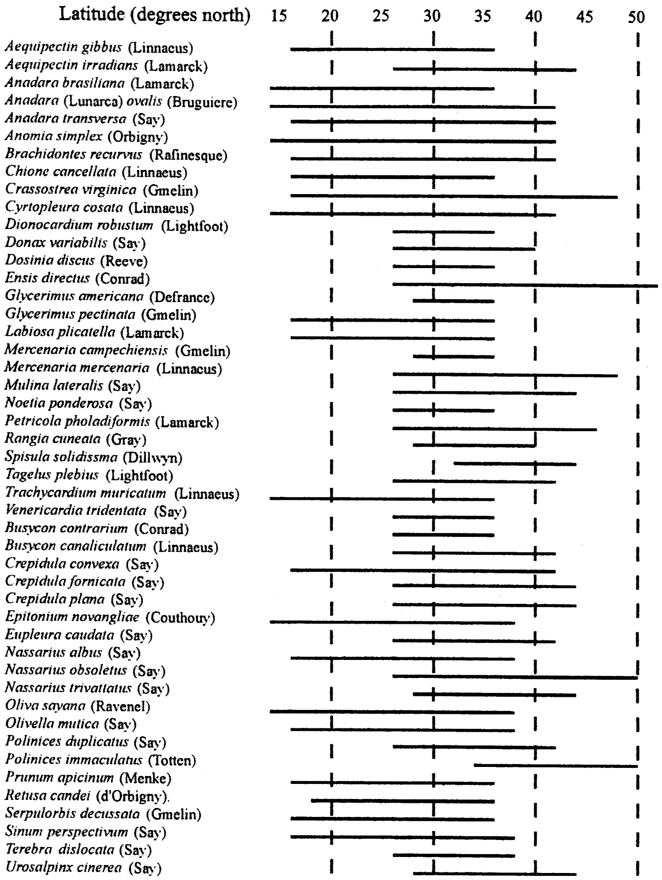


Figure 6. Diagrammatic stratigraphic profiles. I. corresponds to the Holocene or modern (Isotopes Stage 1) beach and slat marsh sediments. III. (shaded) corresponds to the coquina and associated strata (Isotope Stage 3). V? corresponds to earlier strata (Isotope Stage 5 and older). All three profiles trend normal the present beach face. A-A' is located at the top of the area covered by Figure 1. B-B' passes through the center of Snows Cut. C-C' passes directly through Fort Fisher. Surface profile taken from 7.5 minute topographic maps; subsurface control is very minimal. Please note vertical exaggeration is approximately 100 times.

Carolina. All three of these are, however, absent from the coquinas of New Hanover County and were only reported by Fallow (1973) from the Neuse estuary exposures of the Neuse Formation. If these coquinas are truly coeval with the Neuse estuary exposures then the lack of these taxa could be explained as a result of differing environmental niches. On the other hand if they are not coeval then that leaves open the possibility that water temperature during deposition of the coquina was not necessarily warmer than present.

The fauna, based upon the ecological ranges of their modern counterparts, represents a mixture of taxa from several environments: salt marsh, beach surf zone or intertidal, and shallow shelf (water depth less that 10 meters). The presence of a coral which is effectively in growth position and articulated sand dollars indicates shallow subtidal water depth and normal marine salinity (see Heckel, 1972). Furthermore the corals and to a lessor extent the barnacles imply clear water. The dominant foram, *Quinqueloculina,* is a robust thick wall form that would be expected to thrive in a high-energy environment (Fallaw 1973). The presence of the clam *Rangia* and the numerous lithoclasts of both Piedmont and nearby sedimentary rock units suggests close proximity to a fluvial system. The terrestrial mammalian remains may also have been transported via a river or they could represent fauna living close to the sediment depositional site. Fallaw (1973) considered the environment of deposition to be one of high energy possibly a shoal or tidal inlet. Moorefield (1978) suggested that "the coquina may have been deposited in a migrating Cape Fear River mouth, which is essentially a "mega-inlet'." Dockal (1995b) envisioned the coquina and shell hash exposed on the north side of Snows Cut to have resulted from a single storm event where storm debris were deposited above the level of high tide. None of these studies have taken into consideration the bigger picture. The boreholes in the area indicate at least 1 p meters of sediment associated with this package. Furthermore they suggest multiple depositional events of both a high energy and low energy nature. These strata extend north to south for about 15 kilometers forming an arcuate shaped package (Figure 1). In cross-sectional profile (Figure 6) they closely resemble the modern and ancient barrier systems in the region differing only in their rather limited lateral extent and lack of associated back barrier salt marsh sediments. The interpretation of environment of deposition favored here is one of shoreface sediments deposited from the level of the subaerially exposed beach to below the level of low tide, where deposition occurred within a largely sediment starved basin. As sea level rose the shoreface environment shifted laterally landward by storm wave action eroding sediment from the foot of the shoreface and redepositing it at the top, on the subaerial beach. The deposited material was a mixture of old reworked sediment from previous beach face deposits and what fluvial sediment that had accumulated after the last high stand The resultant fossil assemblage consisted of varying amounts of *in situ* forms such as *Donax variabilis,* proximal indigenous forms such as *Crassostrea virginica* and *Nassarius obsoletus,* distal indigenous forms like *Aequipectin gibbus* and *Siderastrea radians,* exotic forms like the terrestrial mammalian bones, and remanie forms reworked from older strata as evidenced by the amino acid racemization results of Wehmiller and others (1995). The modern equivalent of this is the beach deposits found just south of Fort Fisher. There the sediment on the beach contains an abundance of modern and fossil shells, blocks of coquina, and debris that has recently arrived from the Cape Fear River.

CONCLUSIONS

The term "Cape Fear Coquina" should be suppressed and in its place the name Neuse Formation should be used both for the coquina and the associated arenaceous shell hash and carbonate free sands. The coquinas represent a post depositional diagenetic product of a shell bearing sand deposited in a shoreface environment. Initial diagenesis took place at or near an ancient water table where dissolution of aragonitic bioclasts gave rise to calcite spar cements and the formation of the coquina. The ferrugenous sands which were in the past were referred to as the "Kure Sand" also represent a product of the diagenesis of both the coquinas and the associated unlithified sands which were the precursors to the coquina. Here. diagenesis took place during subaerial exposure where oxygenated meteoric waters both dissolved calcium carbonate and oxidized what iron bearing heavy minerals were present, resulting in a ferrugenous stained insoluble residue. The exposed coquinas and ferrugenous residue sands represent only the present surficial expression of a much thicker sediment package of limited lateral extent. These were deposited during a minor sea level high stand which occurred after isotope stage 5 but before stage 2, a period of time dating from approximately 75 ka to 55 ka before present or isotope stage 3.

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SHOREFACE PROCESSES IN ONSLOW BAY

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THE SHOREFACE ENVIRONMENT

The shoreface is the interface between the continental shelf and the subaerial coastal plain. The shoreface can behave as a source, barrier, filter, or conduit for the bi-directional exchange of materials between the land and the sea. The shoreface of barrier islands is the generally concave upward surface extending from the surf zone to the point where the slope becomes the same as the very gentle slope of the inner and central continental shelf. By this definition, the base of the shoreface off southeastern North Carolina is located at 10-12 m water depth (Figure 1).

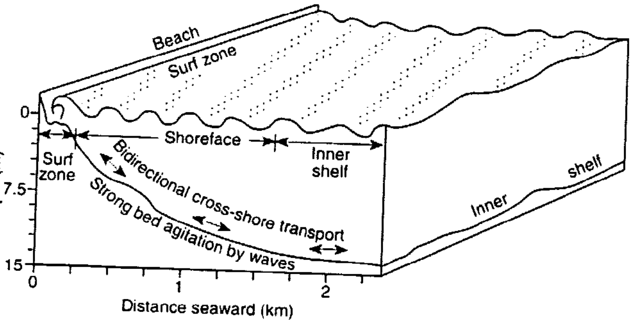

Figure 1. The shoreface is defined as the region between the surf zone and the inner continental shelf. Off southeastern North Carolina, the base of the shoreface is located between 10-12 m water depth. (Modified after Wright *et al.,* 1991).

Oceanographic and geologic processes in this environment determine how a shoreline will respond to storms, to sea-level rise and to human-induced changes in sand supply over time scales from hours to years to millennia. Understanding shoreface processes is also critical to understanding the behavior of replenished beaches, which provide many beachfront communities with storm protection, recreation areas, and an important tourism resource. Sediment transport across the shoreface is a key factor affecting 1) short- and long-term fluctuations of beach and surf zone sand storage (Wright *et al.,* 1985) ; 2) the morphology and stratigraphy of the shoreface (Niedoroda *et al.,* 1985); and 3) the nature of the inner shelf sand sheet (Swift, 1976). On retreating barrier island coasts, the shoreface is also a major source of new sediment to the coastal system, via the erosion and release of previously deposited lagoonal and fluvial sediments. This process, termed "shoreface bypassing" by Swift (1976), is all the more important on the southeastern U.S. Atlantic coast due to the absence of a modern fluvial contribution. Curray (1969) suggested that the present is a unique moment in geologic time with regard to shoreface evolution. Specifically, the relative stillstand in sea-level along most of the U.S. East Coast since about 4500 BP has allowed shoreface environments to mature and steepen as they seek an equilibrium form. If true, this process would minimize the amount of sediment available to beaches from the continental shelf, and perhaps increase the rate of shoreface retreat.

The shoreface is one of the most complex and least understood coastal environments (Wright, 1987; Nummedal, 1991). Geologists, oceanographers and engineers are only just beginning to understand that nearly all shoreface environments are different, where processes and controls vary in importance both spatially and temporally (Niedoroda *et al.,* 1985; Kraft *et al.,* 1987; Wright *et al.,* 1991). The shoreface is also the interface that couples the beach to the shelf. Theory and empirical observations have done much to identify shoreface sediment transport rates under various conditions. Presently, however, we can neither identify nor predict the net transport of material on the shoreface (Wright, 1987; Pilkey, 1993; Nittrouer and Wright, 1994). An applied understanding of shoreface processes is also needed to design coastal engineering projects, as well as to evaluate and improve models used in coastal engineering to predict the behavior of beaches. On a millennial time scale, sedimentation on coastal plain shelves during a time of rising sea-level such as the Holocene is driven by the bypassing of sediment onto the shelf via the shoreface; fluvial sediments are trapped in the estuarine system. Swift (1976) described this process as "shoreface bypassing." This mechanism provides the primary source of new sediment to the shelf as the ravinement surface bevels previously deposited coastal plain material. Thus, shoreface bypassing regulates sediment supply, and in effect the rate and character of shelf sedimentation.

The shoreface maturation process postulated by Curray (1969) seems to have peaked in Onslow Bay. The regressive barrier islands (e.g., Shackleford Banks, Bogue Banks and Bear Islands) are no longer prograding seaward; they appear to have accumulated all of the available inner shelf sand. This process of "inner shelf sweeping up" appears to have been very efficient; much of the inner shelf shows little or no evidence of modem sedimentation (Hine and Snyder, 1985). The transgressive islands (e.g., Topsail Island, Wrightsville Beach and Masonboro Island) exhibit much the same shoreface characteristics, although they have substantially less sediment volume. Nearly all of the sediment in the Topsail Island barrier system, for example, is contained within the body of the island landward of the beach; the shoreface sediment volume is very small.

Over shorter time frames (e.g., individual storm events to several weeks), a variety of processes operate on the shoreface and inner shelf (Figure 2). These processes create high bottom stresses that mobilize sediment. As described by Grant and Madsen (1979), the bed agitation required for sediment resuspension is furnished primarily by gravity waves, but sediment exchange is accomplished by quasi- steady-state mean flows. It is generally recognized that along-shelf flows predominate over across-shelf flows, but that across-shelf transport gradients are relatively high (Nummedal, 1991; Nittrouer and Wright, 1994). Several types of shoreface and inner shelf currents have been recognized, including: 1) storm- driven pressure gradient currents *(e.g.* wind-induced upwelling and downwelling currents); 2) tidal currents; 3) storm surge ebb currents; and 4) turbidity currents. Ekman (1905) predicted the presence of inner shelf currents and Sverdrup, Johnson and Fleming (1942) noted the theoretical basis for currents related to pressure fields in their classic textbook. Shi and Larsen (1984) and Dean and Perlin (1986) suggested that cross-shore transport on the shoreface could also be affected by forced long-period (infragravity) waves associated with groupy incident waves.

Our contemporary understanding of short-term shoreface and inner shelf processes is derived from both sediment transport modeling and field measurements. Early work on bottom boundary layer models was done by Jonsson {1966). Bijker {1967), and Sternberg {1972). Today, a number of different models {see review by Dyer and Soulsby. 1988) are used to examine boundary layer structure and sediment transport. In the past few years the Grant and Madsen {1979) and Glenn and Grant {1987) models for combined wave and current flow have come into wide use {Cacchione *et al.,* 1994; Nittrouer and Wright. 1994). These models coupled with field measurements of the bottom boundary layer, have identified a number of important factors that influence shoreface sedimentary processes. The rates and directions of sediment transport on the shoreface and inner shelf are governed

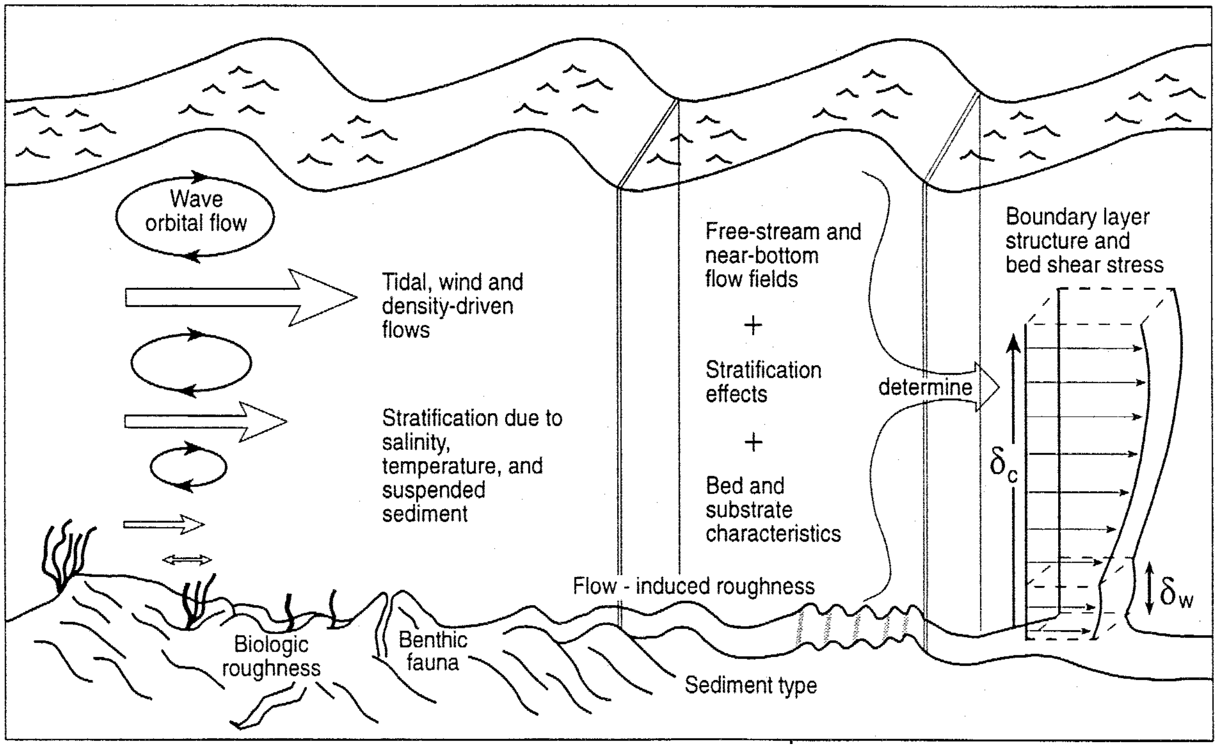

Figure 2. Schematic diagram of the major interacting components of the shallow-water bottom boundary layer. (Modified after Wright *et al.,* 1989).

primarily by wave-current interactions {Madsen and Grant, 1976); the micromorphology (ripple geometry, biologic roughness. *etc.)* and sedimentary characteristics of the seabed {Nielsen, 1979; Wright, 1993); and the geologic framework of the shoreface {Pilkey *et al.* 1993; Riggs *et al.*. 1995). Figure 2 illustrates the combined effects of these factors in determining the nature of the bottom boundary layer and the resultant bed stresses and sediment transport.

A number of field studies have documented that significant suspended and bed load transport occurs frequently on the shoreface and inner shelf. These include Sternberg and Larsen {1975); Gadd *et al.* {1978); Lavelle *et al.* {1978); Cacchione and Drake {1982); Vincent *et al.* {1982); Wiberg and Smith {1983); Cacchione *et al.* {1987; 1994); and Wright *et al.*. {1986; 1991; 1994) among many others. These studies, however, capture only a brief moment in the large-scale evolution of the shoreface. A decade-scale view of shoreface processes and evolution is currently lacking. This is particularly true in engineering studies of coastal processes, which typically require a decade- scale understanding of shoreface evolution.

Engineering models used to predict shoreline evolution and to design replenished beaches usually assume I that the shoreface has an equilibrium shape related I to wave climate and surficial sediment grain size: {Dean. 1977; Zeidler. 1982). As applied to the design of replenished beaches, the profile of equilibrium is considered to be the stable configuration that a beach will try to achieve under the influence of incident waves {Dean, 1983). Maintenance of the profile of equilibrium during shoreline retreat is also central to the concept of Bruun Rule response to sea-level rise (Bruun, 1962). The equilibrium profile equation was first proposed by Bruun (1954) for the Danish North Sea coast, and has the form

$$h = Ayn \quad (1)$$

where h is water depth, y is the distance offshore from the shoreline, n is a variable shape parameter and A is a scaling parameter. Bruun (1962) used this equation to develop a simple model for coastal evolution, in which the shoreface profile responds to sea-level rise by moving landward and upward such that the profile shape remains constant down to a depth of no wave influence (beyond which little sediment is supposedly transported). This simple relationship was one of the first models of shoreface transgression, preceding the more "classic" geologic conceptualizations of Curray (1969) and Swift (1976).

The Bruun Rule was, and still is, a good *concept*. It is *not* a good quantitative model. The concept, as originally conceived by Bruun, provided a strong conceptual basis for further thought about the nature of shoreface evolution. Subsequent work, however, sought to verify its basic principles. For example, Dean (1977) used a least squares approach to fit the data of Hayden *et al.* (1975) to an equation of the form shown in (1), where $n=0.67$. Infixing the value of n, Dean (1977) left the sediment scaling parameter, A, as the only independent variable in the equation. Dean (1987) related A to sediment fall velocity by transforming Moore's (1982) sediment grain size data to the equation

$$A = 0.067\, w^{O.44} \quad (2)$$

where w is the sediment fall velocity in cm S-1. Essentially, this relationship implies that any shoreface profile can be described solely on the basis of the grain size present.

The profile of equilibrium concept makes several fundamental assumptions about the nature of the shoreface and the processes acting on it (Dean, 1977; 1991; *cf.* Pilkey *et al.,* 1993). Pilkey *et al. (1993)* argued that several basic assumptions of the shoreface profile of equilibrium concept are not met in most field settings. The assumptions include: 1) sediment movement is driven solely by diffusion due to wave-energy gradients across the shoreface; 2) closure depth (a seaward limit of significant net sediment movement) exists and can be quantified; 3) the shoreface is sand-rich, and underlying geologic framework does not influence the profile shape; and 4) the profile described by the equilibrium profile equation (Dean, 1977) provides an approximation of the real shoreface shape useful for coastal engineering projects.

The shoreface profile of equilibrium is a fundamental principle behind most analytical and numerical models of shoreline change used to predict large-scale coastal behavior *(e.g.,* Hanson and Kraus, 1989 [the GENESIS model]) and to design replenished beaches *(e.g.,* Hansen and Lillycrop, 1988; Larson and Kraus, 1989 [the SBEACH model]), including those used on beaches in Onslow Bay. There has been no systematic field verification of the physical basis for the equilibrium profile equation (Kraft *et al.,* 1987; Wright *et al.,* 1991; Pilkey *et al.,* 1993). The concept, however, has been accepted as valid and useful by many coastal researchers, and is used to predict coastal evolution in a variety of coastal settings (e.g., Rosen, 1978).

The Bruun Rule effectively states that shoreface slope is the only control of shoreline retreat and that for a given sea-level rise, beaches with gentle shorefaces will recede faster than those with steep shorefaces. In typical applications, retreat rates are based on the slope of the shoreface rather than the slope of the migration surface. As a result, on East Coast shorefaces the Bruun Rule usually predicts a sea-level rise to shoreline retreat ratio of 1: 200. However, the retreat actually occurs across the surface of the lower coastal plain, the slope of which in southeastern North Carolina, for example, averages about 1: 2000. The Rule is also flawed in its assumptions concerning areal restriction of sediment movement on shorefaces, and in its lack of consideration for geologic control of shoreface slope. In actual use, the assumption of the depth of no wave motion (closure depth) has decreased to between 4 and 8 m on East Coast shorefaces, in contrast to Bruun's original 18 to 20 m depth assumption. There is no basis in reality for using the Bruun

Rule, as it is currently being used, to predict shoreline retreat rates.

A PICTURE OF THE MODERN SHOREFACE

Recent studies by Duke University, UNC-Wilmington, East Carolina University, NOAA/NURC and the USGS have examined the shoreface environments from Fort Fisher to Topsail Island. Over the past six years, extensive geologic and geophysical data has been collected off Wrightsville Beach, and more recently (1-5 July 1996) off Coke, Lea, and Topsail Islands, which form the basis of the discussion below. The dataset includes repeated sidescan-sonar surveys of the outer surf zone, shoreface and inner shelf off Wrightsville Beach conducted in 1992, 1994, and 1995, as well as over 240 line-km obtained off Topsail Island one week prior to hurricane Bertha. During the 1992 and 1996 sidescan surveys, seismic reflection data was collected (3.5 kHz and UNIBOOM™, respectively). We have also obtained a suite of over 200 short (-2 m) percussion cores, vibracores, surface sediment samples and diver observations off Wrightsville Beach, Figure Eight, Coke, Lea and Topsail Islands. Much of the area previously covered by sidescan-sonar surveys was resurveyed after hurricanes Bertha and Fran. Preliminary results are summarized below.

The transgressive barrier islands in the southern portion of Onslow Bay are located in a broad, shallow, high-energy shelf environment. Onslow Bay is a microtidal environment, with a mean tidal range of about 1 m. Based on four years of wave gage data obtained at Wrightsville Beach during 1971-1975 (Jarrett, 1977), the mean significant wave height in this area is 0.78 m, with a corresponding period of 7.88 s. The dominant direction of wave approach is from the northeast during the winter months, and from the southeast during the summer. Typically, storm waves approach from the northeast, but the area is also subject to episodic storm wave events from the east and south during the passage of tropical and extratropical cyclones.

The introduction of new sediment to Onslow Bay is negligible due to: 1) no fluvial input (coarse sediments are trapped in the estuarine system); and 2) minimal sediment exchange between adjacent shelf embayments (Cleary and Pilkey, 1968; Blackwelder *et al.,* 1982). Milliman *et al.* (1972) classified the Onslow Bay shelf sediment cover as residual (derived from the erosion of underlying sediments and rocks). The major sources of sediment for the shoreface and inner shelf are shoreface bypassing of unconsolidated, ancient sediments and bioerosion of marine hardgrounds on the inner shelf. Bioerosion of the hardgrounds produces a residual mix of sediment ranging from gravels to lime mud. These residual sediments are mixed with outcrop-associated, relatively fresh invertebrate fragments, including small corals and shell material.

The morphology of the shoreface from Wrightsville Beach to southern Topsail Island is dominated by shore-normal rippled scour depressions (a genetic term used by Cacchione *et al.,* [1984] to describe similar features in other shelf environments). The depressions develop just outside the fair-weather surf zone at 3-4 m water depth, and extend to the base of the shoreface at about 10 m depth. On a sidescan- sonar mosaic (Figure 3), the rippled scour depressions are defined by areas of high acoustic reflectivity (light-colored areas). The depressions are floored with very coarse shell hash and quartz gravel, and on the upper shoreface are scoured up to 1 m below the surrounding areas of fine sand. Long, straight-crested, symmetric megaripples floor the depressions. The depressions terminate and the shore-normal morphologic fabric becomes shore-oblique at the base of the shoreface, due to a series of east- to northeast-trending, relict ridges with 1-2 m of relief. Other features shown in Figure 3 are highlighted in Figure 4.

Recent surveys off Topsail Island show a similar, but less well-developed cross-shore morphology of rippled scour depressions. This is likely due in part to the greater abundance of rock outcrops that control the shoreface profile shape. The shoreface sediment volume, as suggested by our seismic data, also appears to be smaller than that at Wrightsville Beach. Thus, this area encompasses a fairly wide range of shoreface characteristics and morphologic types.

RECENT HURRICANE IMPACTS

As this field trip has highlighted, Onslow Bay has been recently impacted by hurricanes Bertha and Fran. These storms have provided a unique opportunity to investigate storm processes in a well-documented and well-studied shoreface system. Preliminary results from our post-storm studies, which are literally works in progress, are summarized below.

Repeated sidescan-sonar surveys off Wrightsville Beach indicate that the gross morphology of the shoreface and inner shelf did not change appreciably over the 38-month period between the 1992 and 1995 sidescan-sonar surveys described above. A sedimentary facies map presented by Thieler *et al.* (1995) based on the 1992 data is remarkably similar to the digital sidescan mosaics (just completed and as yet unpublished) produced in 1994 and 1995. This suggests that the interannual variability of the shoreface sediment cover is rather small; "typical" storms do not result in fundamental changes in the sedimentary fabric.

Hurricane Bertha appears to have been an event that left a minor, although distinct sedimentologic imprint. We have noted some moderate changes in the textural characteristics of the shoreface sediment cover, as well as a distinct local- to regional-scale storm bed. Hurricane Fran, however, was a geologically more important event. Post-Fran sidescan surveys, particularly off Topsail Island, indicate substantial reworking and redistribution of the shoreface and inner shelf

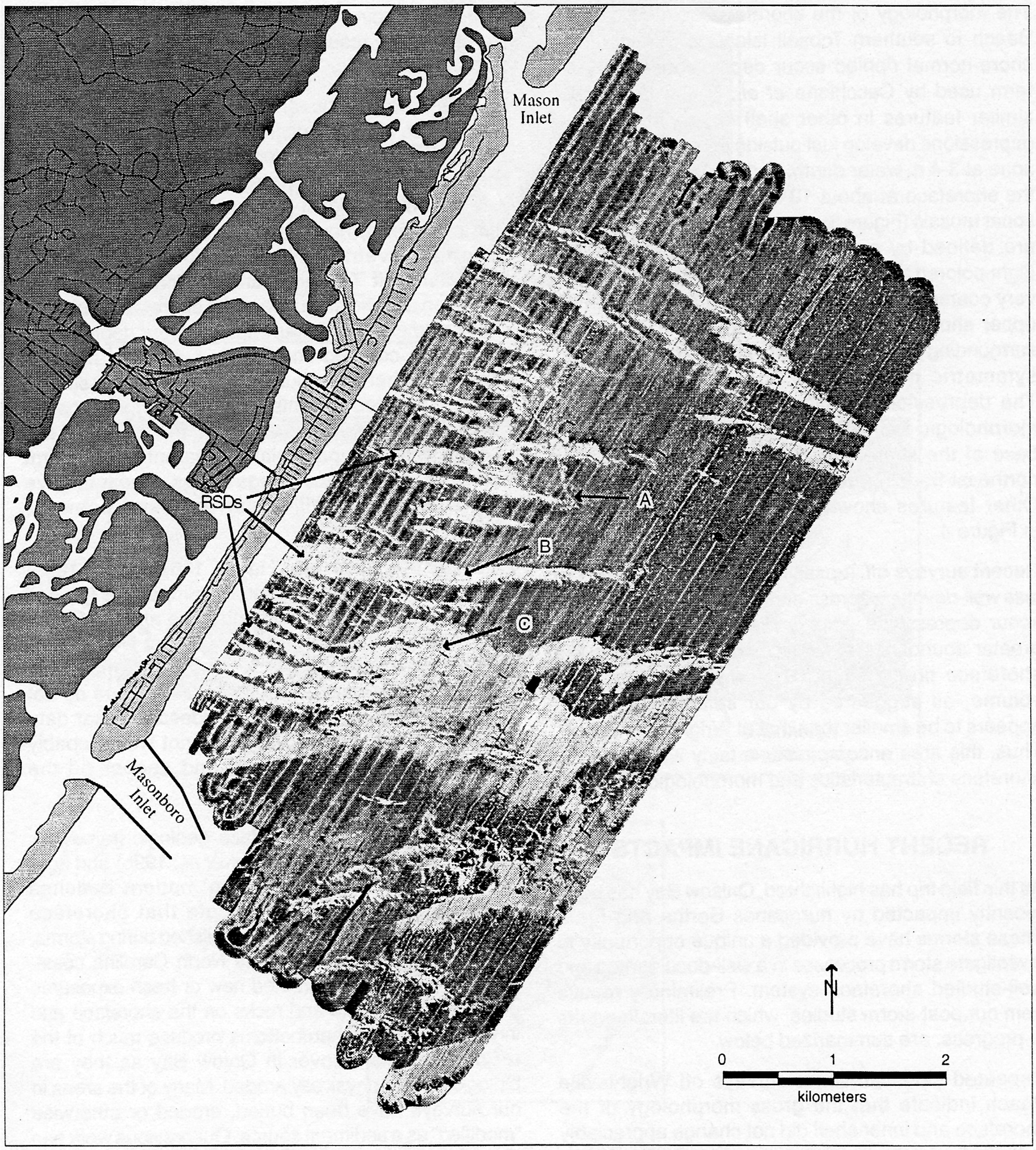

Figure 3. Sidescan-sonar image of the Wrightsville Beach shoreface and inner shelf obtained in March 1994, showing locations of several shore-normal to shore-oblique rippled scour depressions (RSDs), as well as features shown in Figure 4A-C. Areas of high acoustic backscatter are shown as light to white colored (generally medium sand and coarse, including rock outcrops); low acoustic backscatter is dark to black (finer than medium sand, and mud).

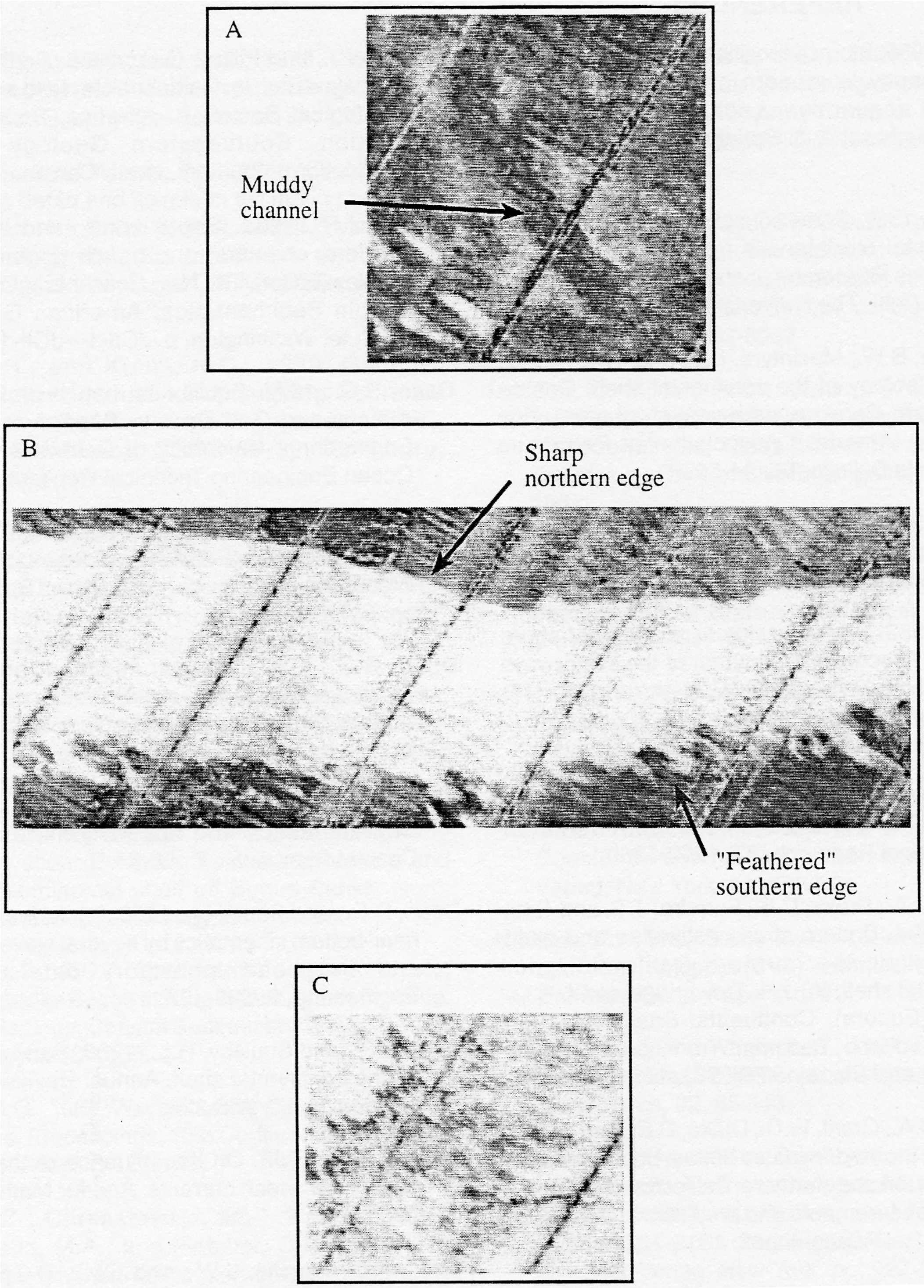

Figure 4. Enlarged view of features identified in Figure 3. A) A mud-filled channel outcropping on the inner shelf is shown here as a band of low backscatter (dark) sediment bounded by areas of slightly higher backscatter. This is a mid-Holocene tidal creek being exhumed by shoreface erosion. B) The rippled scour depressions on the shoreface and inner shelf typically have a sharp contact between coarse (high backscatter- white) and fine (low backscatter-dark) sediment. The southern contacts, however, appear more "feathered" or "wispy." C) Low-relief limestone outcrops in the study area is characterized by a somewhat diffuse pattern of high backscatter on the sidescan image. Rock scarps, however, are identifiable as curvilinear narrow bands of high acoustic backscatter. Several are identifiable in the southeastern portion of Figure 3.

sediment cover. Many rippled scour depressions have been covered completely by fine to medium sand, and there is abundant evidence for strong, seaward-directed currents. These currents deposited large, lobe-like sand bodies at the base of the shoreface. This is particularly apparent where storm overwash did not occur; large dunes appear to have intensified downwelling currents and seaward sediment transport.

A number of studies (e.g., Hayes, 1967; Aigner, 1985) have documented the presence of tempestites (graded storm layers) in shelf sediments. The areal extent of individual event layers, however, is not well known. Hurricane Bertha produced a distinct and mappable tempestite layer on the inner shelf. While we do not have post-Fran vibracores, the sidescan-sonar data suggests that the post-Bertha imprint was probably replaced by a more regional and deeper (in the sedimentary section) event layer.

Recent studies of the shoreface geologic framework *(e.g.,* Riggs, *et al.,* 1995; Thieler *et al.,* 1995) and age- mixing of the shell fraction on modern beaches (Wehmiller *et al.,* 1995) indicate that shoreface bypassing, particularly that accomplished during storms, is an important process on the North Carolina coast. Both hurricanes have created new or fresh exposures of ancient sediments and rocks on the shoreface and inner shelf. Marine hardbottoms produce much of the residual sediment cover in Onslow Bay as they are biologically and physically eroded. Many of the areas in our surveys have been buried, eroded or otherwise "modified" as a sediment source. Our previous work has also identified the importance of sedimentary texture and geologic control on shoreface sediment transport pathways. Have previously identified transport pathways been opened or closed? If so, what is the nature of that change? Will these events have any significant impact on the longer-term evolution of the shoreface? These questions await further study.

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MORPHOLOGY AND DYNAMICS OF BARRIER AND HEADLAND SHOREFACES IN ONSLOW BAY, NORTH CAROLINA

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ABSTRACT

Passive margin coastlines with limited sand supplies, such as much of the U.S. Atlantic margin, are significantly influenced by the geologic framework of older stratigraphic units that occur beneath and seaward of the shoreface. Many U.S. east coast barrier islands are *perched barriers* in which the underlying, pre-modern sediments determine the morphology of the shoreface and strongly influence modern beach dynamics and composition. Perched barriers consist of variable layers of beach sand on top of older, eroding stratigraphic units with highly variable compositions and geometries. Along many parts of the coastal system, stratigraphically-controlled bathymetric features on the inner shelf modify waves and currents and thereby affect patterns of sediment erosion, transport, and deposition on the adjacent shoreface. It is essential to understand this geologic framework before attempting to model the large-scale behavior of these types of coastal systems.

In North Carolina, most shoreline features are controlled by the pre-Holocene stratigraphic framework of the shoreface; the beaches are perched on top of pre-existing Pleistocene, Tertiary, and Cretaceous sediments. The surficial geology of the coastal zone is subdivided into two distinct provinces resulting in different stratigraphic controls of the shoreface. North of Cape Lookout the geological framework consists of a Quaternary sequence that fills a regional depositional basin called the Albemarle Embayment. The coastal zone south of Cape Lookout is dominated by Tertiary and Cretaceous units that crop out across the coastal plain and continental shelf, with very thin Quaternary units only locally preserved. Superimposed upon this regional stratigraphy is an ancient drainage system resulting in a series of fluvial valleys filled with younger coastal sediments separated by large interfluve areas of older stratigraphic units. This results in a coastal system in which the shoreface is either nonheadland or headland dominated, respectively. Headland dominated shorefaces are further divided into subaerial and submarine categories. Nonheadland dominated shorefaces are further divided into those influenced primarily by transgressive or regressive processes, or channel-dominated depositional processes (i.e., inlet migration or stream valley fill). Examples of each of these six types of shorefaces are presented to demonstrate the control that the geologic framework exhibits on shoreface morphologies and processes.

INTRODUCTION

Shoreface Profile of Equilibrium

Fenneman (1902) originally defined a shoreface *profile of equilibrium* as a profile that "the water would ultimately impart, if allowed to carry its work to completion." Recently, many other workers have expanded upon the definition of the shoreface profile of equilibrium including the following: Schwartz (1982): "a long-term profile of ocean bed produced by a particular wave climate and type of coastal sediment"; Dean (1983): "an idealization of conditions which occur in nature for particular sediment characteristics and steady wave conditions"; and Larson (1991): "a beach of specific grain size, if exposed to constant forcing conditions, normally assumed to be short-period breaking waves, will develop a profile shape that displays no net change in time:'

Bruun (1962) developed a simple model to characterize the profile of equilibrium that is assumed to exist for all shorefaces, and which has become the basis for most models in the design of coastal engineering projects. However, Kriebel et al. (1991) argued that "a beach profile in true equilibrium never exists in nature because nearshore water levels, waves, and currents are constantly changing."

Pilkey et al. (1993) believe that there are many "shoreface profiles of equilibrium" and the model as developed by

Bruun (1962) is too simplistic and based upon too many assumptions. Pilkey et al. (1993) attacked the use of such a simplistic model on the grounds that four basic assumptions are erroneous: 1) sediment movement is only driven by incoming wave orbitals acting on a sandy shoreface; 2) a quantifiable closure depth exists with no net transport of sediment to and from the shoreface; 3) the shoreface is sand-rich and the underlying or offshore geology do not influence the profile shape; and 4) if a shoreface is sand-rich, the smoothed profile described by the equilibrium profile equation must provide a useful approximation of the real shoreface shape.

The present paper focuses on assumption three of Pilkey et al. (1993). Our objective is to demonstrate the role of the geologic framework in determining coastal barrier morphology and shoreface dynamics for the North Carolina coastal system. The conclusions seem self evident, but it has become obvious that the concept of *shore face profile of equilibrium* has been over simplified, is poorly understood, and is somewhat controversial. We believe that it is imperative to incorporate the geologic framework into all models concerning the large-scale behavior of any coastal system.

Perched Beach Systems

Many beaches do not achieve profiles of equilibrium due to eustatic sea-level fluctuation, lack of adequate sediment supplies, or the variable influence of the geologic framework upon which the beach is superimposed. Obvious examples of the latter are the active margin coastlines of the U.S. Pacific, which are dominated by wave-cut platforms and associated strandplain beaches. These shoreface profiles are unquestionably dictated by the characteristics of the eroding headlands. In a similar but less dramatic way, passive margin coastlines with limited sand supplies, such as the U.S. east coast, commonly have barrier islands perched upon pre-modern stratigraphic units that occur beneath and seaward of the shoreface. These stratigraphic units control the morphology of the shoreface and strongly influence modern beach dynamics, sediment composition, and sediment fluxes (Riggs and O'Connor, 1974; Pearson, 1979; Riggs, 1979; Crowson, 1980).

Perched barriers will not develop a profile of equilibrium, as previously defined by Bruun (1962), for two reasons. First, perched barriers consist of thin and variable layers of surficial beach sands on top of older, eroding, stratigraphic units with highly variable compositions and geometries. Depending upon the composition and geometry, this underlying platform will act as a submarine headland influencing the shoreface dynamics and resulting profiles. For example, if these submarine headlands are composed of compact muds, limestones, or sandstones there will be a greater effect upon both the planform of barriers and morphology of the shoreface and inner shelf than shorefaces composed of unconsolidated sands and soft muds. Second, along many parts of the coastal system, bathymetric shoal features occur on the inner shelf. These features will modify incoming wave and current energy affecting the patterns of sediment erosion, transport, and deposition on the adjacent beaches.

Fisher (1967) described the mid-Atlantic coastal system as a series of coastal compartments. Each compartment consisted of an eroding mainland beach at the northern end with a barrier spit extending southward and grading into a series of barrier islands fronting a major estuarine system. Fisher (in Swift, 1969) interpreted the entire North Carolina barrier island system as a "southern spit" that formed off a single eroding headland at Cape Henry, Virginia (Fig. 1). Fisher's interpretation was a good first approximation based totally upon subaerial databases and studies. However, when the underlying geologic framework is considered, there are a whole series of eroding headlands that occur along the North Carolina coast (Fig. 2). These underlying framework units generally occur either in the shallow subsurface or submerged below the shallow coastal waters.

Classes of Inherited Geologic Framework

Six general classes of shoreface systems are recognized along the Onslow Bay portion of the North Carolina coast and are based on differences in the geologic framework. The classification scheme is based upon the designation of headland and nonheadland categories (Fig. 2). The headland features and associated valley fill segments represent the topographic or bathymetric features of Pleistocene or older units of varying compositions that produce the regional controls for the North Carolina coastal system (Riggs, 1979; Snyder, 1982, 1994; Riggs et al., 1990, 1992; Snyder et al., 1994).

A. Headland dominated shorefaces are those with morphological features that rise above the active ravinement surface and are dominantly composed of semi-indurated to indurated, Pleistocene or older sediment units. Two subclasses are recognized.

1. Subaerial headland shorefaces are characterized by a wavecut cliff and platform that are actively being incised into Pleistocene or older sediments with a perched beach.

2. Submarine headland shorefaces are submerged morphological features that have been incorporated into the modern shoreface and upon which the barrier-estuarine system is perched. Older sediments crop out on the eroding shoreface and commonly occur on the inner shelf as bathymetric highs seaward of the modern shoreface and thus modify incoming waves.

B. Non-headland dominated shorefaces are those without headland associations and are dominated by Holocene processes and sediments. Four subclasses are recognized.

3. Transgressive shorefaces are composed of compact

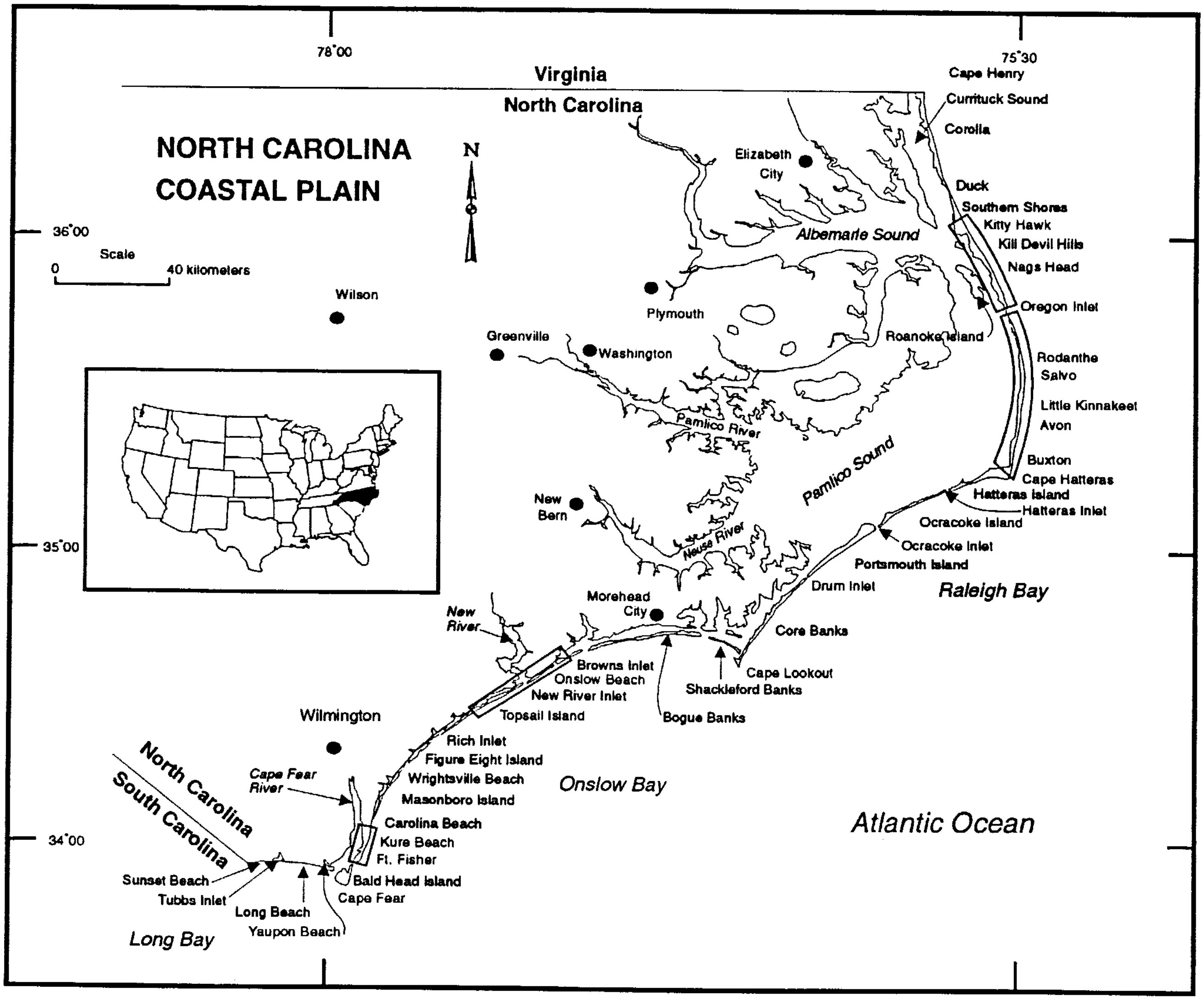

Figure 1. Map of the North Carolina coastal zone showing geographic mentioned in the text, along with the location of the four coastal segments discussed in the text (boxed areas).

Holocene peat and mud that extend from the estuaries, under the barrier sands, and crop out within the surf zone and upper shoreface. The shoreface is often characterized by an irregular geometry with discontinuous, highly scarped dune ridges and abundant washover fans on the barrier island.

4. Regressive shorefaces are composed of unconsolidated Holocene sands and occur along barrier island stretches with adequate sediment supplies. They often form in association with headlands, cape structures, and inlets and exhibit concave progradational geometry with accretionary beach ridges on the barrier island.

5. Channel-dominated inlet-fill shorefaces are composed of unconsolidated Holocene sand and gravel sediments that have back-filled old inlet systems. They have limited longshore extent and form on barrier islands in response to inlet systems that actively open, migrate, and close.

6. Channel-dominated valley-fill shorefaces are sections along barrier islands that have historically been occupied by paleofluvial drainage systems and are underlain by thick accumulations of fluvial- estuarine channel-fill sediments in response to deglaciation and Holocene sea-level rise.

The basic structural and stratigraphic characteristics of any coastal complex significantly influence the resulting barrier island morphology and shoreface dynamics, and therefore prevent the concept of an equilibrium profile from being realized. We present examples of perched beaches associated with each of the six different shoreface classes defined above (Figs. 1 and 2). Although all examples in this paper are from Onslow Bay, NC, we do not attempt to address and classify the entire Onslow Bay ocean shoreline.

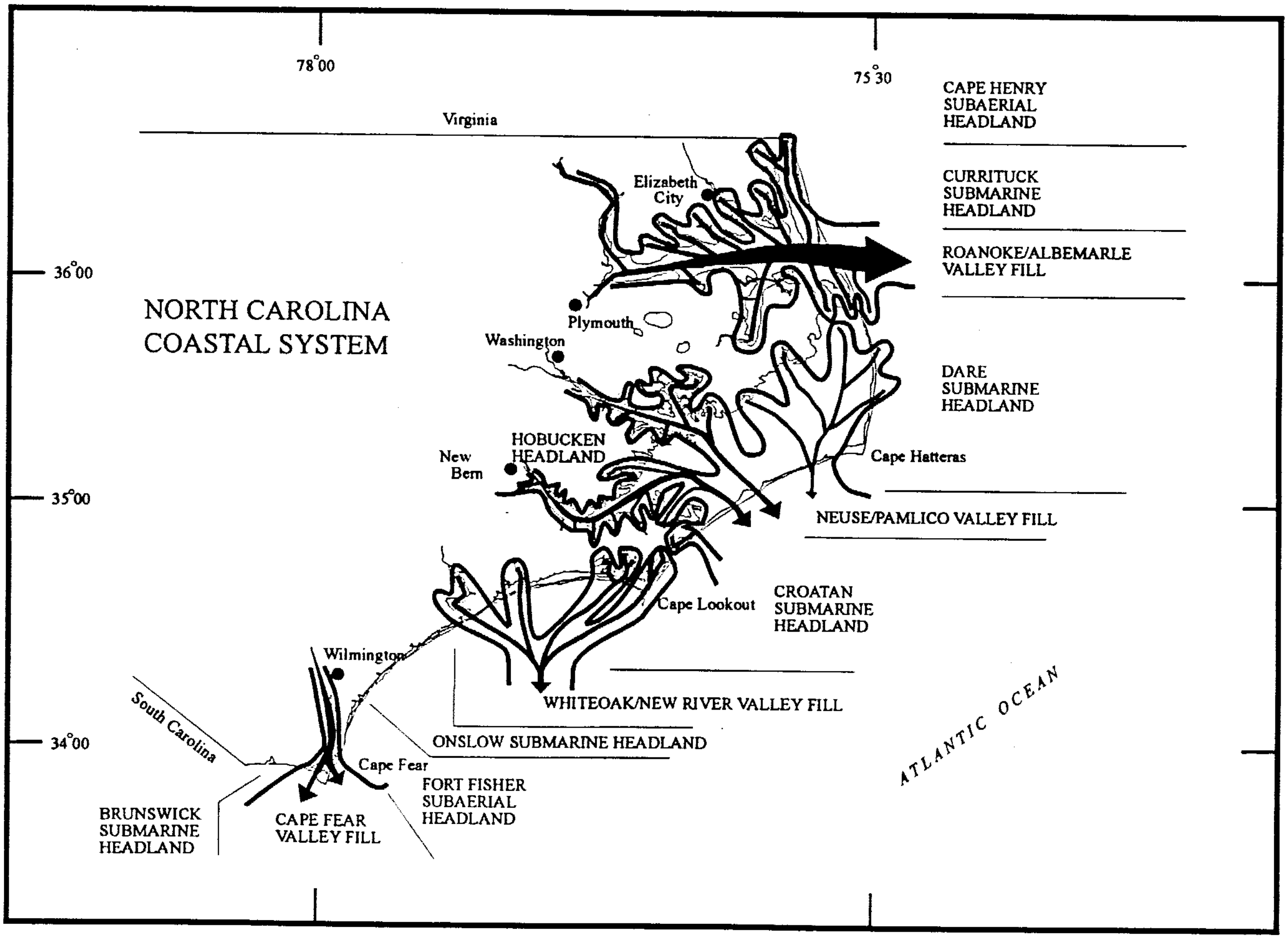

Figure 2. Map of the North Carolina coastal zone showing the major paleofluvial valleys and associated interfluve headland features.

NORTH CAROLINA COASTAL SYSTEM

Structural Setting

The shallow geology of the North Carolina coastal zone can be subdivided into the geologically distinct northern and southern provinces. North of Cape Lookout (Fig. 1), the coastal zone is characterized by a thick Quaternary sequence (50 to 70 m) that fills a regional depositional basin parallel to Albemarle Sound and called the Albemarle Embayment (Ward and Strickland, 1985). South of the Cape Lookout High (Fig. 1), the coastal zone is dominated by Tertiary and Cretaceous units. The older and more lithified, offlapping stratigraphic sequences wrap around the Carolina Platform High, a major basement structural feature that occurs south of Cape Fear, and crop out across much of the continental shelf in Onslow and Long Bays (Snyder, 1982; Riggs et al., 1990). These Tertiary and Cretaceous stratigraphic units, along with local, remnant Quaternary sediment units, form a basal platform with variable topography upon which many of the modern barriers in the southern province are perched.

Influence Upon Beach Sediments

Ancient sediment deposits have been vibracored under many shoreface sands along the entire Atlantic and Gulf coast. Marsh peats, tidal flat muds, fluvial sands and gravels, bay-fill sands and muds, flood- tide delta sands, and inlet-fill sands and gravels commonly occur below a thin veneer of modern shoreface sands that are generally <1 m thick. Such coastal areas are characterized by a seaward thinning and fining veneer of modern shoreface sands resting disconformably on Pleistocene or older strata. The modern sand veneer is ephemeral and easily removed from the shoreface during storms, exposing the older underlying strata on the shoreface to erosion (Pearson, 1979; Niedoroda et al., 1985). Thus, the erosional response and post-storm shape of the shoreface profile is at least partly controlled by degree of consolidation of the underlying sediments.

During storms, ancient strata cropping out on the shoreface also provide an immediate source of 'new' sediment to the modern beach system, a process called shoreface bypassing by Swift (1976). In North Carolina, the general grain size

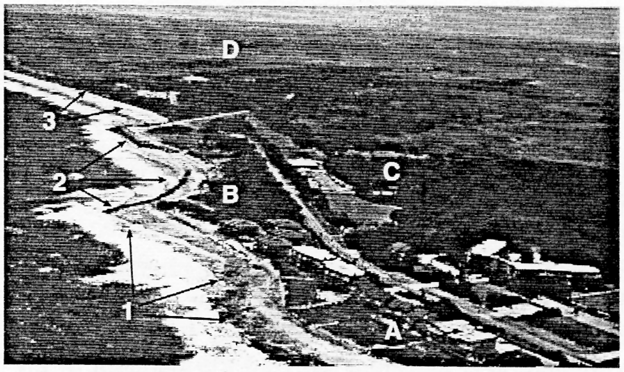

Figure 3. Oblique aerial photograph looking southwest from Kure Beach (A) to Fort Fisher (B), across the Onslow subaerial headland (C), and to the Cape Fear River estuary (D). This photo also shows the following features: (1) Pleistocene coquina sandstone outcrop in the surf zone; (2) man-made rock revetments to slow the rates of shoreline recession along the wave-cut cliff of Pleistocene friable humate quartzose sands; and (3) rapidly retreating shoreline associated with the channel-dominated valley fill shoreface.

characteristics of barrier island beach sands is strong evidence that relict sediments are being eroded from the shoreface (Moorefield, 1978; Pearson, 1979; Crowson, 1980; Pearson and Riggs, 1981; Cleary and Hosier, 1990). Support for the conclusion that relict and residual sediments are actively being eroded from the shoreface and deposited on the beach includes the following.

1. Sections of beach between Nags Head and the Virginia line (Fig. 1) contain abnormally high concentrations of quartz and lithoclast gravel, which was" mined for construction aggregate during historical times. These beach gravels occur in areas where seismic data demonstrate the -presence of paleofluvial channels passing beneath the barrier and cropping out on the adjacent continental shelf (Riggs and O'Connor, 1974; Riggs, 1979; Eames, 1983; Riggs et al., 1992).
2. The extinct fossil oyster *Crassostrea gigantisima,* and associated Oligocene rock lithoclasts, occur in great abundance on Onslow Beach and Topsail Island after storms (Crowson, 1980; Cleary and Hosier, 1987). The eroded gravels are derived from the bioerosion of Oligocene hard bottom scarps that crop out on the inner shelf. These gravels are subsequently transported up the shoreface during high-energy storms and left on the beach in the same fashion as heavy minerals at the top of the swash zone of a storm beach.
3. Overwash terraces on Masonboro Island contain abundant cobble-size coquina clasts and mollusk shells derived from hardbottoms exposed on the adjacent inner shelf. Also, much of the coarse- grained component of the beach sediment can be attributed to the onshore transport of reworked and palimpsest sediments that mantle these hardbottoms. Storm reworking of the thin shoreface sediment cover and the degraded character of underlying rock units appear to contribute significant amounts of coarse material to the adjacent beaches (Cleary et al., 1992, 1993).
4. Black-stained oysters and other estuarine fossils are the dominant shell on many North Carolina beaches. These shells always produce pre- modern, Holocene ages when dated by carbon- 14 techniques (Pilkey et al., 1969; Wehmiller, 1993).
5. Mixed assemblages of Pleistocene age marine shells occur in great abundance on many of the North Carolina beaches analyzed by amino-acid racemization dating techniques (Wehmiller, 1993).

Subaerial Headland Shorefaces

Fort Fisher to Kure Beach

North Carolina's only subaerial headlands occur on either side of the Cape Fear River estuary and include portions of Yaupon and Long Beaches (Griffin et al., 1977) to the south, as well as the shoreline between Fort and Kure Beach to the north. In the latter area, an extensive eroding subaerial headland intersects the coastal zone without a barrier island-estuarine system (Fig. 2). The coastal system consists of a wave-cut platform incised into Oligocene through Pleistocene units of the mainland peninsula with a thin beach perched on top of the irregular geometry of the Pleistocene units (DuBar et al., 1974; Moorefield, 1978; Meisburger, 1979; Cleary and Hosier, 1979; Snyder et al. 1994).

Figure 3 shows the dramatic relationship between three different geologic framework situations in the Fort Fisher area and geometry of the shoreline and upper shoreface. Erosion resistant, lithified and cross-bedded coquina sandstone forms a headland in the shoreline north of Fort Fisher (Fig. 3). Friable humate and iron-cemented Pleistocene sandstone (Fig. 4) forms a 2 m high wave-cut cliff and terrace that fronts the shoreline immediately south of the headland and seaward of the Civil War Fort Fisher. South of Fort Fisher is a nonheadland segment characterized by a channel-dominated, valley-fill shoreface (Fig. 3) underlain by 10 m of muddy estuarine sediments (Swain and Cleary, 1992). The shape and evolution of the three different coastal compartments around Fort Fisher is clearly related to the presence and lithology of the outcropping and underlying Pleistocene geologic framework.

Moorefield (1978) mapped beach outcrops of Pleistocene coquina north of Fort Fisher and their seaward extensions on the inner shelf. Our ongoing studies clearly show that coquina and its associated lithologies form a series of widespread, irregular, bathymetrically high hardbottom features with >3 m of relief. This karstic mosaic includes one extensive hardbottom area known as Sheephead Rock that lies in 9 m of water with pedestal-like hardbottom features rising to within 2.5 m of the ocean surface. Diver observa-

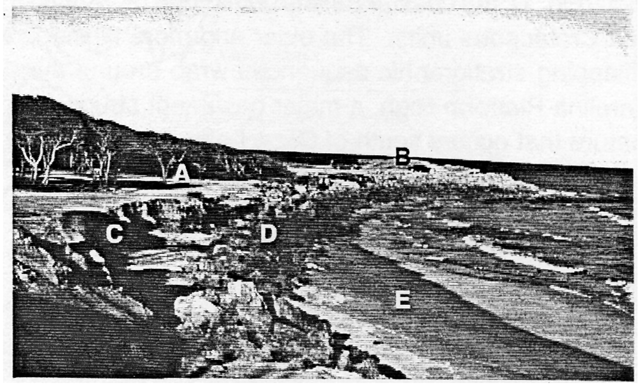

Figure 4. Photograph looking north at the Fort Fisher (A) and the Pleistocene coquina subaerial headland (B). This photo also shows the: (C) Pleistocene friable humate- and iron-cemented sandstone that forms a two meter high wave-cut cliff; (D) rock revetment built to protect the rapidly receeding shoreline and the Civil War Fort Fisher; and (E) the strand-plain beach. Photo was taken in 1977 and the shoreline had already receeded behind the rock revetment; today the shoreline has receeded an additional 20 to 25 meters.

tions and cores suggest that the sediment cover is both patchy and very thin across much of this region and in many areas is totally lacking.

The extensive series of coquina outcrops on the inner shelf act as barriers that could significantly affect the refraction of wave energy, as well as the movement of sand across this shoreface. Moorefield (1978) believes that sand from both the rapidly eroding beach at Fort Fisher and littoral drift, are transported seaward of the rock barrier during storms and prevented from returning to the beach during subsequent low energy periods. The result of this process is a net sediment deficiency in which the rapidly retreating bluff shoreline is consuming the historic Fort. A variance was received from the State to build anew rock revetment to protect Fort Fisher; the present bulkhead structure was completed in 1995.

Submarine Headland Shorefaces and Bathymetric Highs

Onslow Beach to Topsail Island

The New River Inlet coastal area (Fig. 1) is a submarine headland, which forms a small seaward bulge in the coastline of central Onslow Bay (Fig. 2). This shoreline protrusion is produced by the Oligocene Silverdale Formation, an indurated moldic limestone and calcareous-cemented quartz sandstone unit. The Silverdale Formation crops out at or slightly below sea level in the mouth of the New River estu-

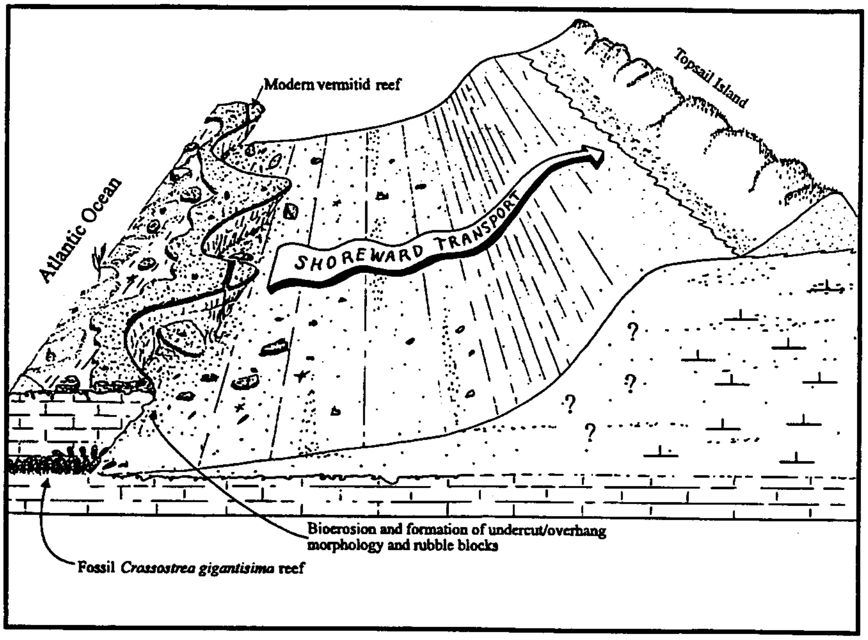

Figure 5. Schematic diagram looking southwest along the hardbottom scarps of the Oligocene Silverdale Formation that crop out on the inner continental shelf off of Topsail Island. The scarps are parallel to and face the beach, up to 5 m high with major overhangs, and dip gently seaward. Extensive bioerosion and wave processes produce "new" gravel sediment which is transported directly to the beach during storms. The sandy limestone crops out at sea level in the estuary behind the barrier; however, it is not known how the barrier is perched on top of this rock unit. Figure is modified from Crowson (1980).

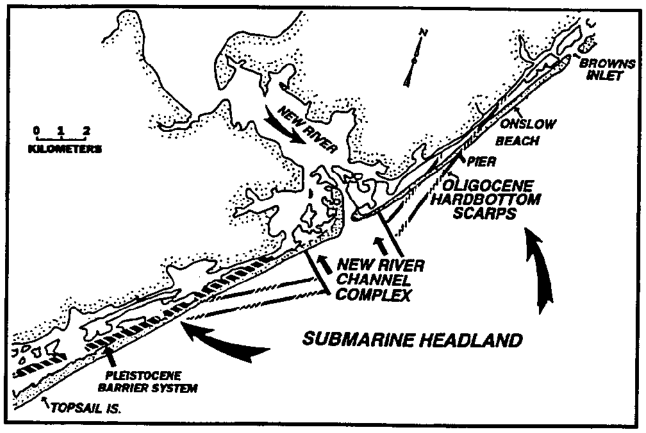

Figure 6. Map showing the outcrop pattern of the Oligocene rock scarps on the inner shelf formed by the Onslow submarine headland. In addition, the map shows the lowstand channel cut by the New River and the area of intersection where the topographically high rock features intersect the barrier islands. Notice the similarity of orientation patterns of both the estuaries and older Pleistocene beach ridges.

ary. It occurs extensively on dredge spoil islands of the Intracoastal Waterway behind Topsail Island and Onslow Beach, and forms a series of bathymetric ridges on the inner shelf on either side of New River Inlet (Crowson, 1980). Crowson mapped these prominent submarine rock features as a series of ridges that occur seaward of the lower shoreface, have steep landward-facing scarps with smooth surfaces that dip gently away from the beach, and have up to 5 m of relief above the surrounding ravinement surface (Fig. 5). The ridges rise locally to about 5 m below MSL, higher than the elevation of the lower shoreface, which is probably high enough to cause major refraction of storm waves and currents and possibly affect the patterns of erosion and deposition on the adjacent beaches.

The ridges are oriented at acute angles to the beach and intersect the shoreface on Topsail Island and Onslow Beach (Fig. 6). Core drilling by Cleary and Hosier (1987) demonstrated that the rock ridges continue under Onslow Beach and into the back- barrier estuarine system (Figs. 7 and 8). Similar limestone ridges pass beneath Topsail Island and into the back-barrier estuarine system (Clark et al., 1986) where the rock structures appear to be related to the occurrence and orientation of Pleistocene barrier island systems (Fig. 6).

The Oligocene submarine headland appears to subdivide these two barriers into coastal compartments that have different orientations and shoreface dynamics. Figures 9 and 10 show the changes in shoreline geometry that coincides with the intersection of the Oligocene rock ridges. The northern segment of Onslow Beach is characterized by a cuspate shoreline geometry with wide beaches, a recurved accretionary beach ridge, a nearly continuous high dune ridge, and shoreline accretion rates that average 2 m/yr (Cleary and Hosier, 1987). In contrast, the southern segment is characterized by a narrow shoreface with abundant rock gravel on the beach, a single discontinuous scarped foredune ridge, presence of major washover terraces, and current erosion rates up

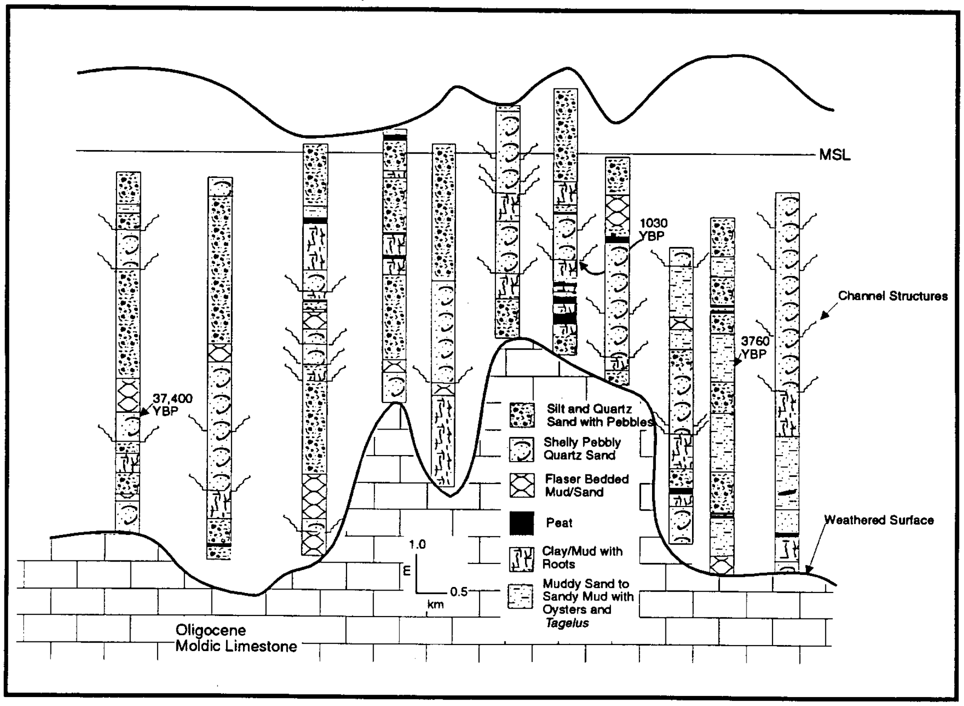

Figure 7. Geologic cross-section along Onslow Beach based upon continuous split-spoon drill holes located in Figure 8. This section shows two Oligocene rock ridges that rise approximately 5 m below sea level and pass under Onslow Beach.

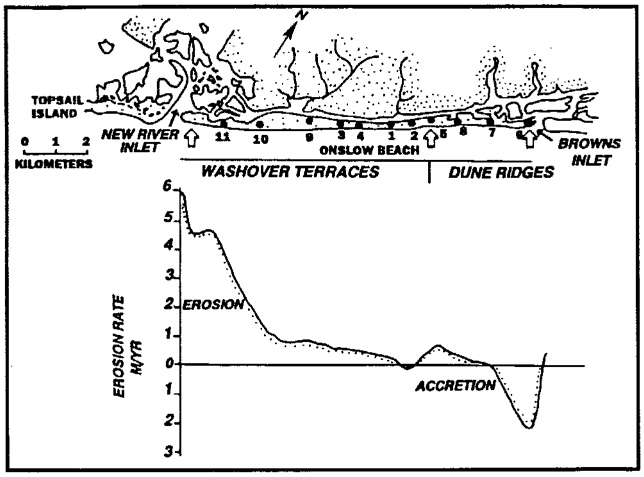

Figure 8. Map of the Onslow Beach showing the 1) location of drill holes used in Figure 7, 2) location (middle arrow) of coastal inversion that takes place where the Oligocene rock ridges intersect the island, 3) plot of average annual rates of shoreline recession from Benton et al. (1993) along Onslow Beach. The southern portion of the island is experiencing severe shoreline recession whereas the northern pint is experiencing accretion and dune ridge development. The area of most severe erosion adjacent to New River Inlet is largely a direct response to inlet modification.

to 6 m/yr.

Crowson (1980) believes that active bioerosion of the rock scarps represent a major source and supply of 'new sediment' to the adjacent beaches (Fig. 5). Abundant gravel, up to boulder-size grains, is derived from the rock scarps and lower shoreface and delivered to the beach during storms where it is rapidly broken down to sand-sized grains in the surf zone.

Figure 9. Oblique aerial photograph looking northeast from New River Inlet to Onslow Beach (A). The approximate location and orientation of the submerged Oligocene rock ridges are indicated on the photo (B); notice the major change orientation of Onslow Beach northeast of the intersection of these ridges with the barrier island (C).

Non-Headland Dominated Shorefaces

Transgressive Shorefaces

Large segments of the NC barrier islands are underlain by deposits of estuarine peat and mud, often with in situ tree stumps. These semi-indurated, back-barrier sediments crop out in the surf zone along major portions of Onslow Bay barrier islands, particularly during winter storms when much of the sand is transported off the beach and is stored in offshore bars. These fossil estuarine units were overrun by barrier island systems as they migrated upward and landward in response to the general Holocene transgression. Obviously, these sediments have very different compositions, densities, cohesiveness, and resistance to erosion and transport than normal beach sands. Consequently, their occurrence in the shoreface will affect the beach width, shoreface profile, and rates of shoreline recession.

Discontinuous zones of 1,200 to 1,700 year old peat have been mapped along major portions of both Masonboro Island (Fig. 1) .At the northeast end of Topsail Island, a 0.5 m thick peat crops out periodically in the surf zone and can be traced laterally around New River Inlet to a modern back-barrier salt marsh. Underlying the peat is a compact gray clay of unknown thickness. Storm erosion produces large boulders (up to 0.7 m) of peat and clay, along with Oligocene rock fragments from the offshore scarps; these gravels represent a significant input of 'new' post-storm beach sediment.

Regressive Shorefaces

Only local and relatively small segments of the North Carolina shoreline are presently characterized by regressive shoreface conditions. These areas generally occur on the flanks of headlands and represent temporary episodes of coastal progradation that usually alternate with episodes of longer-term truncation as the headland recedes. However, during episodes of regression, these shorefaces are relatively stable, are characterized by progradational geometries, beach ridge accretion, dune ridge development, and have the potential for approximating the idealized "profile of equilibrium". In Onslow Bay, Cape Lookout, Shackelford Banks, and Bald Head Island contain local and often temporary examples of this type of shoreface system (Fig. 1).

Shoreface regression also takes place on a small scale on beaches adjacent to some inlets. This process depends upon the individual inlet processes and will develop only if there is an adequate sand supply. The result is the progradation of the shoreface adjacent to the inlet to produce the classic 'drumstick' barrier of Hayes (1976). The drumstick portion of the barrier is characterized by wide beaches, continuous dune ridges, multiple recurved accretionary beach ridges, and shoreline accretion. The northeastern end of Onslow Beach, adjacent to Browns Inlet, displays these characteristics (Cleary and Hosier, 1987). Similar inlet influenced barrier segments include Figure Eight Island downdrift of Rich Inlet

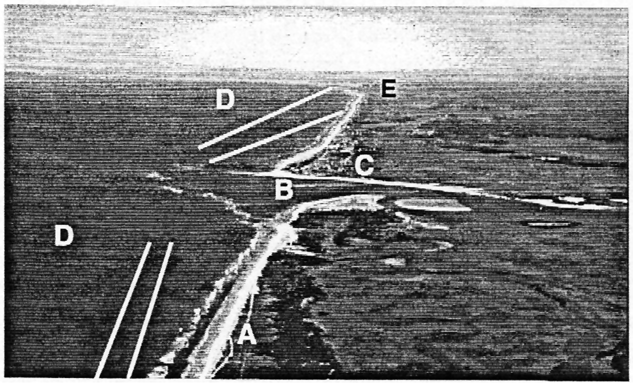

Figure 10. Oblique aerial photograph looking southwest from the southern end of Onslow Beach (A), across New River Inlet (B), and to Topsail Island (C). The approximate location and orientation of the submerged Oligocene rock ridges are indicated on the photo (D); notice the major change in orientation of Topsail Island southwest of the intersection of these ridges with the barrier island (F).

(Fig. 1).

During prior small-scale, sea-level fluctuations that occurred during the overall Holocene transgression, conditions of shoreface regression were common along the NC barrier islands (Fisher, 1967). Under these conditions, shoreface regression occurs in response to a minor drop in sea level; if there is an adequate sand supply, the beach builds seaward through the accretion of a series of beach ridges. The subsequent sea-level rise and transgression truncates the previously deposited set of beach ridges. Numerous barrier islands display a complex system of multiple beach ridges, which include Bogue Banks, Buxton Woods, and Kitty Hawk Woods. The central and western portions of Bogue Banks consist of sets of prograding beach ridge structures that probably formed in this way (Steel, 1980).

Channel-Dominated, Inlet-Fill Shorefaces

Fisher (1962) mapped the spatial and temporal distribution of historic inlets along the North Carolina coast north of Cape Lookout from aerial photographs. An estimation based upon Fisher's map suggests that about 50% of this coastal system has been occupied by inlets during the historic past with >78% having been occupied by inlets based upon the presence of old flood-tide deltas landward of the barriers. These segments of the barriers are underlain by thick accumulations of inlet fill sands and gravels (Cleary and Hosier, 1979; Eames 1983; Hine and Snyder, 1985; Riggs et al., 1992).

Today, the entire North Carolina coast north of Cape Lookout (Fig. 1) contains only three major inlets (Oregon, Hatteras, and Ocracoke) and one minor inlet (Drum). Whereas, the area south of Cape Lookout (Fig. 1) represents a very different coastal compartment that is dominated by the Onslow submarine headland (Fig. 2). Thirteen modern inlets occur within the coastal compartment between Cape Lookout and Cape Fear.

The eight modern inlets along the 76 km between Onslow Beach and Carolina Beach in the southern portion of

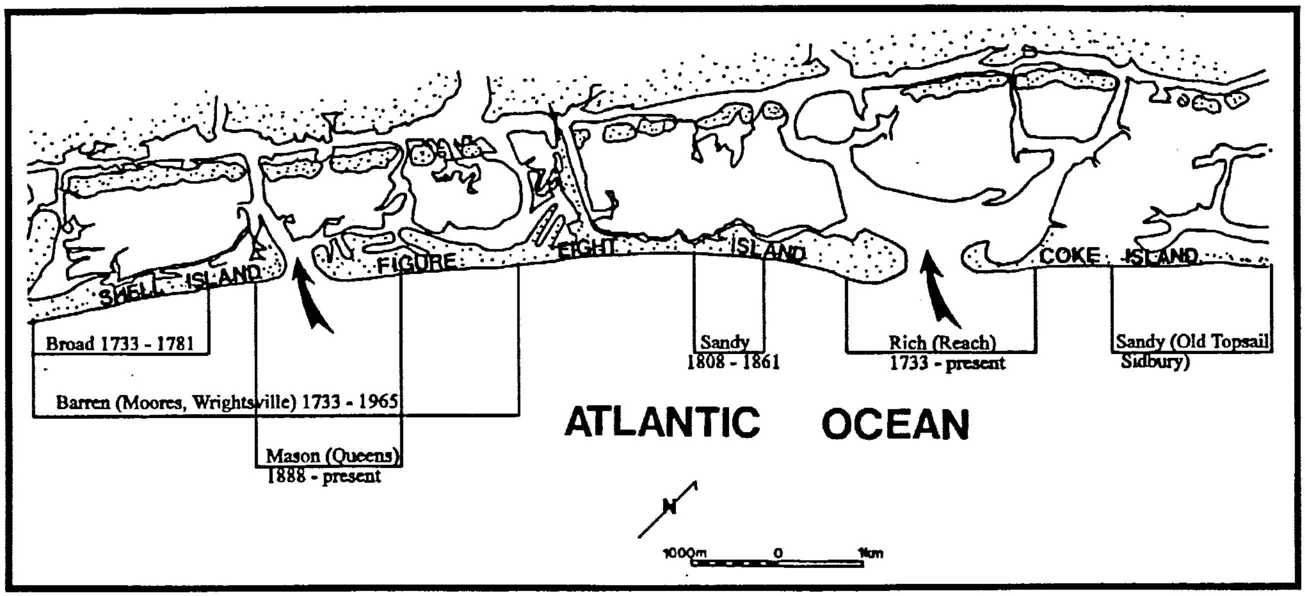

Figure 11. Map showing the position and movement of historical inlet zones on Shell, Figure Eight, and Coke Islands, North Carolina. Notice that the majority of these barriers have been impacted by historic inlets; vibracoring on the islands demonstrates that 100% of these islands consist of inlet channel backfill sediments. Figure is modified from Hosier and Cleary (1977) and Brooks and Cleary (1989).

Onslow Bay are highly migratory (Cleary and Hosier, 1979). They conclude that over 70% of the barrier island length south of New River Inlet has inlet channel-dominated shorefaces as a result of inlets migrating along the island during the last several centuries. For example, most of the coastal area of Shell, Figure Eight, and Coke Islands have historically been occupied by inlets (Fig. 11) .The result is a shoreface system that is underlain by channel sands and gravels that formed in response to a series of rapidly migrating Holocene inlets. Steel (1980) drilled and mapped a minimum of eleven relict inlets in the Holocene record beneath Bogue Banks.

Channel-Dominated Valley-Fill Shorefaces

Portions of barrier islands that are within the valleys of major Piedmont drainage systems (Fig. 2) have shorefaces that are characterized by complex sediment sequences deposited in ancient paleofluvial valleys (Pearson, 1979; Hine and Snyder, 1985; Riggs et al., 1992; Snyder et al., 1994). These drainage systems have repeatedly incised themselves into their valleys and associated valley fill during each Pleistocene glacial episode when sea-level occupied lowstand positions. During the subsequent transgression, these large channel complexes were systematically backfilled with a new vertical succession of fluvial and estuarine sediments. The upper estuarine sediments generally are composed of fine-grained, muddy sediments. As the shoreface recedes in response to ongoing transgression, the portion that is underlain by estuarine valley fill, erodes rapidly relative to the adjacent headland dominated shorefaces (Fig. 2).

CONCLUSIONS

Along continental margins with limited sand supplies, such as the U.S. Atlantic coast, the shoreface is not an infinitely thick pile of sand. Rather, it is a thin, variable, and temporal accumulation of sand superimposed or perched upon a pre-existing and highly dissected geologic framework. Holocene sea-level rise has produced a modern transgressive barrier island, estuarine, and fluvial sequence of coastal sediments that are being deposited unconformably over irregularly preserved remnants of pre-existing stratigraphic sequences consisting of many sediment and rock units of variable ages, origins, and compositions. It is the complex variability in this underlying geologic framework, in consort with the physical dynamics of each specific coastal system, that ultimately determines the 1) three-dimensional shoreface morphology, 2) composition and texture of beach sediments, and 3) shoreline recession rates.

Based upon the pre-Modern geologic framework, there are six general categories of shoreface systems that occur along the Onslow Bay coast of North Carolina. Headlands are morphological features that rise above the active ravinement surface and are composed of semi-indurated to indurated, Pleistocene or older sediment units. 1. *Subaerial headlands* are characterized by the active incisement of a wavecut platform and cliff into Pleistocene or older stratigraphic units with an associated perched beach. 2. *Submarine headlands* are submerged morphological features composed of Pleistocene or older stratigraphic units that have been incorporated into the modern shoreface and upon which the barrier-estuarine system is perched. Ancient sediments crop out on the eroding shoreface and commonly occur on the inner shelf as bathymetric highs seaward of the modern shoreface and thus, modify incoming waves and currents.

Nonheadland shorefaces are dominated by Holocene processes and sediments and can be divided into four general subclasses. 3. *Transgressive shorefaces* are composed of compact peat and mud that extend from the modern estuaries, under the barrier sands, and crop out within the surf zone and upper shoreface. The steep shoreface is often characterized by an irregular geometry and the beach is dominated by discontinuous and highly scarped dune ridges with abundant washover fans. 4. *Regressive shorefaces* are composed of unconsolidated sand and occur along barrier segments that have adequate sediment supplies and are often associated with inlets, headlands, and cape structures. The beaches are dominated by progradational geometries with accretionary beach ridges. Channel-dominated shorefaces consist of two distinctive types of systems. 5. *Inlet-fi!l shorefaces* are composed of unconsolidated sand and gravel sediments with clinoform infill geometry that forms in response to actively migrating inlets. 6. *Va!ley-fi!l shorefaces* have historically been occupied by large paleofluvial drainage systems and are underlain by thick accumulations of fluvial- estuarine channel-fill sediments in response to deglaciation and Holocene sea-Ievel rise. Valley-fill sediments are typically composed of fine-grained sediment and therefore will erode differently than inlet- fill sands and gravels. The sediments derived from valley-fill erosion are often not compatible with the dynamics of the adjacent beach systems. Consequently, valley-fill shorefaces are often characterized by lower slopes and sediment deficient beaches that are actively eroding.

Thus, the basic structural, stratigraphic, and geomorphic characteristics of the pre-barrier land surface interacts in a complex way with modern coastal processes to determine the barrier beachmorphology and shoreface dynamics. Each barrier beach and shoreface are total products of their geologic heritage; the signature of their geologic history controls and influences the present morphology, shoreface dynamics, and rates of shoreline recession. Consequently, the concept of a common equilibrium profile for all shorefaces is neither realistic nor adequate when considering detailed processes along any given coastal segment. It is imperative that society learn to live with and manage our complex shorelines. In order to do this, we must understand the detailed geologic framework underlying the shoreface and the inner shelf, as well as the physical dynamics operating within and upon regional segments of the shoreface system. Then we can realistically begin to model the large-scale behavior of coastal systems.

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INLET INDUCED SHORELINE CHANGES: CAPE LOOKOUT — CAPE FEAR

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INTRODUCTION

During the last several years there has been a renewed interest in tidal inlet research, principally from the management viewpoint. Tidal inlet systems are links between adjacent barriers and act as corridors for exchanging water, nutrients, pollutants and sediment between estuaries and the open ocean. During the yearly to decadal time scales, inlets playa major role in the coastal sediment budget by retaining large volumes of sand impounded from the littoral system. The extent to which these systems interrupt the along shore transport and store sand depends largely upon the local wave climate and the tidal prism.

In the inlet settings in southeastern North Carolina, the flood tidal deltas also represent extensive sinks and choke points in the open . water and marsh infilled lagoons. Maintenance dredging of the Intra-Coastal Waterway at designated access channels, is primarily due to the landward transport and deposition of reworked sediment from flood deltas in the narrow lagoons.

The great majority of the critical erosion zones that have been identified in Onslow Bay are associated with the 13 contemporary inlets (Fig. 1) or those historic inlets which were closed artificially. From a geological standpoint inlets are far more important than their current physical dimensions indicate. Less than one percent of North Carolina's shoreline is occupied by inlets. Despite this low percentage, inlets during the past two centuries have influenced 65 % of the barrier shorelines that comprise the Onslow Bay compartment and 100 % of some shoreline reaches. These percentages are higher than those for other southeastern states.

Inlet systems dictate the erosion and accretion patterns over long shoreline stretches, many times the current dimensions of the typical inlet. The zone of influence is a function of throat size, ebb shoal geometry and migration habit when dealing with locationally unstable inlets. In many cases development has encroached into these environmentally hazardous zones with disastrous results. From 1989-1995, 82% of the flood insurance claims for erosion threatened buildings (Upton/Jones) were along inlet influenced shorelines. These claims involved over nine million dollars in losses, almost 70 % of all erosion loss claims in North Carolina. During a previous three year period, 1978-1981, 60 of 70 structures that were severely impacted by erosion were sited along shorelines directly influenced by inlets (Rogers per. com. 1995). Currently many other structures are threatened.

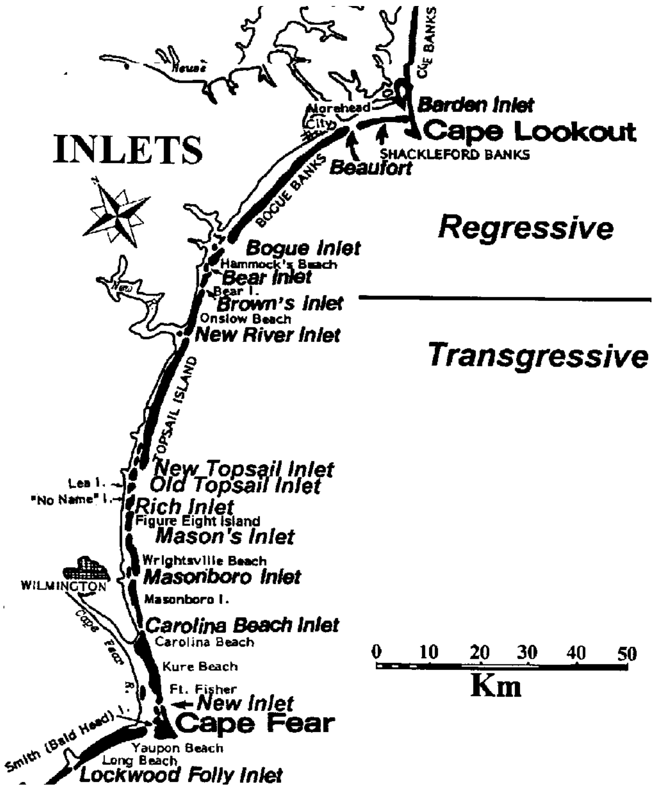

Figure 1. Inlet locations. The 13 inlets long the Onslow Bay shoreline are a diverse group of stable and migrating systems. Eight inlets border developed shorelines, six of these have been modified to some extent. Stable inlets are common along the regressive barriers while locationally unstable systems are typical of the transgressive barrier segment.

Many North Carolina inlets have been modified by dredging for navigation purposes (Fig.1). These activities will likely continue as the coastal region continues to experience rapid development and burgeoning economies. Beach nourishment is approaching the status of the only viable means of "preserving" developed beaches. Tidal deltas with nourishment quality sands will serve as future borrow sites for the rapidly eroding touristic beaches. Because of environmental restrictions regulating the activities within the narrow marsh filled lagoons in southeastern North Carolina, the ebb deltas are likely target areas. Large scale modification of several ebb deltas (Beaufort, Cape Fear River and Masonboro

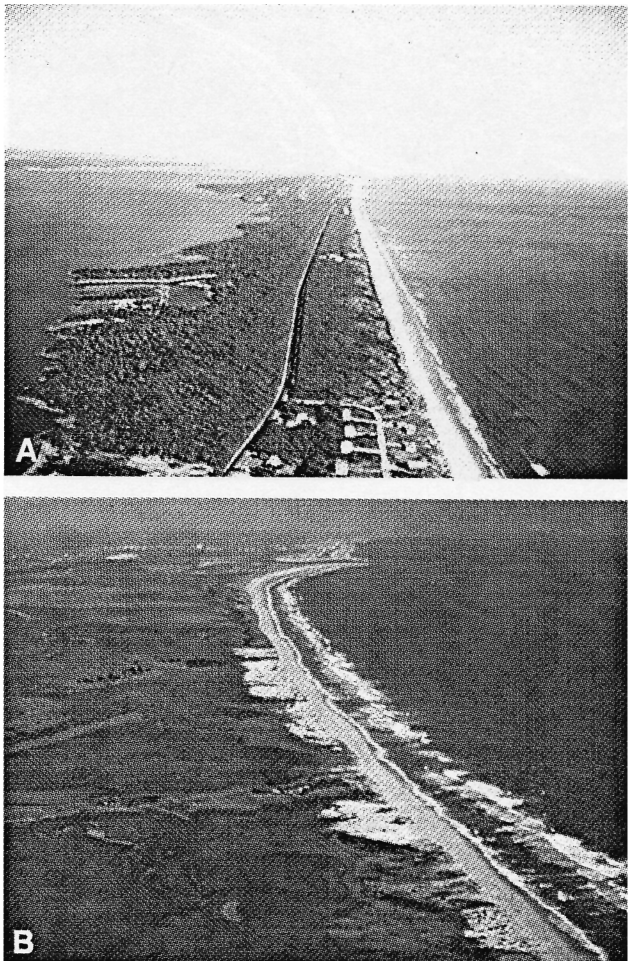

Figure 2. A. Bogue Banks. Forested beach ridges characterize Bogue Banks. Regressive barriers contain 15-25 times more sand per unit of length of coast than do transgressive barriers. B. Masonboro Island. Very low and narrow transgressive barriers are prone to overtopping during storm events. Inlet fill is common beneath the barrier and shoreface.

Inlets) has resulted in dramatic changes along adjacent shorelines and significant morphological changes in the inlet and its associated shoals (Cleary and Hosier 1987, 1989, 1995; Cleary 1994).

It is increasingly evident that the dynamics of inlets are site specific, with each system exhibiting individualized reponses to local environmental and geological factors. It is the intent of this paper to provide a brief overview of the coastwise variability of inlet types, morphological changes within the inlet system and the role the inlets play in the patterns of erosion and accretion on the adjacent shorelines. The overview is based on current investigations and published data from studies of the majority of inlets in southeastern North Carolina.

INLETS, EBB DELTAS AND SHORELINE MORPHOLOGY

Tidal inlets in southeastern North Carolina are mixed energy (transitional) wave-influenced systems. At mixed energy inlets (wave-dominated), a large portion of the various sand bodies are concentrated within the inlet throat. Along southeastern North Carolina, natural inlets display well developed ebb deltas. Mixed energy or transitional inlets are perhaps the most difficult to study due to the variety of factors involved in determining the morphology of the inlet and associated sand bodies.

Ebb-tidal deltas, the seaward shoals of an inlet are formed through the interaction of waves and tidal currents. The general morphology of these features has been described in detail beginning with the studies of Oertel (1972) and Hayes, et al (1973). A number of studies have refined the initial models and described physical processes that shape these features (FitzGerald, 1976; Humphries, 1977; FitzGerald 1984.) The overall morphology and the extent to which ebb deltas are developed is a function of the inlet's tidal prism and the exposure to wave energy (Walton and Adams, 1976; Nummedal et al, 1977; FitzGerald, 1993; Hayes, 1994).

Ebb tidal deltas along the Onslow Bay shoreline are reservoirs of good quality beach fill sand. The volume of sand contained in these systems ranges from less than 750,000 cubic meters to more than 80,000 million cubic meters. Slight changes in the size or shape of ebb deltas can have a significant effect on adjacent shorelines (FitzGerald, et al, 1978; FitzGerald and Hayes, 1980; Cleary and Hosier, 1987 and 1989; Cleary 1994). Regardless of size, the offshore shoals influence the ends of the barriers, acting as natural breakwaters and modifying the wave energy impinging upon the shoreline. Waves approaching the islands are refracted in such a manner that a region of sediment transport reversal occurs downdrift of the inlet (Hayes, et al, 1973; Hayes, 1980 and 1994).

This mechanism of transport reversal had been proposed to account for the bulbous shoreline segment immediately downdrift of mesotidal inlets (Hayes et al, 1973). Cyclical episodes of complex bar- welding events account for a portion of the observed progradation (FitzGerald, 1984). When an inlet changes location or the symmetry (skewness) of the ebb delta changes there is a concomitant change in the pattern of erosion/accretion on the adjacent shorelines (FitzGerald, .et al 1978; FitzGerald, 1984; Cleary and Hosier 1987 and 1989; Cleary 1994).

PREVIOUS STUDIES OF NORTH CAROLINA INLETS

A number of North Carolina inlet studies exist. These investigations range in scope from the distribution and geologic significance of inlets (Cleary and Hosier, 1979, 1986a} to the US Army Corps of Engineers reports dealing with the

Figure 3. Brown's Inlet. Brown's Inlet, a stable system, is located between Onslow Beach and Brown's Island. View toward the northeast and Cape Lookout.

effects of dredging and navigation improvements such as those for Masonboro Inlet (Vallianos, 1975; US Army Corps of Engineers, 1982} and New River Inlet (US Army Corps of Engineers, 1990}. Photographic reviews-currently out of date-depict, using sequential photographs or overlay maps, changes in inlet shorelines during a 35- 40 year period (Langfelder, et al, 1974; Baker, 1977}. An unpublished study by Priddy and Carraway (1978} utilized a statistical analysis approach to evaluate the recent migratory history of North Carolina inlets in an attempt to define an "inlet hazard zone".

ONSLOW BAY SHORELINE OVERVIEW

A series of barrier islands, spits and cuspate forelands form the 185 km stretch of open ocean coast between Cape Lookout and Cape Fear North Carolina (Fig.1 }. The Onslow Bay coastal compartment is comprised of the low energy flank of the Cape Lookout Foreland and the northeastern high energy flank of the Cape Fear Foreland. This low mesotidal shoreline segment is comprised of thirteen morphologically diverse barriers that can be grouped into two distinct classes. The division occurs between Browns Island and Onslow Beach where a submarine headland composed of Tertiary limestone and sandstone forms a prominent protuberance along the coast. Onslow Beach perched atop the headland separates the wide, high beach ridge and modified-beach ridge barriers to the northeast from the transgressive barriers with low narrow profiles to the southwest (Figs. 1 & 2 A & 2 B).

Overwash and historic inlet breaches are more common along the southern segment. The lagoons that back the regressive barriers, principally Bogue Banks, are shallow, open and generally free of tidal marsh. By contrast, marshes have infilled the great majority of the southern lagoons. The lack of tidal marsh behind Bogue Banks is directly attributable to the lack of significant inlet activity along the barrier during its progradational phase during the past several thousand years.

Inlets along the regressive segment are generally locationally stable systems. This group includes those inlets whose throat section has remained in approximately the same location (100 -200 m) for the past 75 years (Fig. 3). The minimum inlet width of this type varies from time to time and is related to throat expansion during storms and subsequent constriction during storm free periods. Browns, Bear, Bogue and Beaufort Inlets (Fig. 1) are stable systems whose locations are controlled by ancestral drainage patterns. Barden's Inlet, a small migrating inlet separating Shackleford Banks from Core Banks (Fig.1) is of relatively recent derivation having formed during a storm breach in the 1920's.

Figure 4. New Topsail Inlet. New Topsail Inlet located at the southern end of Topsail Beach is an unstable system that has migrated over nine km since the early eighteenth century. Small linear vegetated marsh islands paralleling the main channel record the inlet's former positions.

A second inlet type, typical of the transgressive barrier segment are locationally unstable systems that migrate at rates that range from 10- 100 m/y. Typically these systems form during major storm events, generally seaward of small incised coastal plain estuaries and migrate in a down drift direction (southwest). Several of the current inlets, such as New Topsail (Fig. 4), have been in existence for several centuries. Many others that formed subsequent to New Topsail in the eighteenth and nineteenth centuries are now closed. The position of the former inlet is now marked by extensive tidal marsh that has colonized the relict flood deltas.

Several inlets in the transgressive segment, including Old Topsail and Mason's, are in various stages of closure. New River, New Topsail, Old Topsail, Mason's, Masonboro (now stabilized) and New Inlet are migrating systems (Fig. 5A-D). Rich Inlet (Fig. 5 E) is the only naturally stable system in the southern barrier shoreline reach. Carolina Beach

Figure 5. Inlets along the transgressive barriers.
A. New River Inlet. A slowly migrating system located between Onslow Beach and Topsail Island.
B. Old Topsail Inlet. A migrating system near closure.
C. Mason's Inlet. A small migrating system located between Shell Island and Figure Eight is approaching the closure phase.
D. Masonboro Inlet. A dual jettied inlet located between Wrightsville Beach and Masonboro Island.
E. Rich Inlet. Located at the north end of Figure Eight Island, Rich's inlet is the only natural stable system along the transgressive barrier shoreline segment.
F. Carolina Beach Inlet. Located at the northern end of Carolina Beach, the artificially stable inlet was opened in 1952. Periodic dredging allows the inlet to remain open.

Inlet (Fig. 5 F) was artificially opened in 1952 and its stability is artificially maintained through dredging.

METHODOLOGY

Documentation of shoreline positions and former inlet locations were based in part upon data derived from historic maps and charts that date from 1857. A number of additional charts are also available from the early 1700'5. Historical aerial photographs dating from 1938-1995 were used to determine changes in shoreline positions adjacent to an inlet and morphologic changes in the inlet throat and its associated ebb delta. The number of sequential aerial photographs available for each inlet varied from 20-75 sets. The photographs were analyzed for temporal and spatial changes in inlet and ebb delta morphology. Photographs taken at monthly or quarterly intervals were available from the U.S.A.C.E. Wilmington District Office, for portions of the last 20 years for some inlets. Photographs were digitized and baselines were established and relative to these a number of parameters were measured.

Bathymetric charts were used to the greatest extent possible to determine the characteristics of each inlet system. Limited bathymetric charts and partial surveys of the throat and seaward extension of the channels were consulted to provide another dimension. Valuable hydraulic data were determined from the bathymetric charts and used to compare the evolution of the system during pre- and post dredging periods. The variables measured included cross-sectional area (Ac), inlet minimum width (W), Depth (D) and ebb delta volume among others. Tidal prism and ebb delta volume data were calculated in some instances utilizing the methodology of Jarrett (1976) and Walton and Adams (1976).

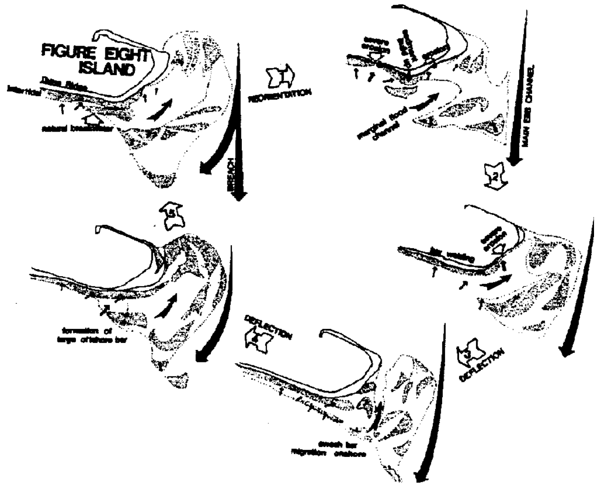

Figure 6. Erosion along stable inlet shorelines. Cycles of ebb channel deflection, and consequent repositioning of marginal flood channels prompts erosion on downdrift shoulder. Repositioning through deflection or reorientation of ebb channel during storms promotes accretion. Cycle is of variable duration.

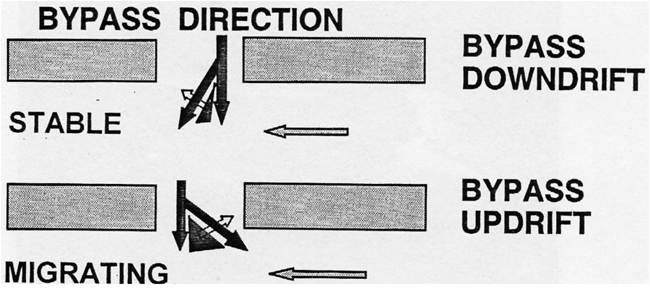

Figure 7. Relationship of inlet stability, local drift direction and the direction of movement of bypassed bar packets following ebb delta breaching events. Size of packet bypassed is a function of shoal size and cycle duration.

INLET MORPHODYNAMICS

Current and recently published studies of the inlets along the Onslow Bay shoreline have shown that the systems that comprise the two major categories of inlets are quite diverse. Analyses of the published and unpublished data sets indicate the following generalizations apply to inlets in the two major barrier reaches that comprise the Onslow Bay shoreline.

1 .Erosion and accretion cycles along stable inlet shorelines were related to cyclical changes in the symmetry of ebb deltas (Fig. 6). The cycles were associated with repositioning and reorientation of the main ebb channel and the corresponding flood channels and where swash bars attached to the adjacent barriers. Cycles ranged in duration from five to 25 years and cycle length correlated with inlet size and storm history. Cycles were shortened by storms: cycles were typically longer in larger inlets.

Figure 8. Rich Inlet. Oblique aerial photograph of Rich Inlet (March 1995). Southward deflection of the ebb channel toward bottom of photo initiates a cycle of erosion on Figure Eight Island. Deflection prompts repositioning of flood channel (F) and subsequent erosion. Reorientation of ebb channel to the north (toward top of photo) initiates accretion on Figure Eight shoulder as bars migrate through flood channel (open arrow) and attach to barrier. Photograph illustrates channel in an early phase of renewed deflection.

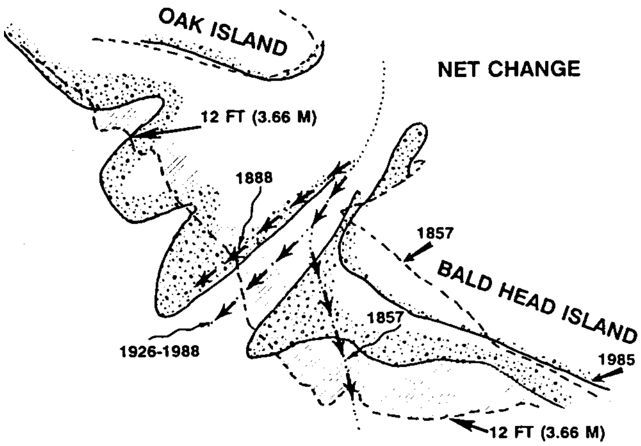

Figure 9. Shoreline and ebb delta changes at Bald Head Island, 1857-1985. A mid 19th century deflection of the entrance channel (arrow) promoted large scale erosion of the Bald Head Island shoreline. A shore normal repositioning of the ebb channel in the 1880's triggered the bypassing of 8-10 million cubic m of sand to the Bald Head Island shoreline. A fixed channel position and the segmentation of the ebb delta has drastically reduced the downdrift supply and prohibited bar bypassing.

The process of channel extension and abandonment provides a mechanism at some inlets whereby sand packets of varying size (range 5×10^3 to 4.0×10^6) are generally bypassed downdrift and ultimately to the adjacent barrier shoreline (Fig. 7).

The northern portion of Figure Eight Island adjacent to Rich's Inlet. a stable system that forms the northern boundary of the island. accreted more than 200 m from 1985-1993 following a reorientation of the ebb channel and flood channel repositioning (Fig. 8). In adjacent Long Bay, Bald Head Island. the barrier adjacent to the Cape Fear River Inlet accreted southwestward more than 800 m from 1885 to 1915 following a breaching event (Fig .9). This large scale accretion episode pre-dated the major modifications of the harbor entrance channel.

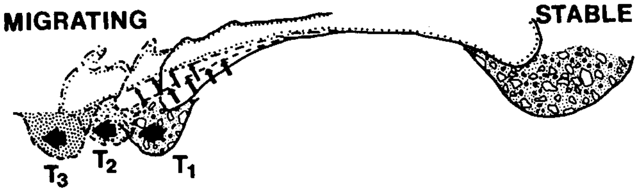

Figure 10. Trailing barrier realignment. Updrift erosion is a consequence of inlet migration and the associated planform adjustment.

2. Locationally unstable inlets are generally restricted to the transgressive barrier segment. These systems migrated to the southwest at average annual rates varying from 5.0 to 150 m /yr. In addition to the erosion of the downdrift barrier, migra-

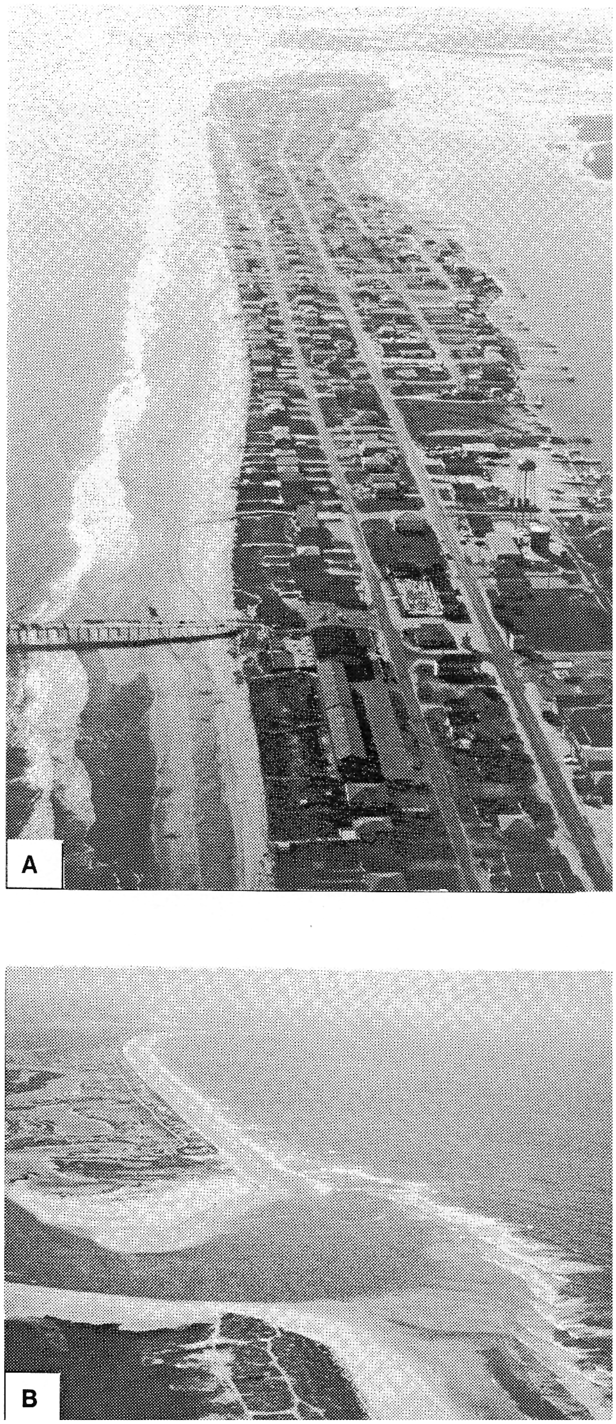

Figure 11. Aerial Photographs of Topsail and Figure Eight Islands.

A. Topsail Beach. Topsail Beach updrift of New Topsail Inlet receded as much as 160m in some areas (1970-1985) due to realignment of the trailing shoreline. South view.

B. Figure Eight Island. Chronic erosion of the southern 4 km of the barrier stems from the platform adjustment of the updrift shoreline as migration occurs. North view.

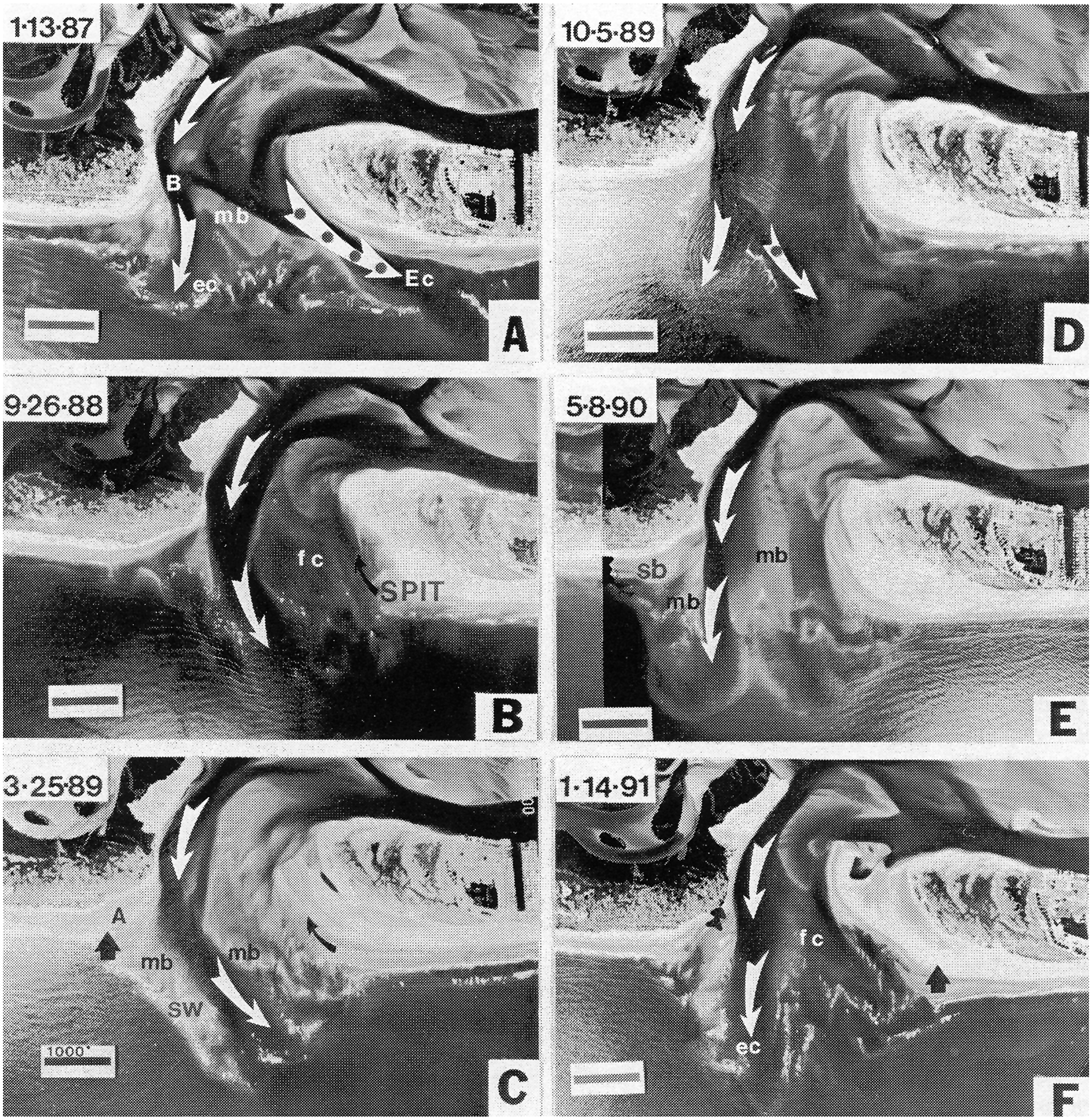

Figure 12. New Topsail Inlet. Ebb delta breaching and bar updrift bypassing at New Topsail Inlet. Portions of several cycles are illustrated. Note ebb delta symmetry changes and ebb channel (ec) orientations. Also note repositioning and expansion of the flood channels (fc).

tion resulted in truncation and realignment of the trailing shoreline (Fig. 10).

Rates of updrift shoreline recession ranged up to 12 *mi* y for as long as a decade. Erosion rates decreased as the updrift barrier planform adjusted to the position of the inlet. The chronic erosion zones along the southern portions of Topsail Beach and Figure Eight Island are located updrift of New Topsail Inlet and Mason's Inlet respectively (Figs. 11 A & B). Erosion stems from the migration of the adjacent inlets. The success of beach restoration projects along these shoreline segments is severely limited due the planform changes dictated by the locationally unstable inlets.

Concurrent with the processes of migration, packets of sand were bypassed to the updrift shoulder of the inlets when ebb deltas were breached. The cycle of ebb delta breaching varied in length from 2-20 years (Fig. 12 A-F). Reorientation of the updrift channel and simultaneous changes in the symmetry of the ebb deltas caused migration and attachment of

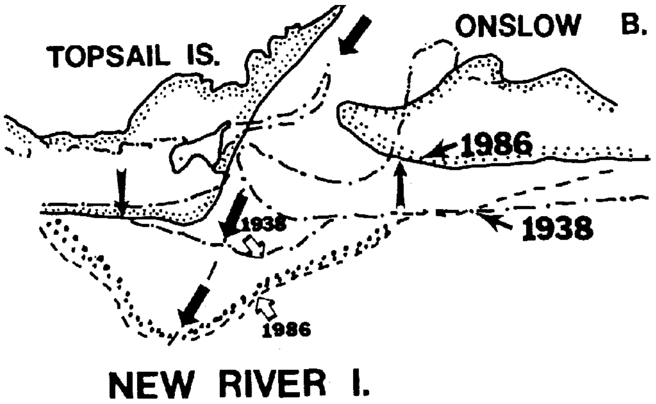

Figure 13. New River Inlet. Line drawing depicting the 1938 and 1986 shoreline positions adjacent to the inlet. Onslow Beach (right) has recessed at rates as high as 8 m/y since the mid 1960's when major dredging efforts began. Although conjectural, it appears dredging has promoted an increase in the tidal prism (40%) and the retention capacity of the ebb delta. Note the accretion on the downdrift shoulder. Channel position and orientation controls accretion trends.

small bar complexes (100x50m) within 1 km updrift of the inlet's ebb channel. Frequently these temporary shoreline convolutions promoted rapid erosion leeward of the location where the sand packets attached. The attachment of sand packets frequently prompts periods of relatively rapid inlet migration as bars move laterally along the barrier's spit complex and into the adjacent bar built estuary.

3. Modifications of inlets by dredging resulted in an increase in the tidal prism, a corresponding larger retention capacity of the ebb delta (Fig. 13) and the disruption of the natural ebb delta breaching cycle. Dredging changes are reflected in an extension and deepening of the ebb channel across the ebb platform. Bypassing to the downdrift shoal segment and the adjacent shoreline ceases when the deepened ebb channel bifurcates the the ebb platform forming distinct shoal segments. Bypassing generally decreases as channel maintenance increases. Shoreline erosion occurs when sand supply is reduced by major inlet dredging. Typically the maximum rate of shoreline erosion and ebb delta morphological change may lag behind the breaching of the shoals by several decades, especially at larger inlets such as Beaufort Inlet (Fig. 14) or at Cape Fear River Inlet (Fig. 9) in adjacent Long Bay.

Inlet stabilization by jetties mimicked the impacts of dredging. The modification of inlets by hard structures has reduced sand bypassing and increased erosion on one or both sides of the inlet. Significant long term coastwise erosion associated with inlet modification is exemplified by Masonboro Island a 13 km long transgressive barrier. The barrier is located between a dual jettied system at Masonboro Inlet and a continually dredged artificial system at Carolina Beach Inlet (Figs. 1 & 5F). Masonboro Island has experienced a major reduction in sand supply, and wash over topography has increased along 80 % of the island's length.

INLETS AND MANAGEMENT PERSPECTIVES

The decade to century scale coastwise sand budget and ultimately the shoreline retreat rate are negatively affected by the increased retention capacity of modified inlets. Because of the large number of inlets and the storm frequency in southeastern North Carolina, sand loss to the adjacent shoreface is likely to be much greater than in regions where natural systems occur.

The designation of inlets as areas of environmental concern necessitates special consideration when dealing with these systems. The dynamic nature of inlets coupled with our inability to predict the magnitude and direction of change, makes management decisions very difficult. Effective management requires an understanding of the processes both natural and man-induced that produce changes. Each inlet is unique and site specific management strategies must be developed for planning purposes.

North Carolina has been a pioneer in developing oceanfront management tools. Although the state's inlet hazard standards are in need of review, it is one of a very few states that attempts to manage shorelines near unstabilized inlets. It is likely that North Carolina will achieve this goal due to the increased awareness of the hazards associated with inlets.

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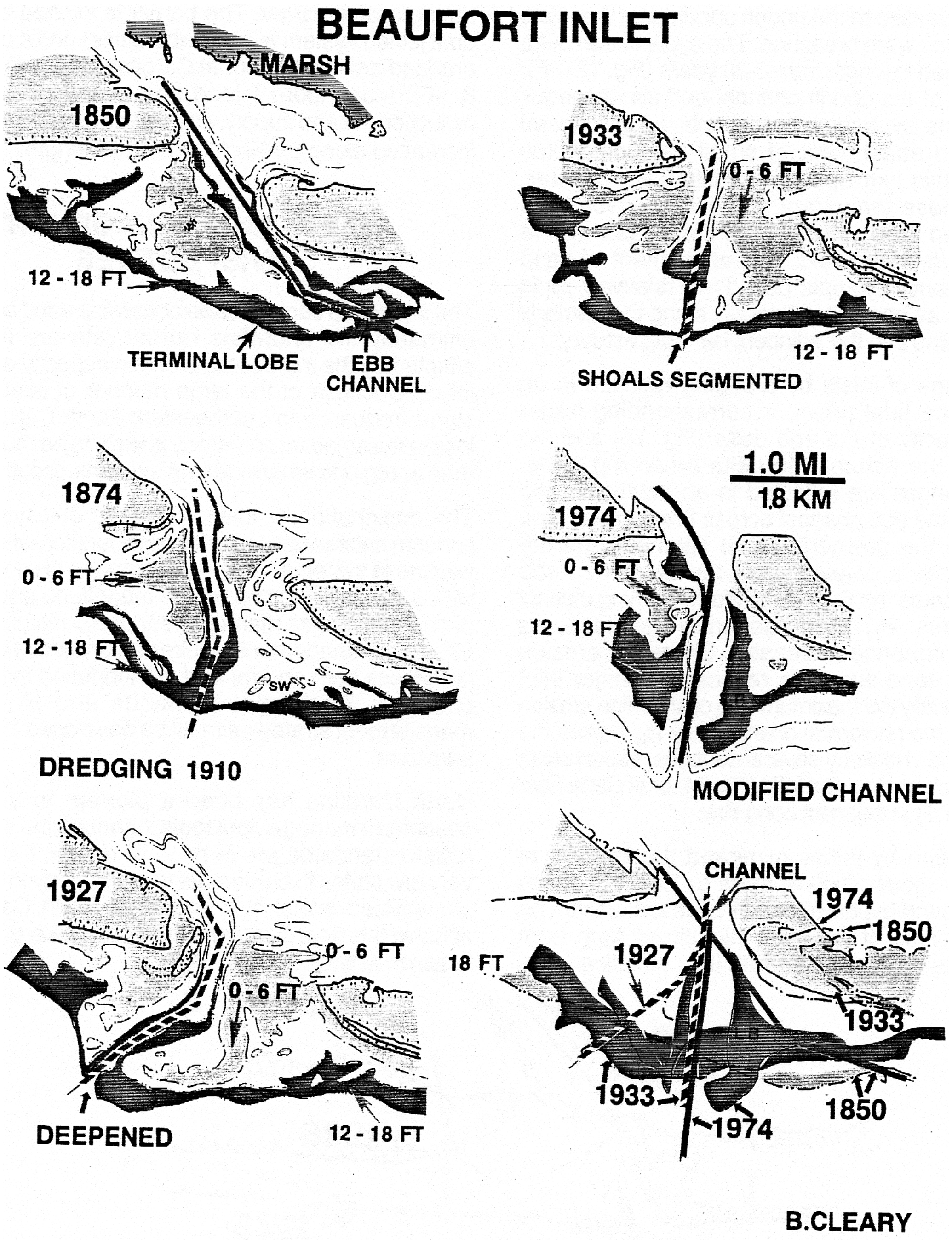

Figure 14. Beaufort Inlet and ebb delta changes. Shoreline and ebb delta morphological changes are directly related to the direction and repositioning of the ebb channel. Dredging of the ship channel since the 1930's has resulted in a deepening and seaward growth of the ebb delta platform. The seaward extension of the shoals has steepened the nearshore profile promoting erosion in some areas. Approximately 20 million cubic meters of sediment has been lost from the ebb delta since 1936 due to a combination of factors. These include annual dredging, storm losses to the shoreface and the shoreward transport sand packages responsible for the westward growth of the Shackelford Bank's spit (Modified after USACE 1976).

This represents UNCW's Center for Marine Science Research contribution #149.

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SEDIMENTOLOGY AND DEPOSITIONAL PROCESSES IN THE TIDAL MARSHES OF SOUTHEASTERN NORTH CAROLINA

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ABSTRACT

Broadly speaking, two different types of coastal marsh exist in southeastern North Carolina; back barrier marshes and tidal creek marshes. These marsh systems differ one from another in terms of surficial sediment characteristics and in terms of the physical processes that control sediment deposition. Back barrier marshes consist of predominantly sand sized, inorganic, quartzose sediment deposited under the influence of episodic, high energy processes such as wave induced washover. In contrast, tidal creek marsh sediments are fine grained, organic deposits which accumulate under steadier, low energy conditions. The sedimentology of both systems has been impacted by human's alteration of the natural environment.

INTRODUCTION

The southeastern North Carolina coastline is markedly different from other segments of the coast. Unlike the "Outer Banks" region to the north, which possesses barrier islands separated from the mainland by wide back barrier lagoons, the coastline from Cape Lookout to Cape Fear is characterized by densely vegetated, narrow lagoons (average width of 1.5 km) which lack major fluvial inputs and which may be dissected by winding tidal channels extending from the short tidal creeks which drain adjacent uplands (Cleary *et al.*, 1979). Within this coastal setting, two different types of coastal salt marsh are present (Figure 1); back barrier marshes (e.g. Masonboro Sound) and marshes associated with incised, mainland, tidal creek systems (e.g. Hewletts and Bradley Creeks).

It is currently believed that most southeastern US marsh systems formed over the last 5-6000 years as shallow marine basins were infilled during a slow rise of sea-level. The ultimate development of individual systems, however, is strongly controlled by the inherent variability of the prevailing physical processes. Back barrier marshes, for example, are strongly impacted by high energy processes due to their proximity to the open ocean. The development of flood tidal deltas during inlet migration and the formation of extensive overwash deposits during periods of increased wave activity (Cleary *et al.,* 1979) are two mechanisms which contribute the large volumes of sedimentary material required by these systems to "keep pace" with local sea level rise. The large sand influxes associated with episodic, high energy events (Hackney and Cleary, 1987) and with inlet migration, however, are usually localized. As a result, the ability of local back barrier marshes to maintain their position with respect to sea level is highly variable.

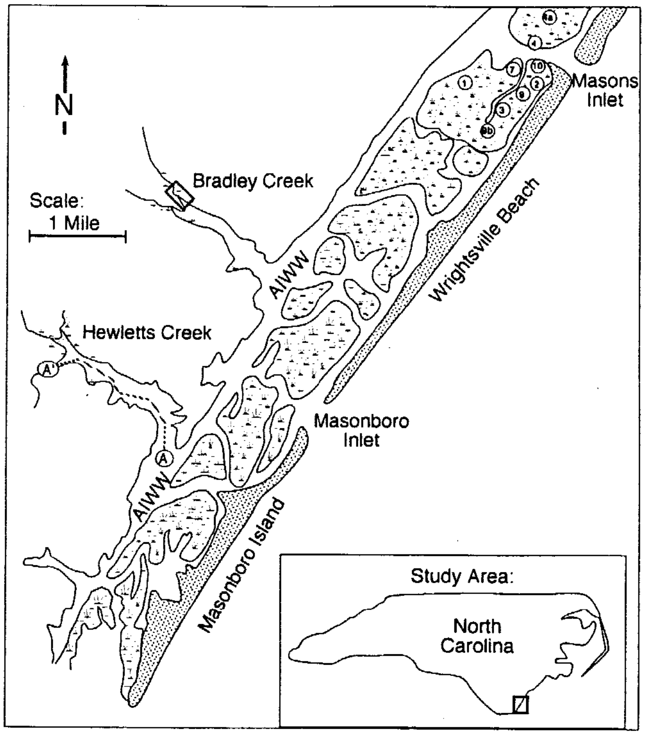

Figure 1. Locations of marsh areas referred to in text. Transect lines, boxes and numerals refer to locations referenced in subsequent figures.

Deposition within protected, mainland tidal creek marshes also results from increased inundation associated with a gradual rise in sea level. According to radiocarbon dates obtained from cores collected in :one local tidal creek (Hewlett's Creek), the leading edge of the Holocene transgression began onlapping the surface of the subaerial Pleistocene and the alluvial valley fill of ancestral Hewlett's Creek by 5300 BP (Figure 2). By about 4200BP, flooding had reached the present upper estuary and conditions became optimal for salt marsh development (Berger, 1993). data suggest that salt marshes have continuously occupied local tidal creek basins since 4000 BP. In contrast to back barrier marsh

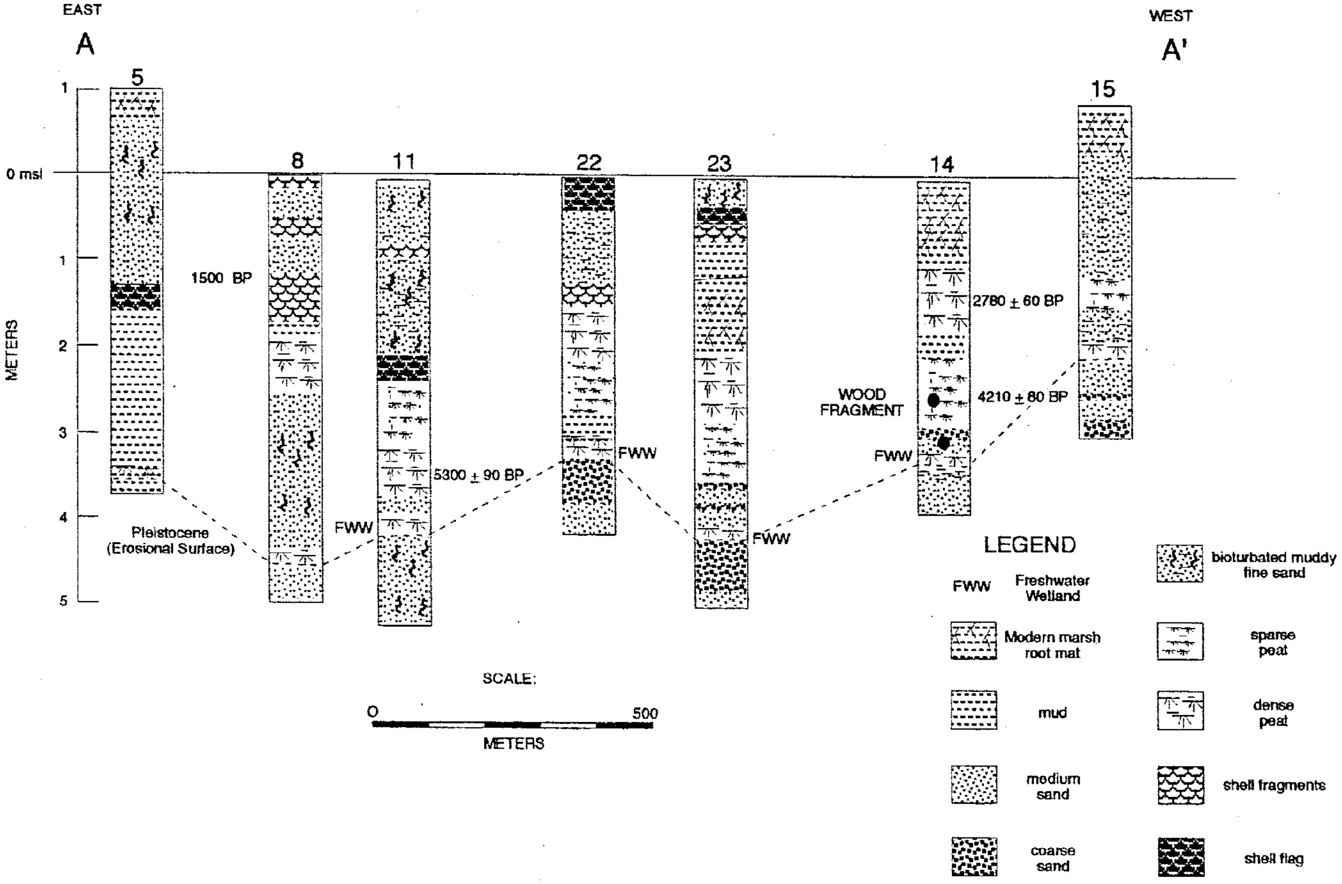

Figure 2. Stratigraphic transect of Hewletts Creek. Transect locations shown in Figure 1. (Modified from Berger, 1993).

systems, deposition in tidal creek marshes has been controlled mostly by low energy, tidal processes since their establishment. The aim of this paper is to describe the sediments and the modern physical processes controlling sedimentation in both back barrier and tidal creek marsh environments.

MODERN SEDIMENTS

Tidal Creeks

The surficial sediments of local tidal creek basins consist predominantly of very fine to fine sands, although medium to coarse sands and gravels may occur in tidal creek channels (Figure 3).

Dry sieve analyses of surface samples collected within one and one-half kilometers of the mouth of Hewlett's Creek (Berger, 1993) indicate that from 77 to 84 weight percent of surficial sediments exhibit diameters in the range of 88 mm to 125 mm (fine to very fine sand). These sediments typify those found on tidal channel floors and on extensive subtidal and intertidal flats. In the landward reaches (>1.5 km from mouth) of the tidal creek basins, where tidal flats give way to vegetated marshes, the relative abundance of sands decreases while silts and clays become more abundant. A characteristic marsh deposit generally contains less than 25 weight percent sand, 30 percent silts and as much as 50 percent clays. In addition, sediments in the landward reaches of tidal creek basins exhibit higher organic contents than their lower basin counterparts. The organic content of surficial marsh sediments average 18-22% (Leonard, 1995), while the organic content observed for tidal flat and tidal channel sediments may be less than one percent (Steenhuis, 1994).

Back Barrier

The characteristics of back barrier marsh sediments differ from the marsh sediments found in tidal creek basins. In general, back barrier marsh sediments are coarser and more closely resemble sediments found near tidal creek mouths. Grain size analyses conducted in marshes behind Topsail (Gamill, 1990) , Masonboro (Steenhuis, 1994), Figure Eight and Shell Islands (Metz and Leonard, 1996) indicate that back barrier marsh sediments generally contain more than 70% sand. Within the sand fraction, the majority of the material usually consists of medium to fine sands (0.5mm-0.25mm). As much as 27%, however, may fall within the coarse (>0.5 mm) sand class. Fine grained sediments (i.e.

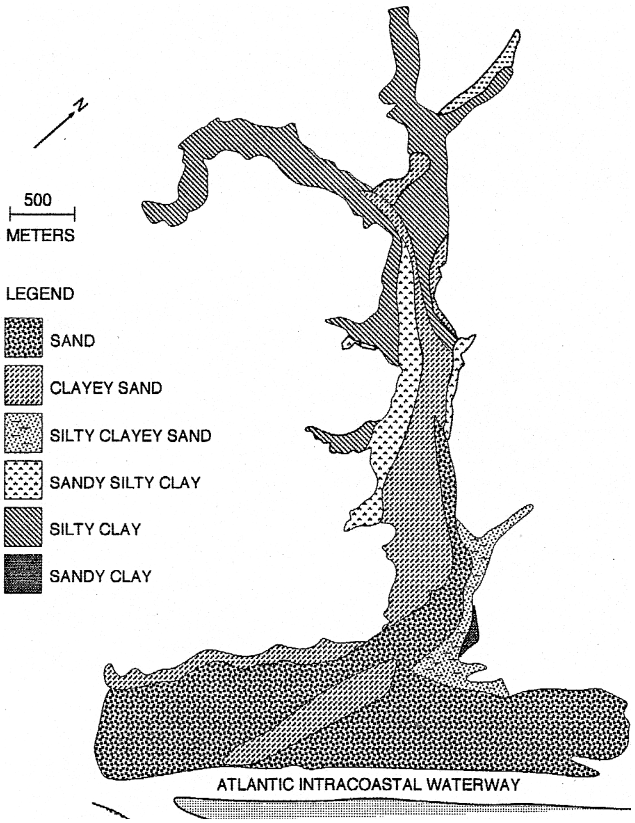

Figure 3. Facies map of surficial sediments in Hewletts Creek basin (modified from Berger, 1993).

silts and clays) comprise less than 20% of atypical deposit although high percentages of clay may be found in isolated salt pond environments (Steenhuis, 1995).

Organic contents, estimated from weight loss on ignition at 400°C, are highly variable and range from 25% to 8% for back barrier marsh sediments. In general, organic content decreases with proximity to major drainage channels and to inlets (Metz and Leonard, 1996) (Figure 4). Sediments collected in different marsh environments behind Masonboro Island (Steenhuis, 1994), contained less than 10% organic carbon by weight in the top 10 cm. The mean organic carbon contents of high and low marsh sediments are 5.1% and 5.3%, respectively. Very low organic carbon contents occur in intertidal flat (1.3%) and channel (0.8%) sediments. The low organic content of back barrier marsh sediments, as opposed to the tidal creek systems, has been attributed to the episodic influx of marine sands as overwash fans during storm activity (Hosier and Cleary, 1977) and to the reworking of coarse sediments derived from local dredge spoil deposits (Steenhuis, 1994).

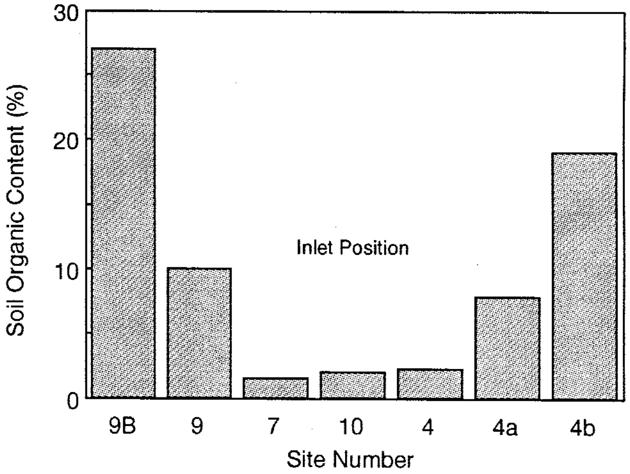

Figure 4. Organic content of marsh sediments along a N-S transect in the vicinity of Mason's Inlet. Site locations are shown in Figure 1.

MODERN PROCESSES

The sedimentologic signature of each marsh area is strongly influenced by the types of physical processes active in each area. While sediment transport and deposition in lower energy tidal creek marshes is dominated by fairly predictable and steady processes such as spring/neap tidal variability and biologic activity, episodic and often catastrophic coastal processes dominate sedimentation in the back barrier marshes of southeastern NC. In these systems, whose formation is closely linked to the deposition of washover fans and flood tidal deltas (Hosier and Cleary, 1977), tidal inlet processes play an important role in maintaining marsh surface elevation.

A number of different techniques (e.g. marker horizons, sediment traps, aerial photograph surveys) have been employed to assess the extent to which modern inlets influence sediment supply in back barrier marshes. The results of these studies (e.g. Hackney and Cleary, 1987; Gammill and Hosier, 1992; Metz and Leonard, 1996) have concluded that inlet processes both constructively and destructively impact back barrier marsh sedimentation. The migration of inlet channels actively erodes adjacent marshes while simultaneously depositing large volumes of sand (Plate 1 A) which effectively bury the vegetated marsh surface. Concurrently, the movement of sands associated with the inlet's flood tidal delta infill existing channels and provide substrate for new marsh development (Plate 1 Band C). In addition, sands imported through the inlet throat provide inorganic material critical to the overall accretionary budget of these systems. Sediment trap data have shown (Figure 5) that maximum deposition occurs in close proximity to the inlet and that deposition rates decrease with distance from the inlet. Anecdotal (Metz pers. comm.) and empirical (Gammill, 1990) evidence suggest that marshes removed from the influence of the tidal inlet are soupy, lack well developed rhizomatous mats, show an increased number of ponds and overall exhibit characteristics indicative of marsh deterioration. These observations are consistent with the findings of Hackney and Cleary

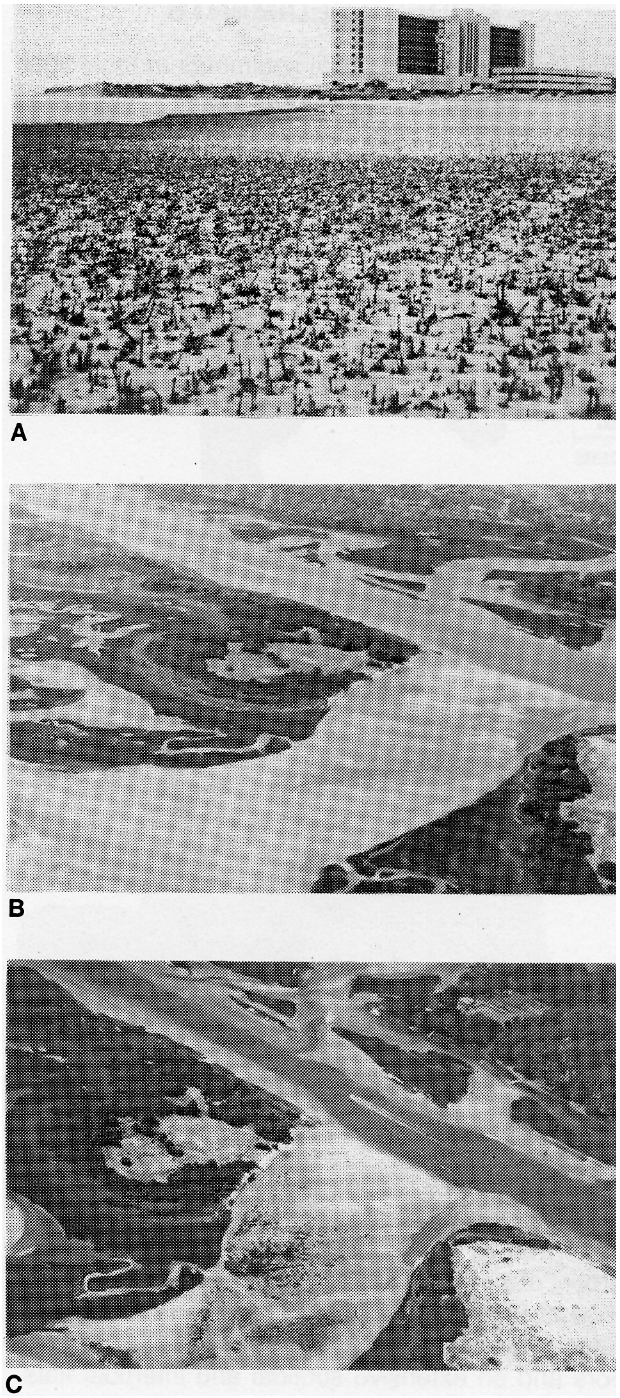

Plate 1
A. Remnants of marsh buried by overwash deposits.
B. Infilling of Mason's Inlet by sands.
C. Establishment of vegetation on newly deposited inlet sands.

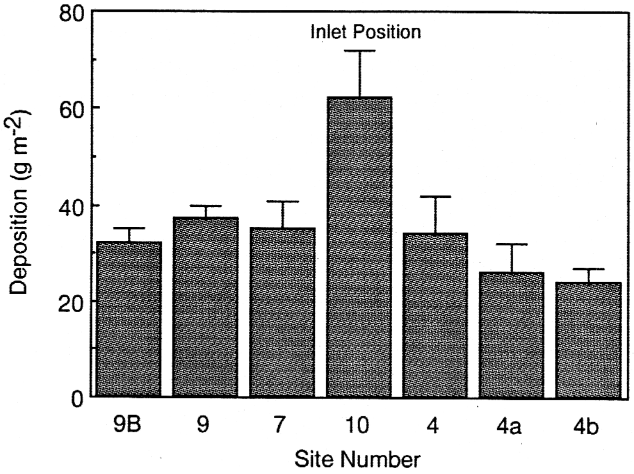

Figure 5. Deposition rates measured by sediment traps along a N-S transect in the vicinity of Mason's Inlet. Site locations are shown in Figure 1.

(1987) who suggested that the lagoonal marshes of southeastern North Carolina would eventually be drowned by rising sea level without the input of marine sands through inlets.

Storm sedimentation is also an essential component of the vertical accretionary budget of back barrier marshes. Cleary et al. (1979) conducted a regional investigation of marsh islands present within local bar- built estuaries and concluded that their formation resulted from storm wave activity and increased wave swash which transported sand from the flood tidal deltas onto the adjacent marsh. Recent data collected in the vicinity of Mason's Inlet concur with these observations. Maximum deposition in the back barrier marsh behind Wrightsville Beach occurred during the offshore passage of Hurricane Gordon in November 1994 (Figure 6). Deposition resulting from the elevated tides and increased wave activity associated with this event were roughly 6 to 10 times deposition rates measured during nonstorm conditions.

Sediment transport in local tidal creek systems is not dominated by the occurrence of episodic, high energy events. Instead, deposition in these protected marshes is controlled by the diurnal inequality of the tides and spring/neap variability. Sediment transport is also strongly influenced by seasonal variability and the occurrence of meteorologic events (e.g. low tide rainstorms, tropical storms and 'nor'easters'). Flux studies conducted within two local tidal creek systems (Hewletts and Bradley Creeks) indicate that maximum sediment transport occurs during spring tides when stronger tidal currents and higher water levels occur. Maximum sediment transport is also favored during summer months when water levels are typically higher and when increased levels of bioturbation contribute to particle disaggregation (i.e. increase mobility).

Sediments in suspension consist primarily of very fine

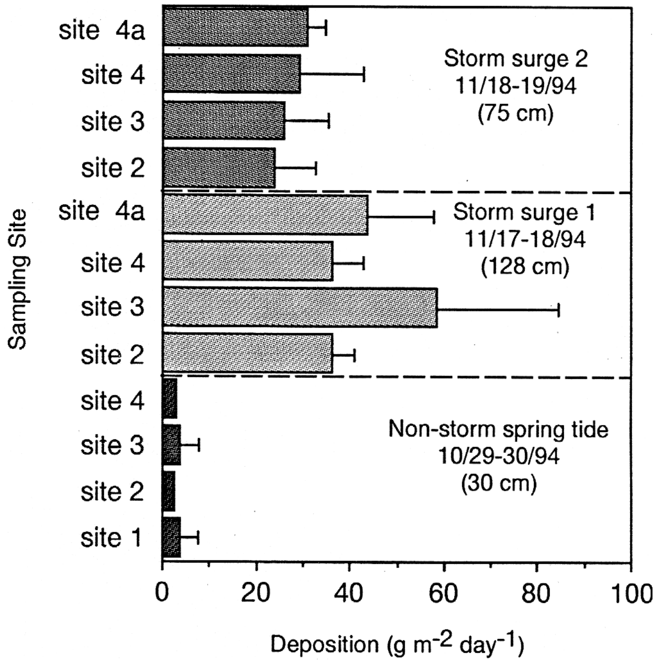

Figure 6. Deposition measured by sediment traps deployed during storm and non-storm conditions in the marshes behind Wrightsville Beach, NC. Site locations are shown in Figure 1.

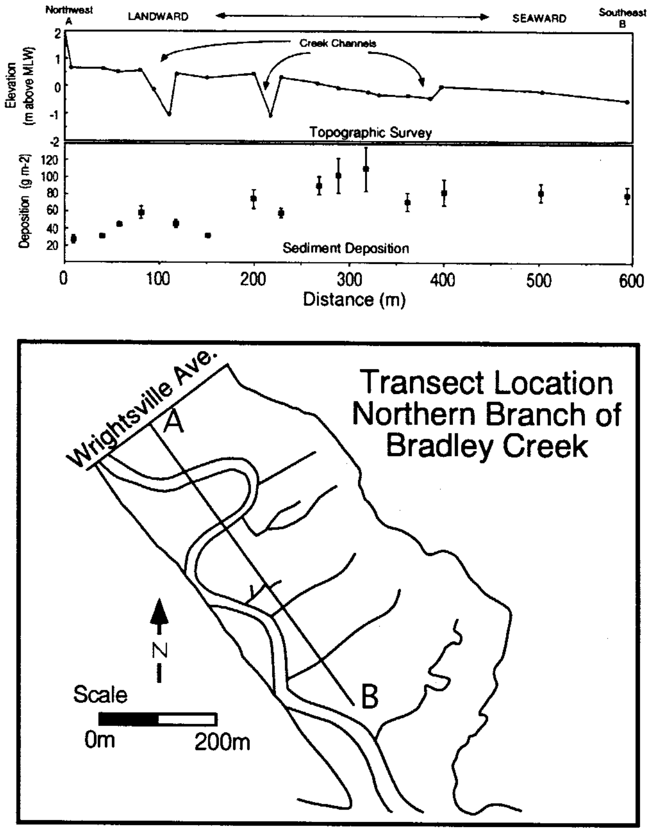

Figure 8. Marsh elevation and sediment deposition measured along a NW-SE trending transect in the Bradley Creek marsh basin. Location of the transect is shown by inset. Location of the inset is shown in Figure 1.

sands, silts, clays and organic aggregates. The coarse gravels observed on channel floors are not usually resuspended by the 40 cm S-1 or lower flow velocities within the creek during 'non-meteorologically' forced conditions. Instead these materials are most likely transported as bedload.

Suspended sediment flux analyses within Bradley Creek (Angelidaki and Leonard, 1996) suggest that fine grained sediments and organic aggregates are imported into the upper reaches of local tidal creek estuaries under normal tidal conditions. This process may be expedited following periods of intense rain when runoff from adjacent uplands may increase total suspended solid concentrations to levels 10X those occurring during fair weather. These flux measurements corroborate Berger's (1993) observation that sediment transport processes are resulting in the deposition of muds in the upper reaches of tidal creek basins and also reflect the observations of long time residents who report that tidal creeks have infilled over the last 50 years.

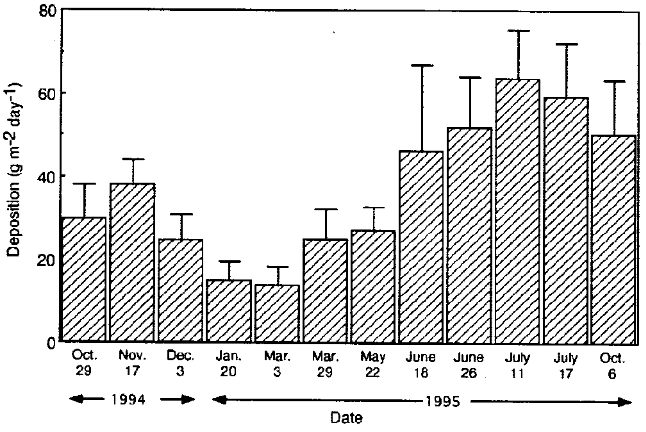

Figure 7. Deposition measured by sediment traps deployed in the Bradley Creek marsh basin. Traps were deployed within the boxed area shown in Figure 1.

Once transported into the estuary, sediments are deposited on the marsh surface during inundation. Sediment trap data indicate that deposition on the marsh surface is highly variable ranging from a minimum of 13.8.:1:. 3.4 g m-2 to 63.7.:1:. 10.3 g m-2 (Leonard, in review). For the most part, sediment deposition mimics the seasonal variability observed in suspended sediment data. Deposition rates measured during summer months exceed deposition measured during winter months (Figure 7).

These results are consistent with the seasonal depositional trends reported for Gulf of Mexico marshes by Leonard et al. (1995) and for Georgia marshes by Letzsch and Frey (1980). Variability observed in the winter data may be attributed to storm activity (Reed 1989, Childers and Day

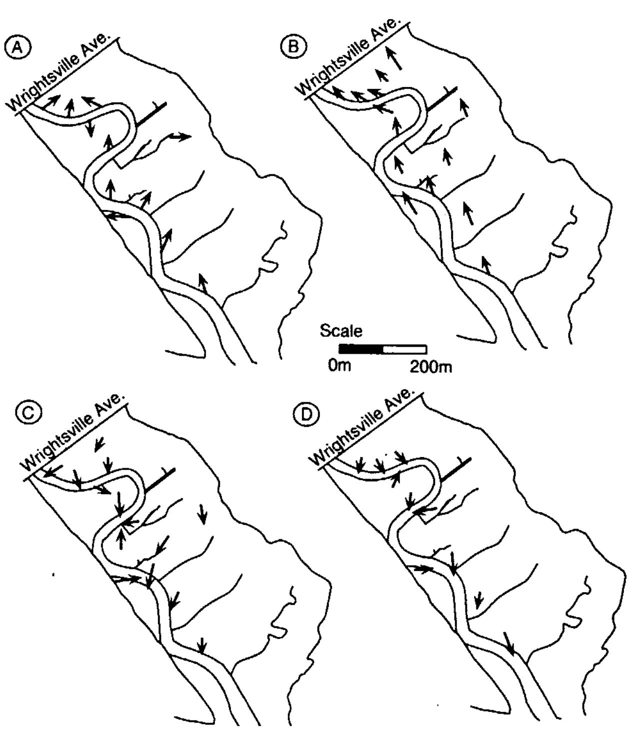

Figure 9. Surficial flow patterns observed during a spring tidal inundation at Bradley Creek. A) Initial flooding of marsh surface, B) sheet flow during mid to late flood, C) initiation of ebb following slack high water, and D) late ebb.

1990) and extreme tides. Data collected in November 1994 coincided with the offshore passage of Hurricane Gordon and the December 1994 data were collected during a perigean spring tide.

Sediment accumulation is also influenced by proximity to potential sediment source and the prevailing hydrodynamic conditions on the marsh surface. Figure 8 shows sediment deposition (as measured by surficial sediment traps) plotted along an E-W trending marsh transect and illustrates three important depositional trends. First, the data indicate that deposition both increases and becomes more variable in the seaward (downdip) direction. Second, the data suggest that deposition on creek margins exceeds deposition in the marsh interior (> 3m from the creek). Lastly, Figure 8 shows that sediment deposition on the landward bank of a creek exceeds deposition on the seaward bank. These depositional patterns can be related to variations in source proximity.

Ultimately, there are two potential pathways by which allocthonous sediments are transported into a tidal creek marsh. The first occurs when water levels exceed bank full conditions and sediments are transported out of the tidal creek and onto the marsh. The second occurs when sheet flows (for this scenario, a sheet of water moving in one direction across the marsh surface) are established. Tidal creek spillage (pathway number one) may be invoked to explain increased deposition on creek margins relative to marsh interior sites, while sheet flow may account for increased deposition in the seaward direction.

In order to explain the observed differences in deposition on landward creek margins relative to seaward creek margins, both surficial flooding patterns and creek hydrology must be addressed. For example, peak flood current velocities in Bradley Creek occur at two separate times; the first coinciding with bank full conditions and the second with sheet flow conditions. During bank full conditions, flow movement is primarily creek normal (Figure 9) such that the potential for sediment transport out of the creek is equally favorable for both sides of the creek. During the second velocity pulse, the one occurring during sheet flow, sediment will be transported onto the marsh surface along landward creek margins only. At seaward creek margins, the dominant direction of transport is off of the marsh surface even though water levels are still rising.

For systems dominated by sinuous creeks, such as the Bradley and Hewletts Creek systems, the implication on sediment deposition is two-fold. First, maximum deposition should occur on landward margins where sediment laden water is first reaching the marsh surface from the energetic creek channel. Second, sediment deposition should be less on seaward margins since the flood water reaching there during sheet flow will have already traversed a vegetated system and presumably lost much of its suspended material in the marsh interior. This hypothesis is corroborated by deposition data shown in Figure 8 which indicate that deposition on the landward margins of tidal creeks exceeds deposition on seaward margins.

Increased deposition during the summer is an observation consistent with the findings of earlier studies (Letzsch and Frey 1980, Leonard et al. 1995) . Such increases, however, are usually attributed to increased bioactivity such as burrowing, algal production and fecal pellet production (Harrison and Bloom 1977, Leonard et al. 1995), increased water levels in the summer (Ward 1981) or seasonal changes in water viscosity (Leonard et al. 1995). Another possible explanation is a physical mechanism; specifically, that the baffling of over marsh flows is enhanced in the summer when the availability of live plant material on the marsh surface is at a maximum (Leonard, in review).

SUMMARY

The tidal marshes existing within local tidal creek systems and behind back barrier marshes can be differentiated one from another in terms of both their sedimentologic signature and the depositional processes. Despite their differences, however, both systems have been impacted by man's activity to the extent that the natural evolution of each area has been altered.

Historically, estuarine marsh systems in southeastern NC have been most significantly impacted by the construction of the Atlantic Intracoastal Waterway (AIWW). Dredging of the waterway in 1932 and the construction of dredge spoil islands have altered the existing sedimentary and hydrodynamic connection between the mouth of tidal creek estuaries and the back-barrier environments. A comparison of maps from 1857 and 1933 (Berger, 1993) has shown that near the mouth of Hewletts Creek, the number of small marsh creeks has decreased and that the marsh area has expanded by approximately 10-15% adjacent to the AIWW.

Aerial photograph analyses (Berger, 1993) , show similar increases in marsh area between 1949 and 1990 and an increase in shoaling within tidal creeks (i.e. formation of intertidal or subtidal sand flats, and oyster flats). These analyses further suggest that the modifications are most severe in the lower portions of the estuaries as opposed to the upper estuaries. Anecdotal and aerial photographic evidence suggest that much of the morphological change within these estuaries has occurred over the past 10 to 20 years.

Data presented in this paper have demonstrated the critical relationship between inlet processes and the ability of a back barrier marsh to maintain its elevation with respect to sea level rise. While many marsh sites are presently accreting at rates (1.5 mm y-1 or more) sufficient to keep pace with local rates of sea level rise, others are not (Gammill and Hosier, 1993). Given the essentially ephemeral nature of these systems, it is clear that they will be highly susceptible to changes in sediment supply.

Hackney and Cleary (1987) report that human activities along the coast, such as the construction of jetties and dredging of inlets, are disrupting the transport of sand into back barrier lagoons. While Hackney and Cleary (1987) report that it is premature to adequately predict whether current dredging frequency is having a significant impact on sand transport to marshes, the available data suggest that the probability of marsh submergence will be hastened by continued sand removal coupled with increases in the rate of sea level rise.

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SHORELINE STABILIZATION IN ONSLOW BAY

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The shoreline along Onslow Bay is retreating landward toward an ever-increasing number of beach front (buildings. Naturally, beach front property owners wish (to preserve their buildings. There are basically 3 ways (in which they may do this: (1) move buildings back, (2) armor the shoreline with seawalls and/or groins, or ((3) nourish the beach.

Of course, there are advantages and disadvantages to each of these approaches. The retreat option is the ~ best way to preserve the recreational beach but could i be costly and certainly is politically difficult. This is because people who own beach front property tend to be politically influential and are unwilling to move or demolish their structures. Armoring the shoreline is the best way to preserve buildings but this approach results in degradation, and even disappearance, of the recreational beach. For this reason, North Carolina prohibits all shoreline armoring with the exception of sandbags. Beach nourishment "improves" the quality of the recreational beach but is very costly and temporary as the long history of beach nourishment at Carolina Beach and Wrightsville Beach demonstrates.

BEACH NOURISHMENT

Beach Nourishment in Onslow Bay I

A surprising number of beach nourishment projects have been carried out along the Onslow Bay shoreline. We found a total of 80 separate pumpings on 11 barrier (islands, a number that is probably incomplete. All these nourishment projects are at least partially federally funded with the exception of 4 pumpings on Figure 8 (Island, a private island not interested in allowing the (general public access to a federally funded beach.

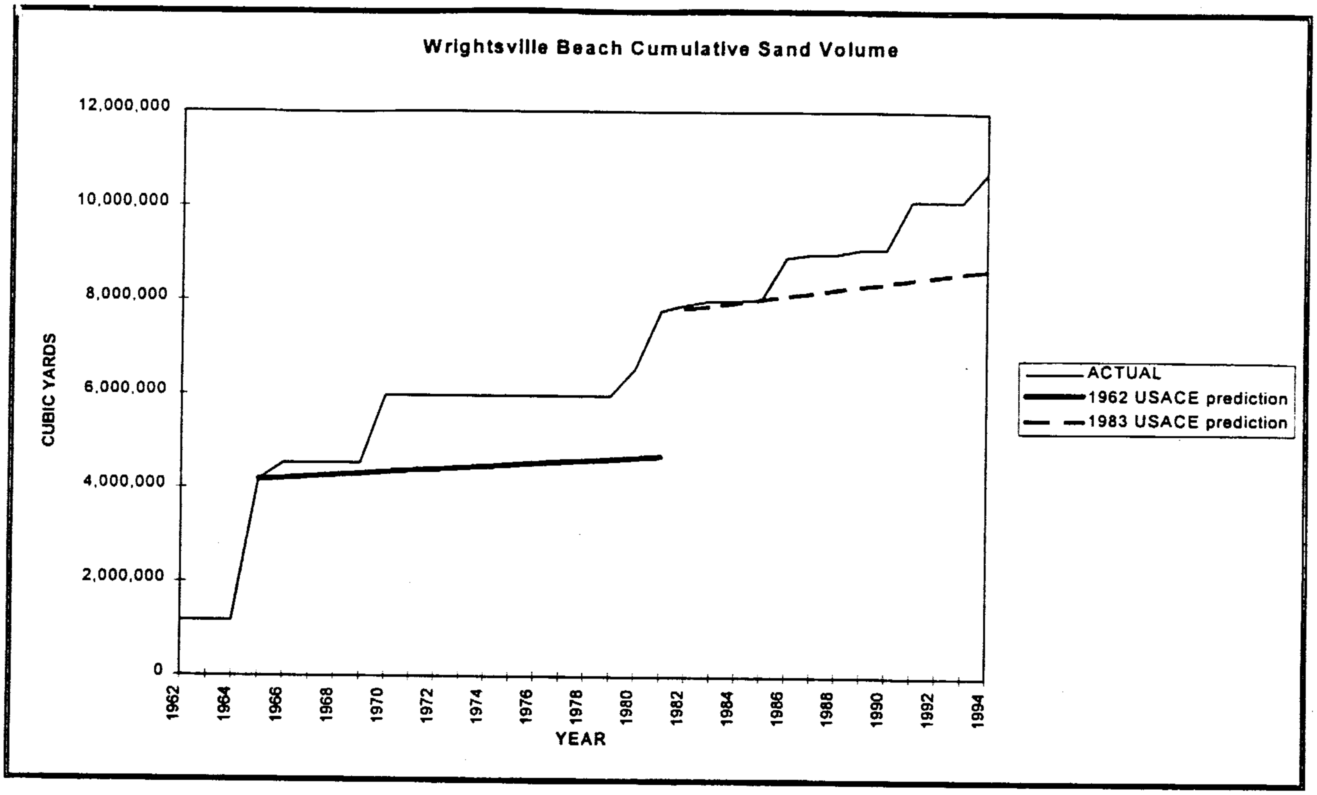
By far the most significant nourished beaches along this shoreline reach are Wrightsville Beach and Carolina Beach. Both have been steadily nourished with federal funding since 1965. These beaches are among the nation's most nourished beaches as measured both by frequency of sand application and cumulative volume of sand per mile (Pilkey and Clayton, 1987). Plots of cumulative sand volumes for Carolina and Wrightsville beaches (Fig. 1) indicates that the rates of sand loss from the beaches are more or less constant and that Carolina Beach has required more sand than Wrightsville Beach. The fact that sand volume requirements do not decrease with time indicates that offshore sand from the nourished beach plays no role in beach durability and nourishment sand is being permanently lost from the profile. This is contrary to what modern engineers tell us, which is that sand lost from the beach remains offshore in the profile affording storm protection and reducing long term sand volume requirements.

There are 2 kinds of federal beaches; (1) shore protection projects best exemplified by Carolina and Wrightsville Beaches and (2) beach disposal projects. The former are beaches "designed" by the Corps of Engineers, usually large ones, intended to mitigate the impact of storms. However, the storm damage mitigation justification to fund nourished beaches is a mere legal formality. Rather than storm protection, most communities are more concerned with maintenance of the all-important recreational beach which brings in important revenue to the local economy.

Beach disposal projects consist of dumping dredge spoil, usually from channel or intracoastal waterway maintenance projects, on nearby beaches. Such beaches are not studied or designed with engineering models, but there is basically no difference in the application of the sand to the beaches between shore protection and beach disposal projects. No predictions are made by the *Corps* concerning lifespan of beach disposal projects. Disposal projects also tend to be quite small and are usually free to the local community. An example of a very large beach disposal project is Fort Macon/Atlantic Beach. Approximately 20% of the total replenishment sand placed on the Onslow Bay Shoreline can be found here, paid for entirely with federal funds.

North Topsail shores has received at least two small disposal beaches (Table 1) in spite of the fact that the community is part of the Coastal Barrier Resources Act system. This is a program that prohibits any federal expenditures on designated barrier islands as a means of discouraging development in dangerous areas.

Nourished beaches classified as shore protection projects are designed by individual Corps districts using deterministic models of beach behavior. We (Young, et al., 1995; Pilkey, et al., 1993) believe the models do not work because assumptions used by the Corps are too simplistic and generalized to accurately reflect natural beach behavior. In addition, the random occurrence of storms requires a probabilistic view of beach behavior and should produce answers in sand volume and cost estimates with error bars. Current practice, however, does not produce estimates that include error bars. This can clearly be seen in figure 1 when one compares actual and predicted cumulative sand volume.


Wrightsville Beach Cumulative Sand Volume
CUBIC YARDS
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
YEAR
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
ACTUAL
1962 USACE prediction
1983 USACE prediction

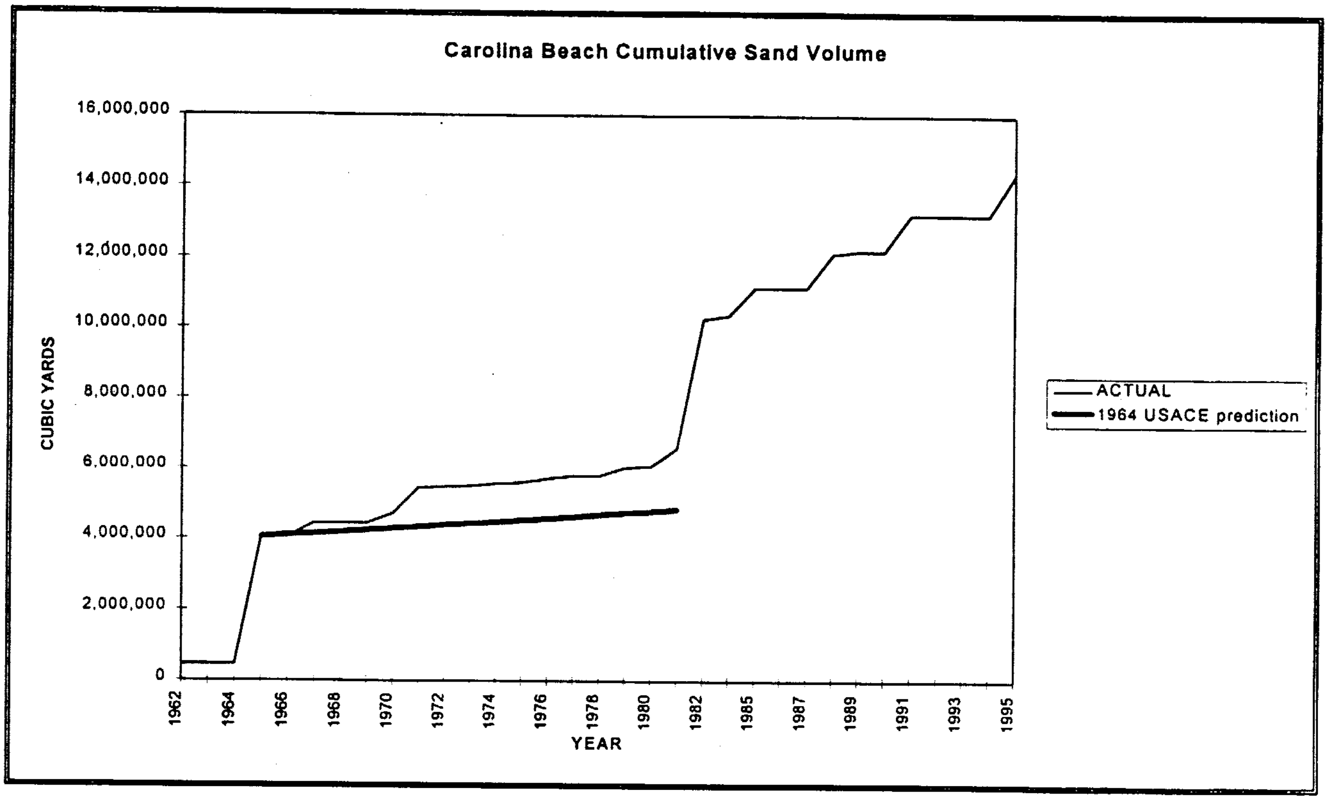

Carolina Beach Cumulative Sand Volume
CUBIC YARDS
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
YEAR
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1985
1987
1989
1991
1993
1995
ACTUAL
1964 USACE prediction

Figure 1

Location	Year	Volume(cubic yards)	Length(ft)	Cost
Fort Macon/Atlantic Beach	*1973	504,266	5,043	$ 414,807
	*1978	1,179,739	11,797	$ 1,565,177
	*1986	3,912,894	39,129	$ 5,316,038
	*1990	312,522	4,000	$ 1,663,911
	*1994	2,473,727	24,737	$ 3,794,727
Emerald Isle	*1989	45,399		$ 164,322
Topsail Beach	*1982	51,715		
	*1988	151,017		$ 423,256
	*1992	75,519	755	$ 177,830
	*1993	80,162	802	$ 269,659
	*1995	38,883	389	$ 174,751
West Onslow Beach	*1990	101,653	4,000	$ 417,984
Figure Eight Island	*1979	181,949		
	1985	46,300	2,000	
	1986	250,000	2,000	
	1993	275,000	3,000	
Wrightsville Beach	1939	700,000	13,728	$ 98,000
	1955	38,000		
	1956	35,000		
	1957	304,000		
	1959	100,000	7,920	
	1965	2,993,100	14,000	$ 739,339
	1966	362,108	12,000	$ 255,941
	1970	1,436,533	8,000	$ 578,545
	1980	540,715	8,000	$ 1,030,736
	*1980	36,108		
	1981	1,249,699	8,000	$ 4,427,792
	*1982	124,533		
	*1983	93,755		
	*1985	19,399		
	1986	898,593	8,000	$ 1,331,715
	*1987	76,556		
	*1989	96,771		
	1991	1,016,684	8,000	$ 2,682,412
	1994	619,031	6,400	$ 1,973,591
Masonboro Island	*1986	1,997,521	5,000	
	*1994	362,009	2,400	
Carolina Beach	1955	252,000		$ 50,000
	1956	200,000		
	1965	3,597,362	14,000	$ 925,506
	1967	389,959	4,000	$ 186,308
	1970	282,423	6,000	$ 291,159
	1971	734,140	14,000	$ 788,005
	*1972	18,816	182	$ 11,419
	*1973	30,547		
	*1974	66,687		
	*1975	40,804		
	*1976	119,971		
	*1977	62,066		
	*1979	230,886		
	*1980	38,075		
	1981	406,352	6,000	$ 1,051,774
	*1981	109,176		$ 174,002
	1982	3,662,181	14,000	$ 8,384,406
	*1983	119,244		
	1985	764,162	6,000	$ 1,652,004
	*1985	28,267		
	1988	950,913	5,700	$ 1,890,535
	*1989	98,843		
	1991	1,008,736	14,000	$ 2,450,286
	1995	1,157,742	14,000	$ 3,185,642
Bald Head Island	1992	800,000	12,300	
	1996	715,000	13,000	
Long Beach	*1986	130,000		$ 215,000
	*1989	104,803		
	*1993	160,091	1,601	$ 1,389,967
Holden Beach	*1971	108,802	1,088	$ 70,259
	*1973	108,627		
	*1974	92,774		
	*1975	62,303		
	*1977	76,149		
	*1984	76,867		
	*1986	95,927		
	*1987	173,963		
Ocean Isle	*1974	82,831		
	*1976	20,925		
	*1980	37,325		
	*1983	54,905		
	*1984	38,880		
	*1986	30,630		

Table 1. Beach Nourishment History of Onslow Bay Shoreline. An asterick* denotes a maintenance dredging project with beach disposal. Projects without an asterick are "designed" shore protection projects. Sources: Pilkey and Clayton (1989), records of the U.S. Army Corps of Engineers, Wilmington District, and North Carolina Division of Coastal Management.

All of the predictions depicted underestimated sand volume requirements due to "unexpected' storm events. Storms, however, should not be considered unexpected, especially on the barrier islands of North Carolina. Engineers need to recognize storms as geologic agents, existing as part of a very dynamic system, that can be expected to occur and should be planned for.

SHORELINE ARMORING

Relative to most states, the North Carolina shoreline is only lightly armored. According to Pilkey and Wright (1991) approximately 5% of the state's *developed* shoreline is impacted by shoreline armoring. This compares with 25% of the developed shoreline of South Carolina, 45% of east Florida's developed shoreline and 50% of the developed New Jersey shore.

Seawalls are designed to prevent shoreline retreat and in the case of very large seawalls, absorb storm wave impact. Along the South Carolina shore, virtually every seawall in the Hurricane Hugo impact area was overtopped by waves and storm surge. These seawalls, however, were low and were designed more to prevent shoreline retreat than to prevent wave attack on buildings.

Seawalls destroy beaches. This was once a controversial statement but not any longer. Such beach degradation may occur in 3 ways: placement, passive, and active loss. *Placement loss* occurs when a wall is actually constructed seaward of the high tide line. *Passive beach loss* occurs as a result of placement of any fixed object (seawalls, highways, buildings) at the landward side of the beach. Eventually (2 to 4 decades in Onslow Bay), the beach backs up against the wall and becomes narrower. *Active* beach degradation occurs as a result of the interaction between the surf zone and a seawall but little is known of such processes. Most of the controversy concerning the impact of seawalls on beaches centers on the *active* degradation mechanisms. However, where there is no controversy is the fact that once seawalls protrude into the surf zone, they can behave like groins and actively cause beach retreat on adjacent beaches through the reduction of sand in the longshore transport system.

Two major seawalls exist in Onslow Bay. One in Atlantic Beach on Bogue Banks, was constructed shortly after and in response to the 1962 Ash Wednesday Storm. Gradual beach narrowing occurred in front of this wall leading to the Corps' beach nourishment projects involving sand pumping from Beaufort Inlet and Morehead City harbor, located behind the island. The second large wall was constructed in 1995 for protection of the confederate earthworks of Fort Fisher, south of Carolina Beach. The Fort Fisher seawall was the first variance to North Carolina's anti-armoring regulations which were put into effect ten years earlier, in 1985. This wall will eventually increase shoreline erosion rates both to the north and to the south. One of the justifications for this wall is prevention of inlet formation across Fort Fisher which could cause sedimentation in the Wilmington Harbor navigation channel. To us, this is a poor justification for a seawall because, like all other east coast inlets formed during storms over the last 40 years, anew inlet at Fort Fisher would immediately be filled in by State or Federal agencies. Using the inlet formation argument on all North Carolina islands could justify the armoring of most beaches, even undeveloped ones.

Besides the Fort Fisher and Atlantic Beach seawalls, only a few others exist along Onslow Bay. These are mostly isolated walls or bulkheads in front of individual buildings on Kure Beach, Topsail Island, and Bogue Banks. A few sandbag revetments exist here, permitted by the State in order to "temporarily" protect exposed buildings.

RELOCATION

The conclusion of a white paper (Howard et al., 1985) produced by a group of coastal scientists, planners and engineers was as follows: Sea level is rising and the American shoreline is retreating. We face economic and environmental realities that leave us two choices: (1) plan a strategic retreat now or (2) undertake a vastly expensive program of armoring the coastline and, as required, retreating through a series of unpredictable disasters.

The relocation alternative has been "practiced" on most of Onslow Bay's islands, especially in the early days when moving shorefront buildings was a common event. Still, many more houses have been destroyed by storms than moved back by their owners.

Communities where beach front buildings have been relocated because of the erosion threat include Baldhead Island, Topsail Island, and Bogue Bank. The island with the greatest need for the relocation alternative is Topsail, where hundreds of dwellings, most built decades ago, are now perched on the brink of disaster. Because of this, most of the development on Topsail was recently destroyed by hurricane Fran. Along the Long Bay shoreline to the south, Long Beach and Holden Beach also have many buildings very close to the surf zone.

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FORT FISHER REVETMENT PROJECT

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ABSTRACT

Fort Fisher, North Carolina's most visited historic site, has been subject to shoreline erosion for more than a century. In 1996, the construction of a major rubblemound revetment was completed to prevent further loss of the historic property. This $4.6 million 3,040-foot-long structure consists of 3-ton granite armor stone placed over marine limestone bedding and underlayers. The project background, including major historic shoreline changes and past shore protection efforts leading to the selected plan, is discussed. Also, the hydraulic design details, shoreline impacts of the structure, along with a description of the revetment construction are presented.

INTRODUCTION

Fort Fisher was built by the Confederacy to guard the entrance of the Cape Fear River allowing vital supplies to reach the port of Wilmington during the Civil War. On a cold January day in 1865, Union forces assembled a massive naval attack capturing the fort following a bloody day of fighting and some 1 ,800 casualties. On a hot July day in 1996, more than 131 years later, ground was broken for construction of a large stone revetment in another battle of sorts, this time against storm attack and beach erosion, that had claimed more than one-half of the original fortifications. The construction of the 3,040-foot-long structure followed decades of planning by local, State and Federal agencies, along with several prior shore protection efforts of limited scope and effectiveness.

The project site is located along the southeastern coast of North Carolina in southern New Hanover County, on a peninsula that separates the lower Cape Fear River from the Atlantic Ocean (Figure 1). The historic site is immediately south of Kure Beach and is located approximately 20 miles south of the city of Wilmington. The revetment also affords protection to a portion of US Highway 421 that passes through the project area providing access to the North Carolina Aquarium, the Fort Fisher State Recreation Beach, and the Fort Fisher/Southport Ferry.

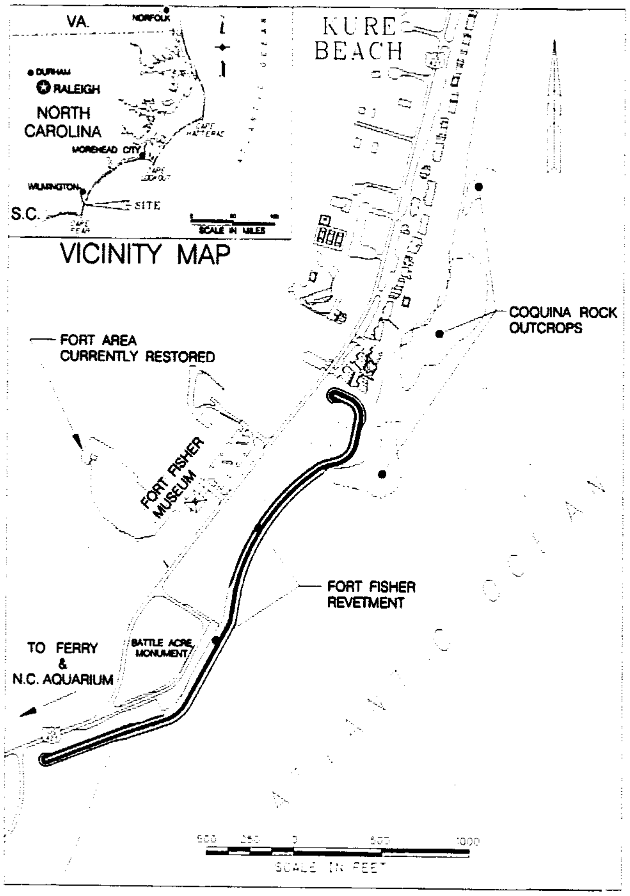

Figure 1. Location map of Ft. Fisher project area.

BACKGROUND

The original fortifications consisted of a series of interconnected earthenmounds stretching east-west one- third of a mile across the peninsula and then generally north-south along the ocean frontage for about one mile. Beneath the mounds was a complex system of interior bunkers and bombproofs that protected men, ammunition and supplies during bombardment. The present site covers 264 acres and is administered by the North Carolina Department of Cultural Resources. Fort Fisher is North Carolina's most visited State historic site and in 1962 was the first State site to be designated as a National Historic Landmark. This is the highest designation given by the Federal government in recognizing and encouraging preservation of the nation's important historic properties. The current historic site includes the remaining earthenwork fortifications (part of which has been restored), a museum/visitor center, a picnic area along the beach front, and a memorial and ocean view parking at "Battle Acre."

MAJOR SHORELINE CHANGES

When Fort Fisher was constructed in the 1860's there were two entrances into the Cape Fear River. The fort was built along the northern shoulder of the northernmost entrance which was known as New Inlet. The southern entrance was located at the site of the present Cape Fear entrance near Southport, NC. Since the time of the Civil War, the Fort Fisher area has experienced major shoreline changes. These have been the result of man's action, as well as those induced by natural causes.

"The Rocks"

The first major change occurred as a result of the construction of a rock dam across New Inlet beginning in the 1870's. This work, known locally as "The Rocks" was undertaken to prevent a persistent shoaling problem in the Cape Fear River. The dam prevented tidal exchange between the river and the ocean at this location and forced the main tidal flow south through the primary river entrance near Southport. The construction resulted in significant change in the inlet complex. The much reduced tidal prism allowed for the onshore migration of sand from the ebb tidal shoal and the development of a southward migrating sand spit into the inlet. The outcome of these processes was the modification of the shoreline from one with a large seaward bulging planform along the shoulder of the inlet, to a more linear alignment along the fort. Figure 2 depicts these major shoreline changes, comparing the modern day shoreline (1992) with that which existed in 1865.

These changes had both positive and negative impacts. On the positive side, navigation was improved in the river and miles of new beach formed south of the fort. Today, this new strand comprises much of the Fort Fisher State Recreation Area. On the negative side, the shoreline realignment resulted in severe erosion in the area of the earthenmound fortifications. For example, since 1865 the shoreline has eroded about 1,200 feet in the vicinity of the fort, for a long-term average erosion rate of 9.5 ft/yr.

Coquina Outcrops

The second major influence on the shoreline in the immediate vicinity of the fort has been the emergence of natural coquina rock formations just offshore and to the north of the fort (Moorefield, 1978). For at least the last 60 years, the rock outcrops have modified sediment transport patterns along the shoreline fronting the fort, causing accelerated erosion along this reach. The net longshore sediment transport for the area is from north to south, placing the project site downdrift of the coquina rock outcrops. The characteristic shoreline response to the emerging rock formations is the development of a large embayment downdrift of the more erosion resistant rock formations. Unfortunately, much of the fort itself falls within the shoreline embayment caused by the outcrops, resulting in accelerated erosion of the historic fortifications.

SHORE PROTECTION EFFORTS

Although numerous studies addressing the erosion problem at Fort Fisher have been accomplished over the years, beginning as early as 1931 (US H.DOC 204, 1931), no action was undertaken until 1955. During this year, the County undertook the first of a series of emergency actions aimed at preventing further erosion of the historic site. This action consisted of constructing two short groins in front of Battle Acre, following severe erosion that resulted from a series of hurricanes which affected the area in 1954 and 1955. These included Hurricane Hazel which is recognized as the storm of record for the area. Subsequent shore protection actions are summarized in Table 1.

Table 1. Fort Fisher Shore Protection History

YEAR	ACTION TAKEN
1955	Two Short Groins Constructed in Front of Battle Acre
1959	700 lf Revetment Along Battle Acre (Concrete and Brick Rubble)
1965	Rubble Added to North and South Flanks of Battle Acre Revetment
1965	15,000 cy of Sand Placed Along 700 lf North of Battle Acre
1967	Repaired Breach in Revetment
1967	Placed Additional 15,000 cy of Sand Along 700 lf North of Battle Acre
1970	Emergency Revetment Constructed of Marine Limestone from Battle Acre to Coquina Outcrop
1970 to 1995	Sporadic Placement of Construction Rubble Along Battle Acre Revetment
1996	Construction of 3,040 foot-long Granite Revetment

The most significant measures have been the construction of two revetments prior to the major revetment construction that is the subject of this paper. The first of these involved the placement of concrete and brick rubble along about 700 feet fronting the Battle Acre area. Over the years, this structure had been maintained through the sporadic placement of construction rubble. This material consisted chiefly of concrete slabs and masonry debris collected from structural demolition. This structure had proved to be fairly

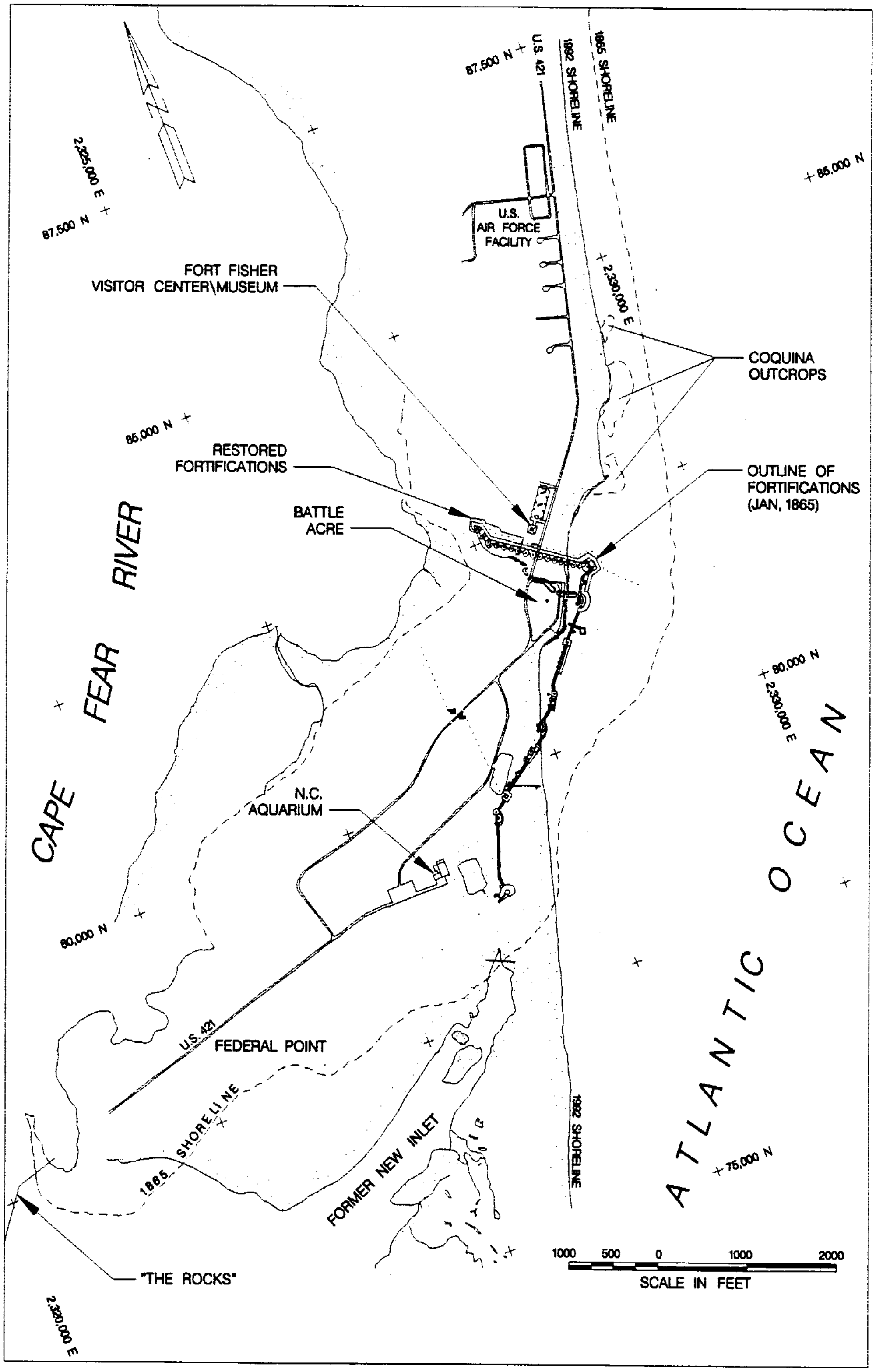

Figure 2. Map showing shoreline changes between 1865 and 1992 and footprint of the original fortifications.

effective in erosion control, mainly through the replenishment of the rubble material over the last 25 years. The second measure was undertaken by the State in 1970 involving the construction of an emergency revetment. This structure was built of locally available marine shell limestone and extended from Battle Acre northward to the coquina outcrop. During the 1975-76 timeframe, the revetment was breached near its midlength and began a gradual progressive failure extending both northward and southward from the midpoint. Presently, remnants of the revetment are visible along its length with the stone having settled into the beachface. Some of this material had to be moved since it was along the alignment of the 1996 revetment project. The material was repositioned just seaward of the new work as an added scour protection measure.

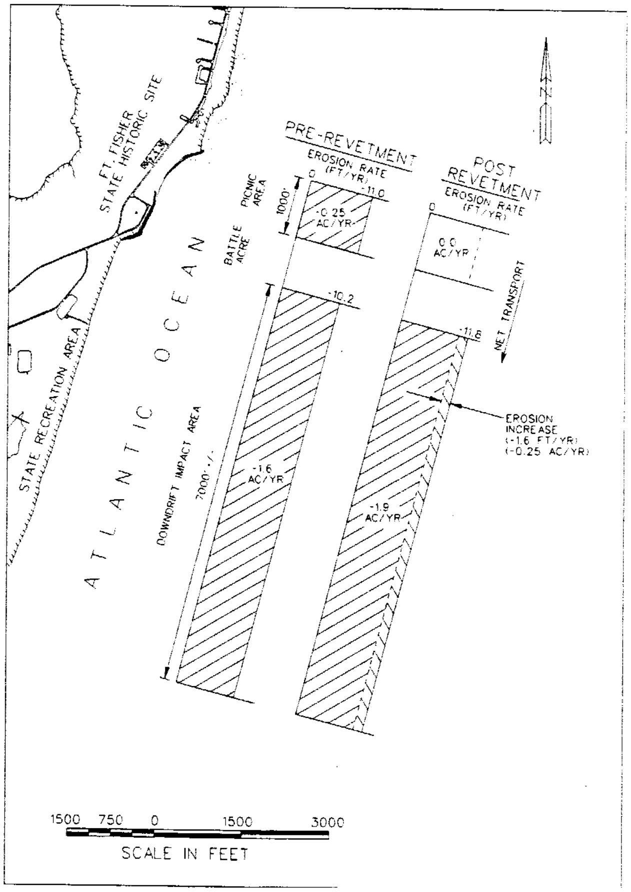

Figure 3. Schematic showing idealized shoreline impacts of the Ft. Fisher revetment.

SELECTED PLAN

Given the importance of protecting the remaining fortifications and with the effort to do so being beyond the local means, a beach erosion control protect was authorized by the US Congress in 1976. Under this authority, the US Army Corps of Engineers, Wilmington District, initiated a planning and design effort addressing a number of alternative shoreline protection measures (US Army Corps of Engineers, 1981) .The alternatives considered were a revetment, beach nourishment, offshore breakwaters, groins, and various combination plans. From this initial effort, the recommended plan consisted of a stone revetment to protect the upland portions of the fort along with a beach fill and groin field to maintain a beach in front of and to the south of the stone wall.

Upon completion of the general design, the project became inactive until the early 1990's due principally to budget restraints with State matching funds. At that time, an active group known as The North Carolina Committee to Save Ft. Fisher organized and was successful in lobbying to get the project reactivated. In the spring of 1993, plans to construct the revetment were finalized; however, the beachfill and groin field portions of the plan were deferred based on cost considerations and environmental issues associated with the selected beachfill borrow area.

Shore Hardening Issue

The selected plan consists of a rubblemound structure that extends from the northern property line of the historic site, near the coquina outcrop, southward beyond Battle Acre where US Highway 421 would be protected (See Figure 1). The purpose of the structure is to protect the upland behind the revetment and not to preserve the beach fronting the structure. This proposed plan was contrary, however, to the North Carolina state regulations governing development in the coastal area. Since the mid-1980's, standards established by the Coastal Area Management Act prohibit the use of hard structures in the coastal environment. These rules were adopted to prevent possible adverse impacts to adjacent properties or public access that could be caused through the indiscriminate use of hard structures.

The rules, however, did not recognize the public benefits to be realized through the long-term protection of an historic site of national significance. In this regard, anew rule was adopted in December 1992, following significant controversy, that would permit a coastal structure to be used to protect an historic site under certain conditions. The following year, the Fort Fisher plan was found to be in compliance with the rule, and a permit was issued allowing the project to go forward.

Central to the controversy was the concern over the impact that the proposed revetment could have on the downdrift beach south of the site. Future erosion conditions at the site, with or without the revetment are expected to be dominated by the presence and continued emergence of the coquina outcrops. With the construction of the revetment, the major difference will be that the upland containing the remaining fortifications and adjacent picnic area (area between Battle Acre and the coquina outcrop) will be stabilized. Prior to construction this area was eroding at an average rate of 11 ft/yr. The material from this area served as a source of sediment elsewhere in the littoral zone. With the revetment in place, this source is no longer available. Assuming that most of this material fed the downdrift beaches to the south, the primary impact of the revetment will be increased erosion to the south equal to the induced deficit. This impact is quantified and shown schematically in Figure 3.

As indicated on the figure, the picnic area was losing about 0.25 ac/yr prior to stabilization. The reach downdrift of Battle Acre was eroding at an average rate of 10.2 ft/yr and had experienced an average area loss of about 1.6 ac/yr. This reach extends approximately 7,000 feet south of Battle Acre. Beyond this reach, the erosion rate was found to decrease significantly indicating the southern limit of the downdrift impact zone that existed prior to the revetment construction. With the revetment in place, the loss within the picnic area has been eliminated. However, this loss will in effect be displaced to the downdrift zone. This increases the erosion to 1.9 act yr or 11.8 ft/yr for this zone, which amounts to a 15% increase in erosion along the downdrift reach. It is noted that this estimate is considered conservative and probably overstates the increase in construction induced erosion by assuming that all the sediment that was being lost from the picnic area served as a source to the downdrift beach. A portion of this area contained an actively eroding layer of humate-rich sand. Once eroded, this fine peat-like material was most likely transported offshore and out of the active littoral zone and, therefore, represented a loss to the overall sediment budget.

The predicted 15% increase in erosion associated with the new revetment construction would be felt along beaches to the south of the structure. This area is public State owned land as is part of the Fort Fisher State Recreation Area. Therefore, in terms of overall public benefit, the use of the revetment represents a trade- off between the preservation of historic lands versus an increase in the loss of public beach. A condition of the permit requires that if the future erosion is found to exceed the 15% threshold, appropriate mitigation measures will be undertaken.

REVETMENT DESIGN

The revetment was designed to stabilize the eroding shoreline and protect against storm wave attack and overtopping (US Army Corps of Engineers, 1993) . The selected design conditions represented those :hat were associated with Hurricane Hazel, the storm of record for southeast North Carolina. Specifically, these conditions were a peak storm surge of 10.7 feet above mean sea level and a breaking wave height and maximum wave period of 11.8 feet and 12 seconds, respectively. In terms of water level, 'his represents an event with a peak surge slightly greater than the 100-yr base flood elevation as reported by the Federal Emergency Management Agency (1986).

The structural design of the rubblemound revetment was accomplished primarily through the use of two dimensional hydraulic model tests conducted at the US Army Corps of Engineers, Waterways Experiment Station, (Markle, 1982). The tests were performed in a wave flume at a scale of 1 :24, model to prototype. Atypical 48-foot wide section of the prototype (2-foot model section) was subjected to depth limited breaking waves and varying storm hydrographs simulating design loading conditions. Additional tests were performed

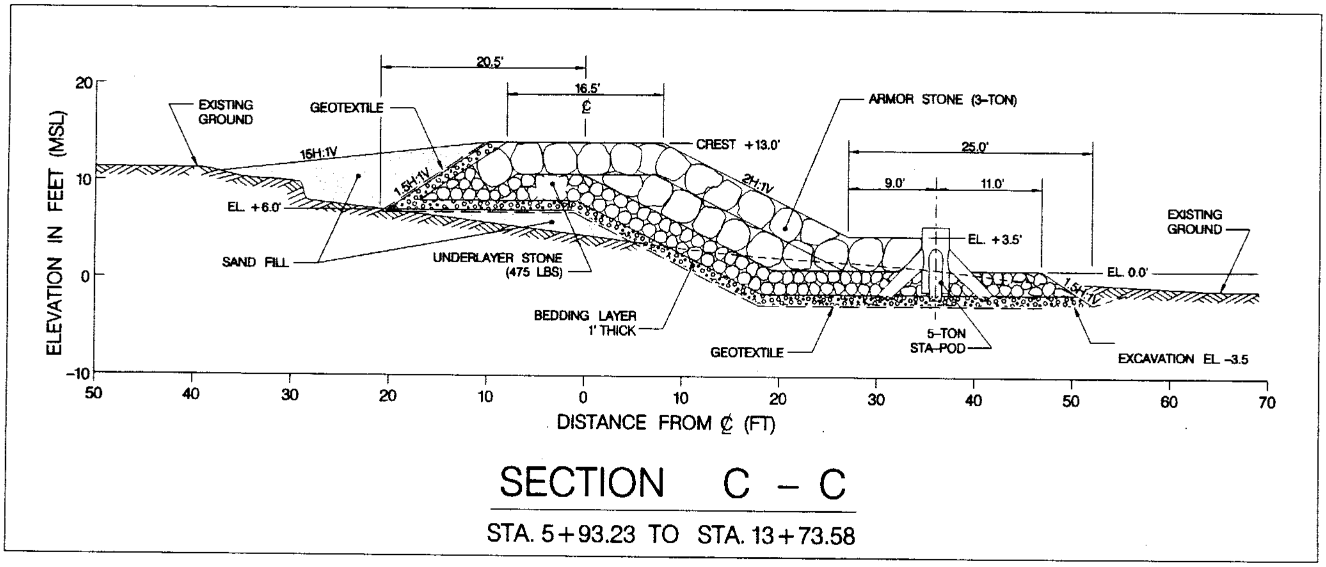

Figure 4. Typical revetment x-section showing various stone layers and position of STA-POD units.

Figure 5. View of completed revetment looking northward from the Battle Acre area.

in assessing the stability of the structure to conditions both substantially greater than and less than the design condition.

A typical x-section of the revetment, as shown in Figure 4, consists of three layers of successively smaller size stone placed over a synthetic filter cloth. Sand backfill is provided landward of the stone structure providing a sloping grade between the existing ground and the crest of the revetment. The three layers known as the armor layer, underlayer and bedding consist of individual stones with median weights of 3 tons, 650 lbs. and 20 lbs., respectively.

The crest elevation of the 3,040 foot-long revetment is + 13 feet above mean sea level, except at the southern end of the structure and Battle Acre. At the southern end, the crest is lowered to + 10 feet to follow the existing topography. For the area along Battle Acre, the crest is gradually increased to an elevation + 15 feet, maintaining this elevation along a 180-foot reach immediately fronting the remaining earthen fortifications. The base elevation of the revetment is - 3.5 feet throughout its length.

Another design feature is a horizontal stone apron located at the seaward toe of the structure to prevent wave induced scour from undermining the revetment. The scour apron is anchored by a unique interlocking concrete unit known as a STA-POD[1]. The STA-POD consists of a cylindrical main trunk with four stabilizing legs. The legs are slightly longer than the central trunk which allows them to settle into the supporting stone bed for greater stability. Each unit is steel reinforced and stands about 7.5 feet tall, has an overall base width of 12 feet and weighs 5 tons. When positioned, the legs of adjacent units overlap, forming a continuous interlocking line of defense along the toe of the structure. In addition, underlayer stone is placed around the legs of the units further enhancing their stability.

PROJECT CONSTRUCTION

The revetment construction began in June 1995 and was completed in January 1996 (Figure 5). The $4.6 million contract was awarded to Misener Marine Construction Company of Tampa, FL. The cost was shared 50/50 between State and Federal governments. The work involved transporting and placing about 70,000 tons of rock. The 3-ton armor stone consisted of biotite granite that was obtained from Neverson Quarry located in Bailey, NC, about 125 miles from the site. The underlayer and bedding stone consisted of less dense marine limestone which came from the Martin Maritetta Quarries in Castle Hayne, NC, and Rocky Point, NC, about 25 and 35 miles from the site, respectively. All stone was truck hauled to the project and either stockpiled or offloaded directly into the work.

The STA-PODs were cast on site in an area located just to the north of museum (Figure 6). Six intricate forms were

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[1] The STA-POD was invented in the 1960's by Mr. Raymond O'Neill, Concrete Armor and Erosion Consultant, Spring Lake Heights, NJ.

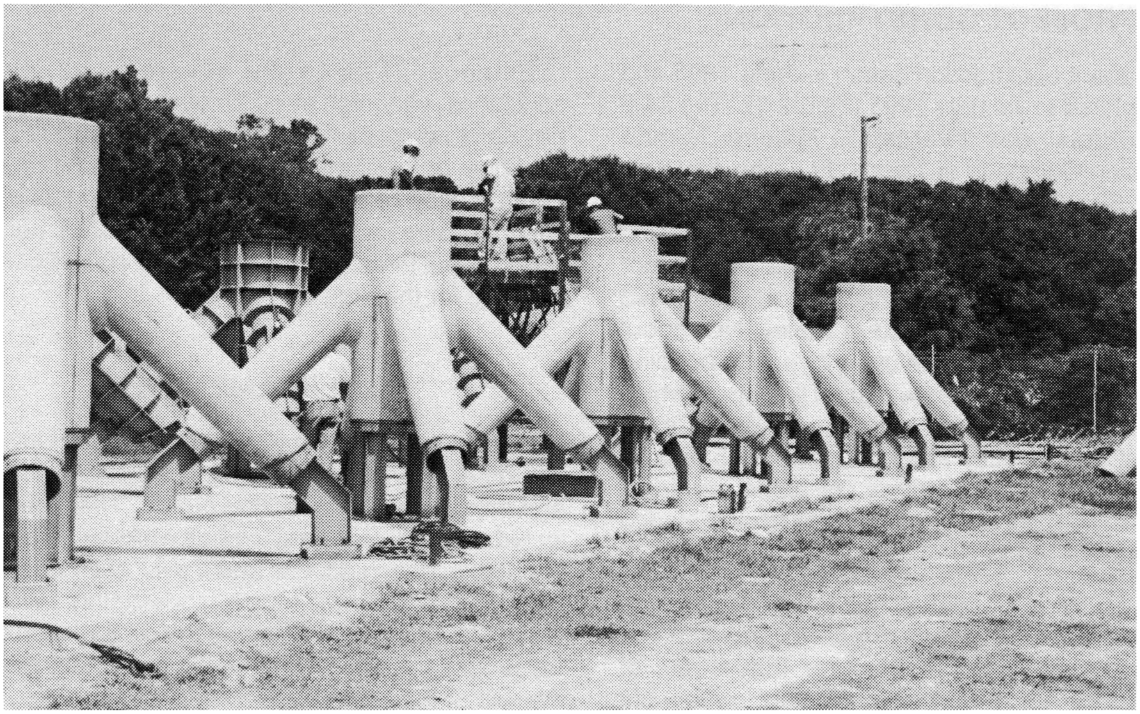

Figure 6. The STA-POD casting area showing the units shortly after removal of the steel forms.

fabricated by Helsner Industries, of Tualaton, OR, which consisted of eight removable sections for each unit. The reinforcing steel cages were hand fabricated at the site for positioning in each leg. All rebar was epoxy coated for corrosion resistance. Due to the severe wave loading conditions, very high strength concrete was required having a compressive strength of 6,000 psi and a minimum unit weight of 150 pcf. Each unit required about 2.3 cy of concrete. Once in production the casting operation could produce six units per day, taking about three months to cast the 400 STA-PODS required for the project.

PUBLIC AMENITIES

In addition to the revetment itself, the project involved a number of ancillary features to enhance the safety and enjoyment of the visiting public. These features include a 2,770-foot-long asphalt walkway, two timber overlooks, beach access stairs over each end of the revetment and native beach landscaping. Work on these features began following the construction of the revetment and was completed in June 1996 marking the end of the construction contract.

POST-CONSTRUCTION MONITORING

With the construction of a major coastal structure it is of interest to document the impact that such a structure may have on the adjacent shorelines. In this regard, a monitoring program has been initiated to measure the post-construction shoreline response and then compare this with shoreline changes that existed prior to construction.

The impacts of the revetment on the adjacent shorelines are being monitored using beach profile surveys and aerial photography. The beach profile surveys are being performed two times per year, during March and September. Surveys at these times of the year will generally capture the range of shoreline changes, with the surveys following the erosional winter storm season and the accretional summer season. The aerial photography is taken during the March survey period so the changes from the photos can be correlated with measured changes from the beach profiles. In addition, the photography provides spatial continuity between the individual beach profile locations.

The monitoring area covers a 20,000-foot reach of shoreline, extending 3,000 feet northward and 17 ,000 feet southward from the Fort Fisher Museum. This involves the periodic survey of 50 beach profiles generally spaced 500 feet apart, except those near the structure which have spacings of 200-300 feet. The beach survey cover the onshore area (from a stable upland bench mark to wading depth) with offshore portions of the profile (approximately to the 30-foot contour) being taken on alternate surveys, i.e. September only. In addition to the beach surveys, 30 control points located on the revetment are being surveyed semi-annually to monitor settlement and stone movement.

To date, a base-condition survey, a during construction survey, and two post-construction surveys have been accomplished. The first in a series of monitoring reports, documenting the findings over the initial 2-years, is scheduled for publication in the spring of 1997.

CLOSING

Years of planning, study, and design culminated this year with the construction of the revetment for shore protection of Fort Fisher. This effort was accomplished by individuals at all levels of government, as well as concerned historic preservationists. With construction of the revetment, which is designed to withstand a rather rare storm event, at least 50 or more years of protection should be provided to the fort without significant maintenance or rehabilitation.

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Environmental Coastal Geology: Cape Lookout to Cape Fear, NC

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ENVIRONMENTAL COASTAL GEOLOGY: CAPE LOOKOUT TO CAPE FEAR, NORTH CAROLINA REGIONAL OVERVIEW

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The Georgia Bight is the 1,200 km coastal reach extending from Cape Hatteras NC to Cape Canaveral, Fl. The coast of the bight consists of a nearly continuous chain of barrier islands situated on the tectonically stable trailing edge of the North American Plate. The North Carolina coastline, on the north flank of the bight, consists of a sequence of large capes and associated shoals, barrier islands, spits, and occasional headland areas. A natural division of the North Carolina coastline occurs near Cape Lookout (Fig. 1). North of this Cape, the islands are separated from the mainland by relatively wide open water lagoons and sounds, that back the barrier islands are narrow and nearly filled with marsh.

The continental shelf segment between Cape Lookout and Cape Fear is referred to as Onslow Bay. Only small coastal plain rivers empty into this coastal segment which probably was also the case during most of the late Pleistocene. The larger rivers that originate in the Piedmont province empty into Raleigh Bay to the north and Long Bay to the south. As a consequence, this shelf area probably has the lowest sedimentation rate on the US East Coast continental shelf. The thin shelf sediment cover as residual, meaning that it is derived from underlying ancient sediments that frequently crop out on the shelf. Other shelf areas of North Carolina are mainly covered by relict sediments, left stranded after being deposited at lower sea levels.

The 13 barrier islands that comprise the 150 km coastline between Cape Lookout and Cape Fear have a wide variety of physiographic forms. ranging from overwash- dominated narrow barriers to wide barriers with massive dunes and no washovers. The approximate division between the two morphologic classes occurs between Browns Island and Onslow Beach (Fig. 1).

In this area a submarine headland composed of Tertiary

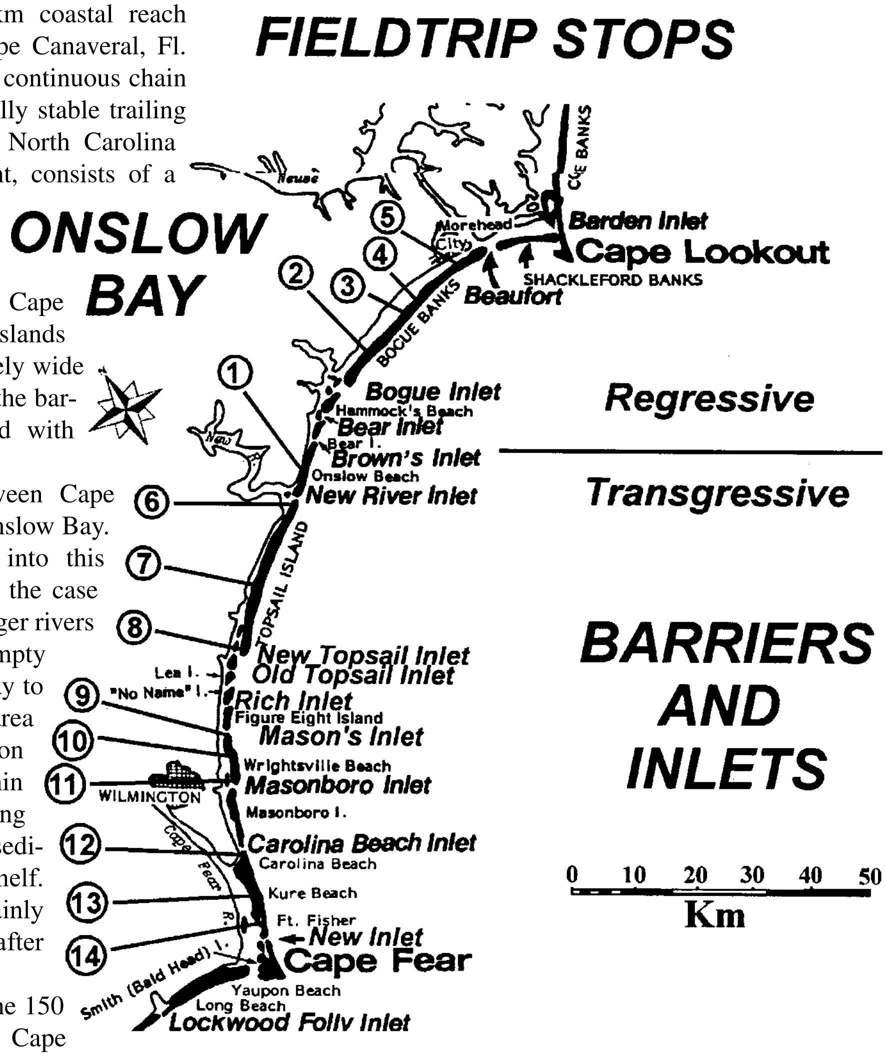


Figure 1. Location map depicting the barriers, inlets and fieldtrip stops. R=Regressive barrier segment, T=transgressive barriers.

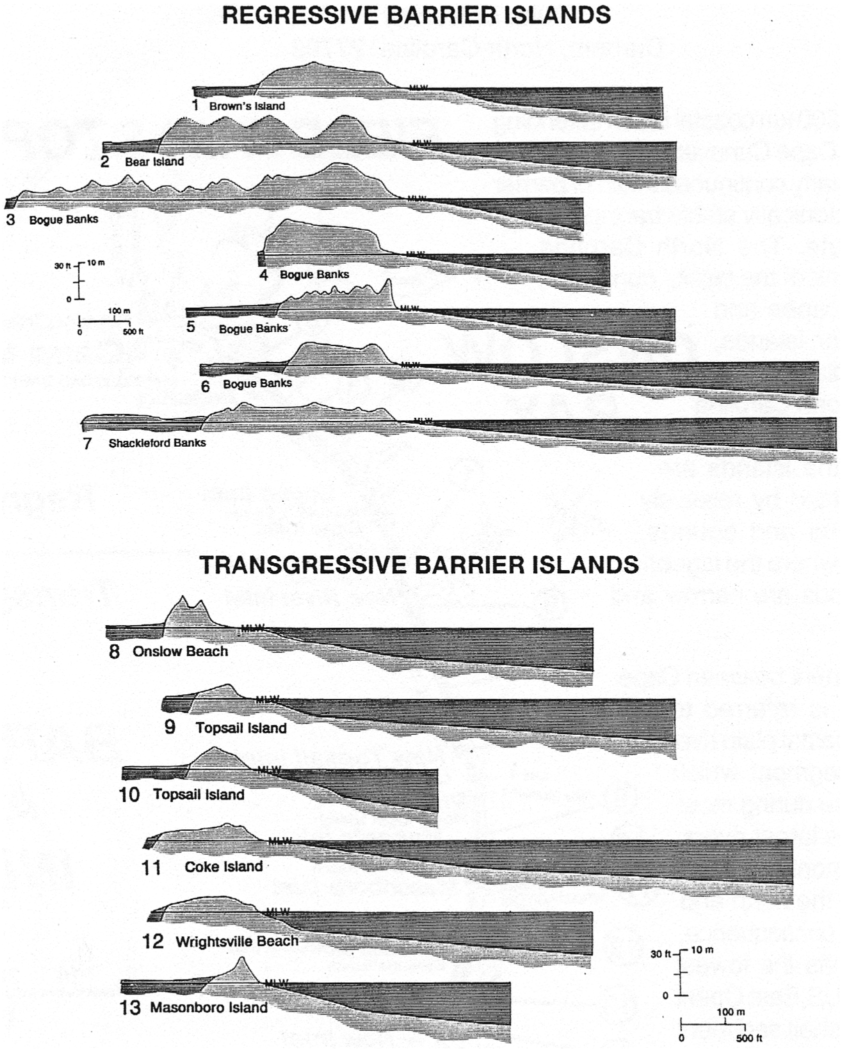


Figure 2. Cross-sections of Onslow Bay barriers.
A. Regressive barriers are sand rich and contain 15-25 times more sand per unit length of coast than transgressive barriers.
B. Transgressive barriers are low, narrow and prone to frequent overtopping.

limestone and sandstones. forms a small bulge in the coastline that separates the relatively stable, sand rich regressive barriers to the northeast from the transgressive eroding barriers to the southwest (Fig 2A, 2B). At Fort Fisher/Kure Beach, a short stretch of mainland shoreline exists in the form of a subaerial headland composed of Pleistocene sandstones and coquina. This forms the southern boundary of the sand poor transgressive segment. A narrow spit extends southward from the headland to the Cape Fear Foreland.

The longest of the barriers along the Onslow Bay shoreline is Bogue Banks, 45 km long; Lea Island is the shortest in the chain, approximately 2 km long. Lagoons are widest (4.1 km) in the north, behind Bogue Banks, and generally decrease and finally disappear where the islands have overridden the subaerial headland at Fort Fisher/Kure Beach. The northern lagoons, principally Bogue Sound, are largely shallow, open, and free of vegetation. By contrast, tidal marshes generally have infilled the southern lagoons. Elevations on the islands range from less than three meters on Masonboro Island to more than 10 m above MSL on Bear Island.

These microtidal to low mesotidal barrier shorelines (Hayes, 1979 and 1994), have a mean tidal range of about one meter. The direction of wind approach fluctuates annually. During the spring and summer the winds are from the south and southwest, while during the winter, north and northeast winds will prevail. The coastline just south and west of Cape Lookout is more protected from northeast storms than the area north of Cape Fear. All sections are highly vulnerable to hurricanes approaching from the south and east.

Inlets vary from wide, deep, stabilized and maintained inlets such as Beaufort Inlet (Fig. 3A), separating Bogue and

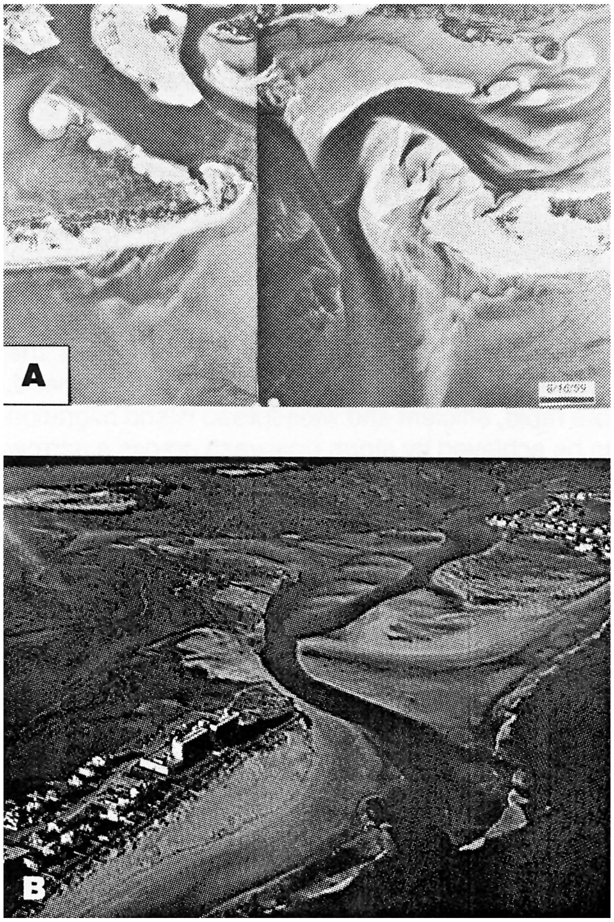


Figure 3. Inlet types. See figure 1 for locations.
A. Beaufort Inlet is a large modified stable system that serves as the port of entry for Morehead City Harbor. The 1956 photograph shows large sand bars migrating and welding onto the Shackleford Banks shoulder.
B. Mason's Inlet is a small migrating system that is the center of controversy. It is slated for relocation. The inlet borders Wrightsville Beach and Figure Eight Island.

Shackleford Banks, to narrow, shallow, shifting inlets such as Mason's (Fig. 3B), separating Wrightsville and Figure Eight Islands. Human impacts on the islands vary from extensive development on portions of Wrightsville Beach, Bogue Banks, and Topsail Island to uninhabited islands such as Shackleford, Coke and Bear Islands.

ORIGIN OF BARRIER ISLANDS

Barrier Islands make up about 10% of the world's shoreline. Chains of barrier islands (3 or more inlets) front three percent of the coasts of the world. Because barrier islands are virtually the most important coastal type in North America, they are perhaps the most intensely studied coastal features in the world. All barrier islands have four parameters in common: a rising sea level, a gentle lower coastal plain surface, a sand supply large enough to build islands and sufficient wave energy to move sand. Almost all barrier island chains are found on the trailing edges of continents although a few chains (eg. the Pacific Coast of Colombia and the Copper River Delta, Alaska) occur on leading edges where a very large supply of sand exists. The Florida shoreline bordering the northeast corner of the Gulf of Mexico has no barrier islands because the wave energy is too low to move significant amounts of sand.

The fundamental reason that barrier islands exist is that a straight shoreline, oriented in such a way that longshore movement of sand is minimized, is astable shoreline configuration. Given an unconsolidated shoreline with waves coming from the same direction, erosion and depositional patterns would eventually result in a shoreline orientation parallel to incoming wave crests. This, of course, never happens in nature because incident waves come from many directions. The barrier islands effectively straightened out a very irregular shoreline formed when the lower coastal plain was flooded by a rising sea level.

When sea level began to rise 18,000 years ago, the river valleys were flooded and ridges between the valleys became seaward protruding headlands. Wave erosion of the unconsolidated headlands furnished sand to form spits extending into the deep water across the throats of the newly formed estuaries. Sand from the eroding headlands formed spits rather than being deposited inland along the shorelines of the estuaries. These spits were deposited when waves refracted around the entrance to the estuaries, thus loosing energy and thus a bulk of the suspended sand load. Thus it can be said that another fundamental reason that barrier islands exist is that waves loose energy when they are refracted by landmasses.

Once the spits form they are eventually segmented into islands by the formation of new inlets during storms. Simultaneously, the rising sea level flooded the region behind the ridges of sand dunes and overwash fans formed along the open ocean shoreline, in effect lengthening the spit. Once the islands are formed through a combination of spit breaching and backbarrier flooding during a time of rising sea level, an entire new set of processes takes over. The barrier islands begin to migrate apace with the rising sea level.

The process of island formation does not occur during times of lowering sea level and seaward advancing shorelines. No estuaries exist to promote the formation of spits and no particular advantage is gained or fulfilled by straightening an already regular shoreline. Rising sea level is the key component of barrier island formation and evolution.

BARRIER ISLAND MIGRATION

Once formed, the islands are believed to have migrated across the continental shelf apace with the rising sea level. During times of particularly rapid sea level change the islands may have existed as spits or they may not have existed at all. Sand supply may have been the key factor in island survival. A large sand supply would aid in island survival in a rapidly rising sea level. A small sand supply would lead to the demise of the islands under the same circumstances of sea level change. Since Onslow Bay has a very small fluvial sand supply and a very thin sediment cover, it can be assumed that during significant parts of the Holocene transgression, no barrier islands lined the coast. The evidence here, and on other continental shelves, that barriers did at least periodically exist at lowered Holocene sea levels is the presence of back barrier lagoon deposits and the occurrence on the shelf of filled, discontinuous channels believed to be ancient inlets.

Barrier island migration occurs through the combined processes of open ocean shoreline retreat and island widening through the landward extension of the back barrier environment of the island. The net result is an island that moves landward and upward in response to sea level rise, a rather amazing natural phenomenon.

The open ocean shoreline retreat, more commonly known as shoreline erosion, commonly occurs as a result of seaward removal of sand as a result of storms. Island widening may occur several ways including incorporation of tidal deltas, formation of overwash fans extending into the back-barrier sound and the formation of wind flats. Incorporation of tidal deltas (further discussed below) occurs when the flood tidal delta is abandoned because of inlet migration or inlet closing. The former subaqueous shallow sand body becomes part of the island by subaerial buildup thru salt marsh, dune and storm overwash sediment accumulation. If an inlet is migrating, the flood tidal delta may become attached to the island and widen it along the entire path of inlet movement.

Island widening by tidal delta attachment is a relatively slow process which often affects only short stretches of the island. The southernmost two miles of Bodie Island, along the Northeast Outer Banks, has been widened since 1843 by the incorporation of the migrating tidal delta of Oregon Inlet. On the other hand, more rapid, efficient and widespread island migration can be achieved by storm overwash across a narrow island. Such overwash can simultaneously widen and in instances elevate the island. During virtually every significant storm, the 13 km long Masonboro Island has migrated. On Masonboro overwash fans readily extend into the adjacent salt marsh behind the island, extending the backbarrier shoreline in a landward direction. For efficient migration by the overwash mechanism, an island must be relatively narrow, perhaps 100 m wide or less, depending upon storm magnitude and frequency.

The incorporation of wind blown sediments from the island into overwash fans or salt marshes in the back barrier environments is probably a significant component of the island migration mechanism in North Carolina. In Texas, especially on Padre Island, wind flat extension of the back barrier shoreline is the principal mechanism of island widening.

Barrier Island migration on the North Carolina Coast probably in large part came to a halt 3 to 4,000 years ago when sea level rose close to its present position. Since that time some of the islands have widened by the incorporation of beach ridges on their open ocean sides.. Such prograded islands are classified as regressive. Islands that remain in a stratigraphic mode indicative of island migration are classified as transgressive. Bogue and Shackleford Banks are regressive islands. Topsail and Masonboro Islands can be considered to be transgressive barriers.

Currently a very common behavior of undeveloped barriers world wide, is island narrowing. That is, shoreline retreat is occurring on both sides of the islands. Shackleford Banks is a good example of this phenomenon. One interpretation of this behavior pattern is that the islands are responding to the current sea level rise and that island narrowing is a precursor of island migration which will occur when the islands are sufficiently narrow for efficient cross-island overwash to occur.

COASTAL PROCESSES

The natural processes operating to maintain the shape of the barriers along the Onslow Bay portion of North Carolina's shoreline are the same as they are elsewhere along the world's coasts, although the rate and dominance of the processes may differ. In addition to sea level oscillations and littoral drift, three additional processes affect the shape and positions of the barrier beach shorelines. These processes include inlet formation, migration and closure, oceanic overwash, eolian transport, and influence of underlying geologic framework. In addition to these natural processes, man's influence has had and will continue to have a negative effect on the islands.

Oceanic Overwash

Oceanic overwash characterizes barrier beaches with low tidal range and moderate to strong wave climate in a climatic zone of intense storms. Overwash is the process whereby sediment from the lower portions of the active beach zone are transported through breaches in the dune system to the back barrier environments during periods of storm surge and increased wave activity. These environments include the grasslands, marsh and open lagoons. Sand supplied to the island during major storms is used to maintain elevation and volume as the island retreats landward.

The depth of the overwash penetration (i.e., ocean to marsh distance) is determined by an array of site- specific characteristics such as island width, height, gradient and intensity of the storm (tidal surge, etc.). Overwash plays an important role in island migration and the overall sediment budget along the barriers. Overwash is also a major impediment to transportation on some low lying barriers such as Pea Island and Topsail Island. It can even be a threat to life when it prevents evacuation of storm threatened communities.

Inlets

Inlets form during storms when trapped soundside *water* overtops the narrowest and lowest areas of the barriers. Analysis of historic charts indicates there has been a general decrease in the number of inlets along the North Carolina coast during the past 300 years. During the seventeenth century, as many as seven additional inlets occurred between Cape Lookout and Cape Fear. The reason for this decrease is open to speculation but is probably related to storm cycles and the fact that the lagoons have infilled and hence have a reduced potential tidal prism.

Inlets vary in respect to size, tendency to migrate, and the number of years each remains open. One of the contemporary inlets, New Topsail Inlet, opened prior to 1738 and has migrated in a southwesterly direction. Bogue Inlet, one of the largest and most stable of the contemporaneous inlets in the Onslow Bay section, has been open and more or less in the same location since before the arrival of the first Europeans in the 1580's.

Following inlet closure, the flood tidal delta which occurs on the lagoon side of these inlets is preserved. Typically the flood tidal delta in microtidal regions is larger than the corresponding offshore ebb tidal delta. In the wide open water lagoons backing the Outer Banks, the tidal deltas are well-developed and commonly well-preserved. Some extend as much as 8 km into the adjacent sound. The flood tidal delta located on the landward side is an important inlet-related sand body for three reasons: 1) subsequent attachment to the barrier adds volume and elevation, 2) after inlet closure, it forms a substrate over which the barrier migrates, and 3) it is a mechanism for infilling the lagoon. The supratidal and intertidal portions of the abandoned tidal delta become colonized by salt marsh grasses. This combination of processes (migration and closure) effectively widens the island as the inlet migrates downdrift.

Many relict flood tidal deltas are readily discernible along the North Carolina Coast (Fisher, 1962). In the northern part of the state where the sounds are large and consist of open water, the principal geomorphic evidence is the vegetated flood tidal delta. In southeastern North Carolina, small, narrow elongate islands are found in the partially marsh-filled lagoons. These lagoon islands, indicative of former inlet locations, commonly parallel the main tidal channel, are usually vegetated, and may reach elevations of up to 3 m. Development of these features occurs in a zone where sands from the constricted flood tidal delta overtop the marsh during unusually high wave activity. Continued migration of the inlet leads to development of additional islands and subsequent preservation of earlier formed features (Cleary and Hosier, 1979).

Eolian Action

A variety of depositional and erosional forms associated with wind are observed along this segment of North Carolina's shoreline. These include small mobile sand sheets, medanos, and a variety of vegetated dunes, including natural foredunes, parabolic dunes, and man-made stabilized dunes. The nature and integrity of the dune system is dependent upon sand supply, island orientation, dominant wind direction, the extent of vegetation cover, and man's historical influences.

Factors which determine the dune morphology observed on the barrier islands include the density of vegetation; the wind regime; the degree of stabilization and the time since the most recent disturbance; the availability of sediments; and the position of the shoreline.

Islands or portions of islands where washovers are frequent, recent, or chronic, possess either no dunes or scattered foredunes which generally do not form continuous ridges. An example of this dune morphology can be seen on portions of Onslow Beach and Topsail Island.

Where overwash has occurred in the past, yet recovery has taken place, usually a single foredune ridge exists. This morphology can be observed along Topsail Island and Carolina Beach. These barriers are often narrow and susceptible to breaching during storms.

Several islands have a history of progradation resulting in the development of multiple parallel dune ridges. The shoreline is generally stable and possesses a dense vegetation mantle which is primarily responsible for maintenance of the structure of the dune system since its formation. Much of Bogue Banks possesses this dune morphology.

Where, for one reason or another, the vegetation mantle has been broken open or destroyed, massive dunes result. Generally, all or the majority of the former beach ridge dune system is destroyed and massive mobile dunes (medanos or parabolic) are formed. Bear Island and Browns Island exhibit this type of dune morphology. Portions of these dune fields are presently partially vegetated.

BARRIER SHORELINE OVERVIEW

Shackleford Banks

Shackleford Bank is an east-west trending island separated from Cape Lookout by Barden Inlet. Shackleford Bank was recently attached to Cape Lookout, however, a severe hurricane in 1933 opened Barden Inlet and Corps of Engineer dredging has maintained the channel since.

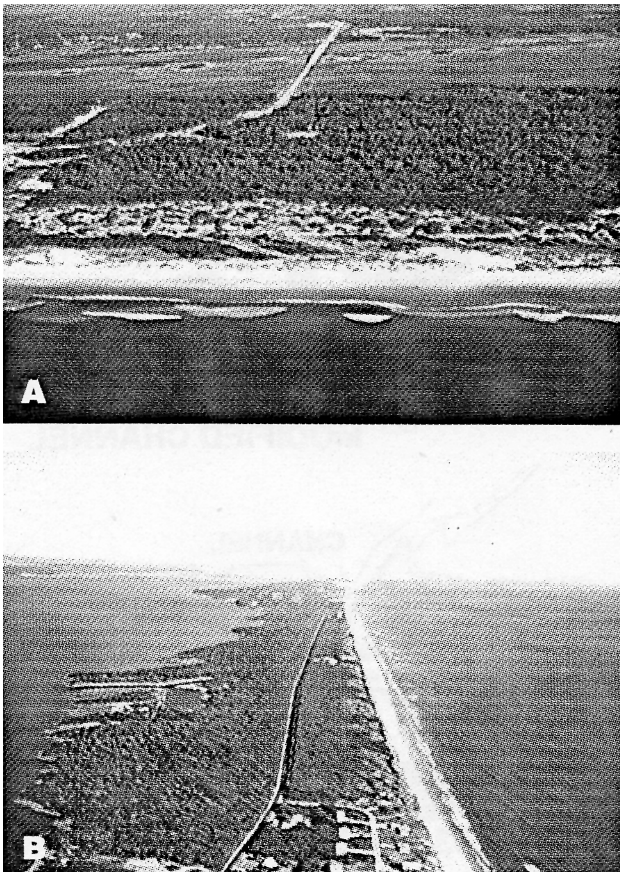


Figure 4. Bogue Banks aerial photographs (1974).
A. Forested beach ridges are typical of this regressive barrier. Parabolic dunes disrupt the dune line. Tidal marsh forms on the flood delta material.
B. An open water lagoon along much of the central section of the island indicates a lack of inlet activity.

Before the turn of the century, the western half of Shackleford Bank was heavily forested. A series of dune ridges indicating previous progradation was evident. Much of the island was probably similar to Bogue Banks as it is today. A combination of severe hurricanes, overgrazing by feral livestock, and human disturbance of the forest resulted in the disintegration of the vegetation mantle in the late 1800's and the subsequent migration of the dunes across the island. On the lower elevation, narrower eastern end, Shackleford is a washover island with a very high (perhaps 10 feet per year) rate of erosion near its eastern tip. On the western end, the migration of the dunes first slowed and then stopped before the forest was entirely overwhelmed. A 5 km long slipface marks the landward migration limit of the interior dunes on Shackleford Bank. Relict ghost forests were first engulfed and then re-exposed by the migrating dunes, providing evidence of the magnitude of the dune migration event. Large swales or 'slacks' have developed where dune blowouts occurred.

The western end of Shackleford Bank has been growing westward during the past 30 years. Since 1947, the island has extended more than 1000 m. This region is characterized by low scattered dunes generally in an arcuate or 'recurved' pattern. Fresh and brackish marshes occupy the low swales between arcuate dune ridges.

Unlike Core Banks, Shackleford Bank has had a history of habitation. In the mid-1800's, the town of Diamond City was located on the eastern end of the island. The inhabitants, numbering a maximum of 500, were fishermen and whalers; the island was used as a lookout for whales passing Cape Lookout. Hurricanes in 1899 devastated the island and Diamond City was abandoned. Remaining buildings were barged to Morehead City and Harkers Island. Today Core Banks and Shackleford Bank are part of the Cape Lookout National Seashore. The seashore development plan calls for maintenance of the islands in a near-wilderness condition.

Bogue Banks

Bogue Banks is the longest and widest island in the Onslow Bay section of North Carolina (Fig. 1). This may be the largest volume Holocene island on the US East Coast. Its large sand volume is indicative of a large sand supply in spite of the fact that the Onslow Bay shelf overall has a very thin sediment cover (Fig. 4A).

This beach ridge barrier island is approximately 45 km long and averages 600 m in width. Unlike the areas to the south, the lagoon behind Bogue Banks is generally open water (Fig. 4B). The lack of significant areas of tidal marsh suggests that inlets have not been active on an island scale in recent historic times. However, historic maps show isolated occurrences of old inlets at several sites. These areas include the low, narrow sites at Emerald Isle and at Atlantic Beach. At this last locality, the vegetated flood tidal delta of Cheeseman's Inlet (ca. 1850) now forms the site for extensive development (Atlantic Beach).

Bogue Banks, located on the low energy limb of the Cape Lookout foreland, is morphologically unlike the majority of islands in North Carolina. It is characterized by an extensive forested beach ridge system with isolated ridge elevations in excess of 12 m (Fig. 4A). This sequence of ancient dune ridges indicates a period of progradation. Recent studies indicate progradation began 3800 years B.P. (Steele, 1980; Heron, et al, 1984).

The island's fronting dune system is largely intact. Multiple or massive dunes are characteristic. Within these areas are sites of blowouts and migrating parabolic dunes. The initiation of these features was presumably due to fires, storms, and man, all of which destroyed the binding vegetation and permitted remobilization of the sand (Fig. 4A). A few areas do have a poorly developed dune system. In these regions, the dunes are low, narrow and scarped.

Overwash is not an important environmental parameter except in those areas where dunes are lacking or poorly

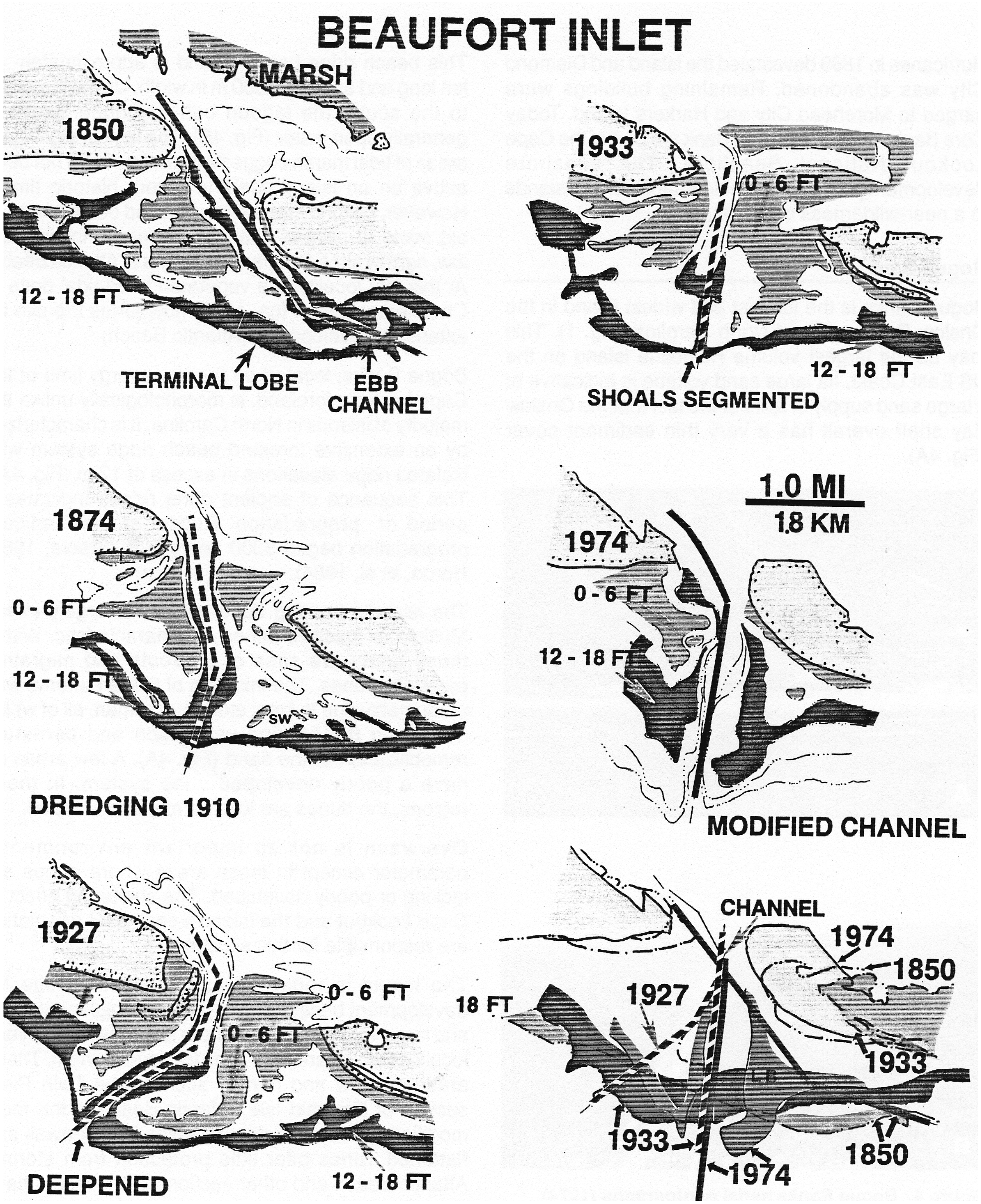


Figure 5. Beaufort Inlet line drawings. Line drawings from bathymetric charts depict channel and ebb delta morphologic changes. Dredging of the ship channel has resulted in a seaward growth of the ebb platform and significant volume losses.

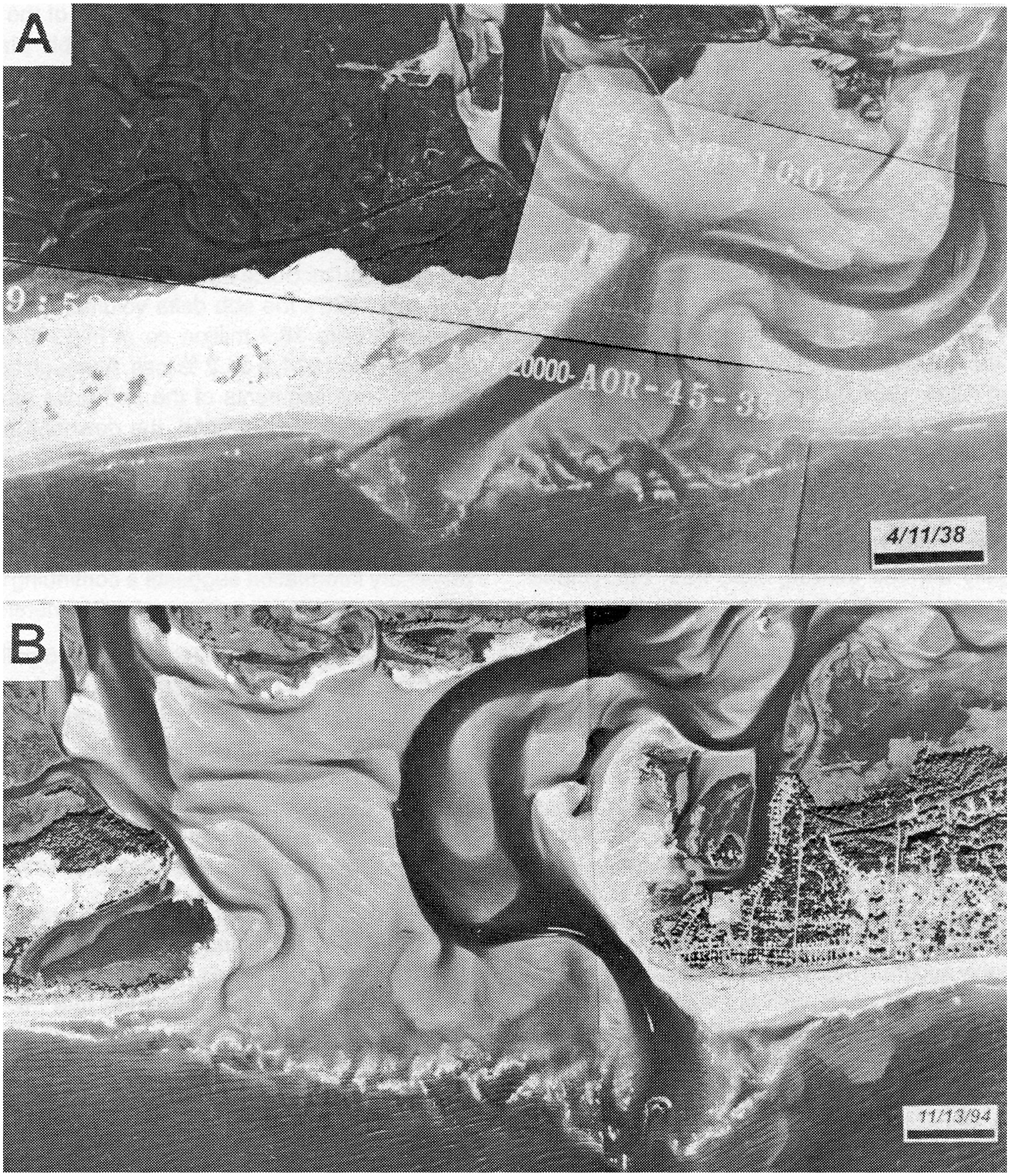


Figure 6. Aerial photographs of Bogue Inlet.
A. 1938. Ebb channel is located on western shoulder of the inlet. A large spit extended westward from Bogue Banks.
B. 1994. Channel reorientation and repositioning has occurred several times since 1940. Channel orientation dictates ebb delta symmetry and erosion patterns on adjacent barriers. Spit growth on Bear Island (left) began after breaching of Bogue Banks spit (see "A") and the concomitant relocation of the ebb channel.

developed. The sheltering effect of Cape Lookout and the island's east-west orientation are responsible for this situation.

The island is regarded as an excellent site for development because of its generally high elevations and large volume of sand. There are, however, several localities which are poor sites for development. These areas are low and narrow such as the Twin Piers section of Emerald Isle. Atlantic Beach is the most modified area due to development. The seawall and flattened dunes offer little protection from storms. Atlantic Beach and other sections of the island have been the recipient in recent years of several "free" navigation replenishment projects.

Beaufort Inlet located approximately 9 miles west of Cape Lookout serves as the connection between the Atlantic Ocean and Morehead City Harbor, North Carolina's second major port. The inlet is utilized by commercial and recreational vessels and is one of two inlets in southeastern North Carolina which have been modified for commercial traffic. The inlet forms the eastern border of Bogue Banks and separates the barrier from Shackelford Banks to the east (Figs. 3A & 5A-F).

Seismic data indicate the postion of the inlet is controlled by an ancestral drainage pattern that can be traced across the inner shelf. Historic maps that date to the early part of the seventeenth century confirm the existence of the inlet. Since the Colonial Period the inlet has served as an entry to the port of Beaufort (Stick 1958; Angeley 1982). Beaufort Inlet has remained in relatively the same location throughout its recorded history. The large tidal prism associated with the Newport and North Rivers that empty into the adjacent sound contribute to the stability of the inlet. A tidal prism of 3.4 x 10 9 cu. ft. has been empirically derived utilizing data from bathymeric surveys.

Prior to 1936, throat characteristics were quite variable. However over the past 60 years, since the channel has been in a fixed position, the inlet's cross sectional area has fluctuated very little, although the inlet's minumum width has decreased. During the same period, the average depth of the throat has increased as the navigation channel was deepened and widened. As a result, the inlet's aspect ratio *(wid)* has decreased markedly since 1952 as the inlet constricted and deepened with dredging.

Reasonably accurate bathymetric charts are available from 1839 to present and provide a means of tracking the changes in the inlet, shoal morpholgy and general shoreline movements. Data from these surveys indicate Bogue Banks has accreted 70 m in an easterly direction since 1839. By contrast, the Shackelford Banks margin has been extended to the west a net distance of 580 m. The dramatic changes on the eastern margin of the inlet are even more striking when one considers that the Shackelford Banks margin was relatively stable for 75 years, and since 1952 has extended 1,325 m in an westerly direction. Accretion on both shoulders has resulted in a constriction of the inlet. These changes over the last 50 years are primarily related to dredging of the outer bar channel. Since dredging of the fixed channel began, there has been a deepening and steepening of the profile and a generally lowering of the ebb platform (Fig. 5A-F).

Calculations involving changes in the volume of sediment stored in the 1854 ebb delta, indicate there was 37.4 million cu.m of sand contained in the shoals to depths of 6 m. Between 1854 and 1936, the ebb delta volume ranged from a low of 35.7 to a high of 43.3 million cu m. Since major dredging efforts began in the mid 1930's the ebb delta volume has steadily decreased from 36.9 million cu m in 1936 to 24.2 million cu m in 1974, a 34.2 % loss. Although both the east and west segments of the ebb delta have lost appreciable volumes of sand, the downdrift eastern lobe has lost 46 % or 8.4 million cu m since 1936. By contrast, the western lobe has lost 4.2 million cu m or 22 % during the same period. Studies are currently underway to determine the shoal changes since 1976. Preliminary information suggests a continuing loss of sediment amounting to millions of cubic meters.

A substantial portion of the total loss (12.5 million cu m) can be related to dredging activities which average 608,000 cu m/y. Tidal flushing of sediment beyond the ebb platform and into the estuarine system are additional mechanisms that can account for part of the loss. USACE data suggest storm events remove substantial quanties of sediment from the ebb delta, transporting it to the inner shelf (USACE 1976).

Bogue Inlet, a wave-dominated inlet, is one of North Carolina's largest inlets and is located at the mouth of the White Oak River (Fig. 1). Recent seismic studies of the adjacent continental shelf indicate the inlet's position is controlled by the paleochannel of the ancestral White Oak River (Hine and Snyder, 1985). The inlet is relatively stable, although the shallow gorge has migrated within a 2.4 km zone along Bogue and Bear Islands during the last 200 years.

Since 1938, the main ebb channel has changed its orientation and position several times. The consequence of this reorientation is the landward migrations of extensive packets of swash bars which weld onto the adjacent beaches (Figs. 6A&B). The large spit which extends in an easterly direction from Bear Island indirectly stems from the above mentioned cyclical reorientation.

Bear and Browns Islands

Bear and Brown Islands are 3.5 and 4.5 km long respectively. They average 600 m wide. They can be classified as altered beach ridge barriers (Fig.7). Large medano-like and parabolic dunes characterize major portions of both islands. The earliest aerial photographs (1938) show the majority of both island surfaces were covered by large sand sheets with little vegetation cover. The existence of large steep spillover

Figure 7. Bear Island (Hammocks Beach). Large eastward migrating parabolic dunes have grown in elevation and volume since the 1930's. Dune forms are end products of the remobilization of sand from the original forested ridges.

lobes in the adjacent lagoon provides evidence for the landward migration of the sand dunes.

Onslow Beach

In the vicinity of New River Inlet (Fig. 1) a submarine headland forms a small seaward bulge in the coastline of central Onslow Bay. This mid-compartment shoreline protrusion is produced by the Oligocene Silverdale Formation, an indurated moldic limestone and calcareous-cemented quartz sandstone unit. The Silverdale Formation crops out at or slightly below sea level in the mouth of the New River estuary. It occurs extensively on dredge spoil islands of the Intracoastal Waterway behind Topsail Island and Onslow Beach, and forms a series of bathymetric ridges on the inner shelf on either side of New River Inlet (Crowson, 1980; Riggs et al1995; Cleary et al 1996). Crowson mapped these prominent submarine rock features as a series of ridges that occur seaward of the lower shoreface, have steep landward-facing scarps with smooth surfaces that dip gently away from the beach, and have up to 5 m of relief above the surrounding ravinement surface. The ridges rise locally to about 5 m below MSL, higher than the elevation of the lower shoreface, which is high enough to cause refraction of storm waves and currents and possibly affect the patterns of erosion and deposition on the adjacent beaches.

The ridges are oriented at acute angles to the beach and intersect the shoreface on Topsail Island and Onslow Beach (Fig. 8). Core drilling by Cleary and Hosier (1987) demonstrated that the rock ridges :ontinue under Onslow Beach and into the back- barrier estuarine system. Similar limestone ridges pass beneath Topsail Island and into the back-barrier estuarine system (Fig. 9) (Clark et al., 1986) where the rock structures appear to be related to the occurrence and orientation of a Pleistocene bay barrier system.

The Oligocene submarine headland appears to subdivide these two barriers into coastal compartments that have different orientations and shoreface dynamics. The northern segment of Onslow Beach is characterized by a cuspate shoreline geometry with wide beaches, a recurved accretionary beach ridge system, a nearly continuous high foredune ridge, and shoreline accretion rates that average 2 *mi* yr

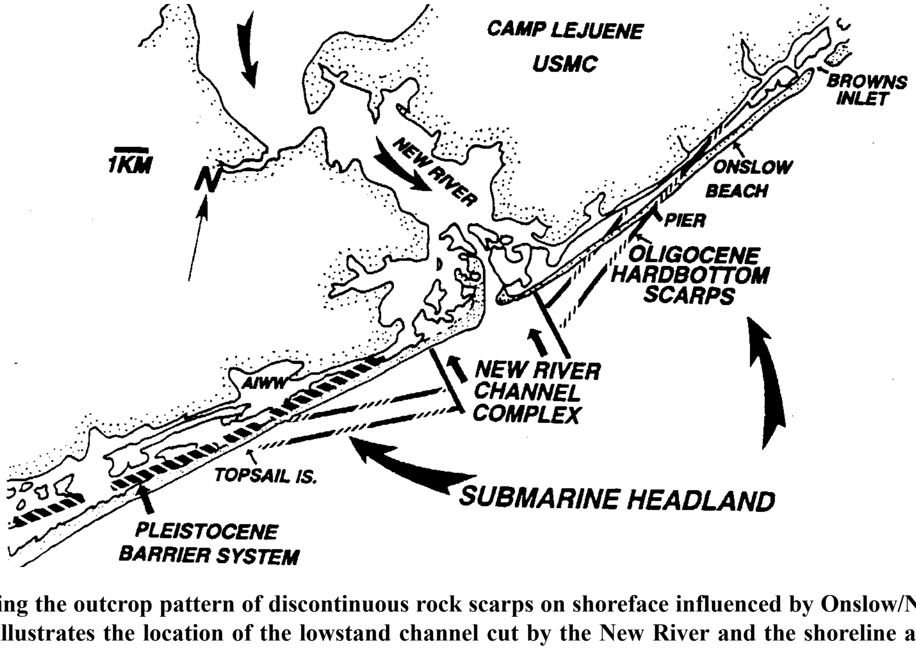


Figure 8. Map showing the outcrop pattern of discontinuous rock scarps on shoreface influenced by Onslow/New River submarine headland. Cartoon illustrates the location of the lowstand channel cut by the New River and the shoreline area where the ridges intersect the barriers (After Riggs et al. 1995).

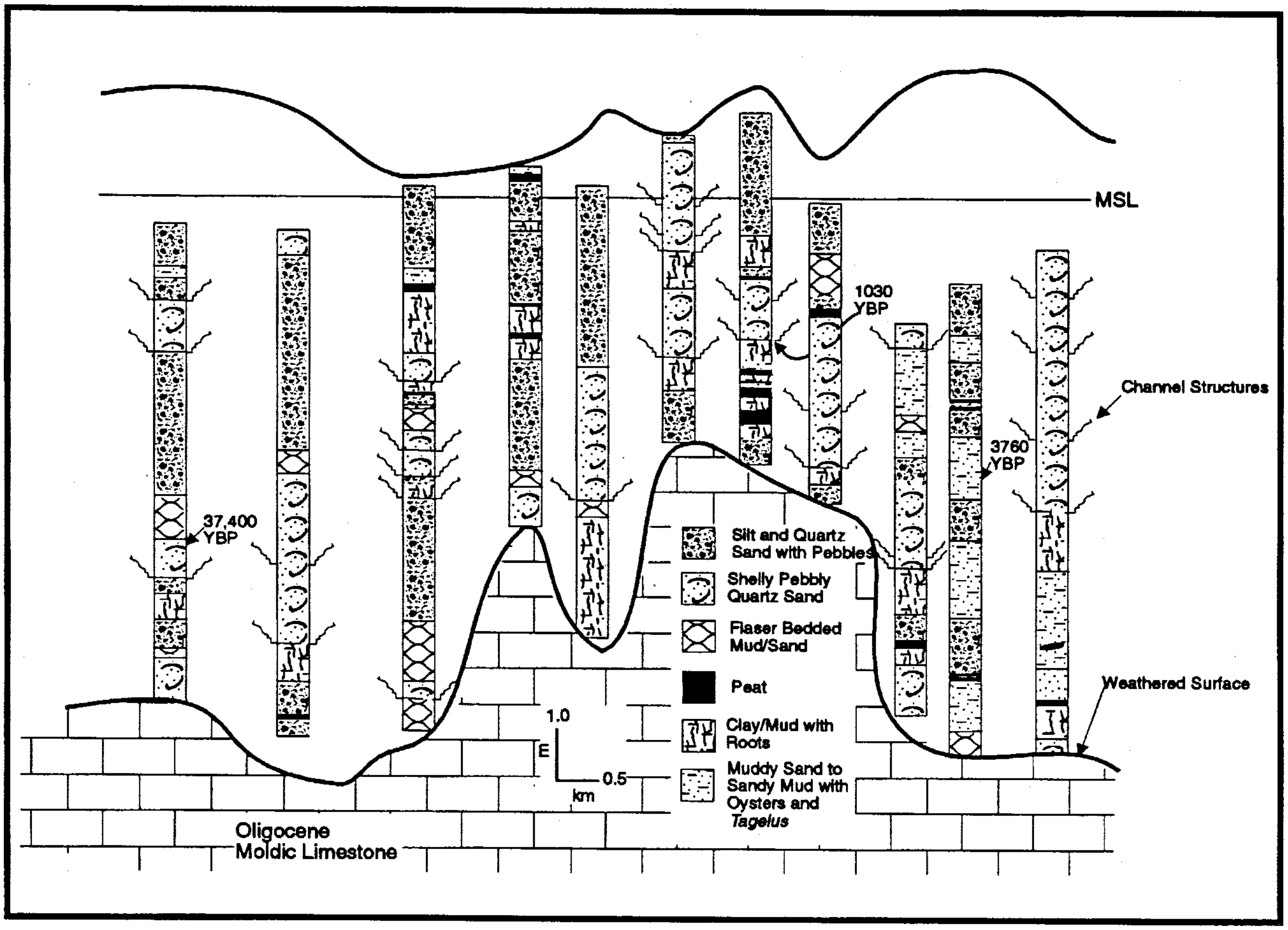


Figure 9. Shore-parallel cross-section along Onslow Beach based on continuous split-spoon cores. The two rock ridges rise to within 5 m below sea level and pass beneath the island. A variety of channel and estuarine units characterize the section recovered (after Cleary unpublished data and Riggs et al. 1995).

(Cleary and Hoiser, 1987). The ridges front a narrow marsh filled lagoon and are covered with mature maritime forest indicating old and stable topography (fig. 10A). Toward the central portion of Onslow Beach, the lagoons along the northern and southern segments narrow (Fig. 10B), and the barrier is perched on top of the limestone comprising the headland (Riggs et al 1995; Cleary et al 1996). At the narrowest width the limestone lies within 3 meters of the surface of the fringing backbarrier marsh (Cleary and Hosier 1987).

The southern segment of the barrier is characterized by a narrow beach strewn with gravel and a discontinuous dune system composed of isolated "haystack" dunes with numerous washover terraces extending into the marsh. The structure of the dune field is largely a result of the damage caused by the numerous manuvers and operations of the U.S. Marine Corps. Staging and landing operations involving Marines and heavy equipment including tanks and large "airboats" have been carried out for decades. Current erosion rates approach 6 m/yr.

Active bioerosion of rock scarps represent a major source and supply of "new sediment" to the adjacent beaches. Abundant gravel, up to boulder-size grains, is derived from the rock scarps and lower shoreface. and delivered to the beach during storms where it is rapidly broken down to sand-sized grains in the surf zone (Crowson 1980; Cleary and Hosier 1987; Riggs et a11995; Cleary et al1996).

The highest erosion rates characterize the area immediately updrift of New River Inlet. The southernmost portion of the barrier is currently undergoing very rapid eosion (Fig. 11). Changes in the symmetry and volume of sediment stored in the fronting ebb delta have accelerated the erosion. The erosion scenario is complicated due to the large number of factors involved. The slow southward migration of the inlet coupled with the dredging activities since the mid 1960's are major contributors to the rapid recession of the shoreline at the southern end of the island. Since 1960 there has been a dramatic change in the offset pattern of the shoulders bordering the inlet. Currently the Onslow Beach shoulder is eroding rapidly while the Topsail Island shoulder is

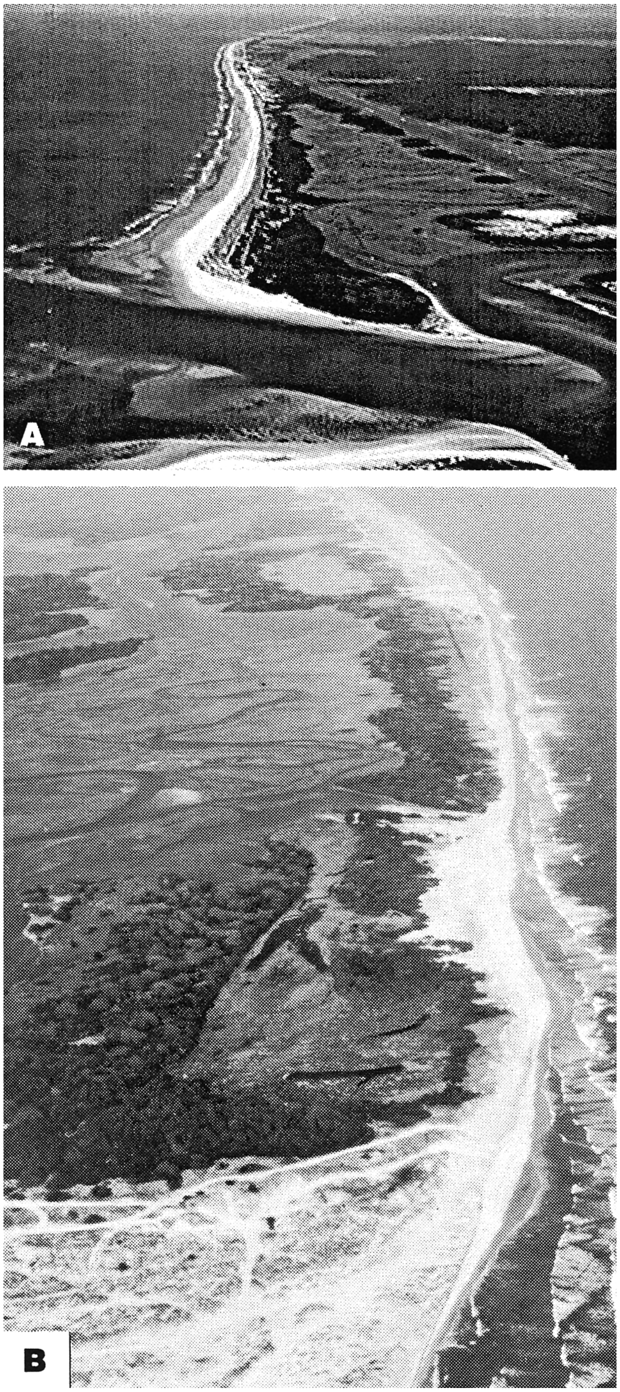


Figure 10. Onslow Beach
A. Oblique aerial view looking southwest from Brown's Inlet. The marsh filled lagoon narrows to the south where the limestone ridges rise to within 3 m of the marsh surface. Accretionary dune ridges are evident in photograph.
B. Oblique aerial view looking northeast from New River Inlet. The lagoon widens to the south towards New River Estuary. Pleistocene estuarine fill underlies much of the southern portion of the barrier. This area has undergone considerable recession during the past 30 years. Overwash is the dominant process involved in the barrier's translation.

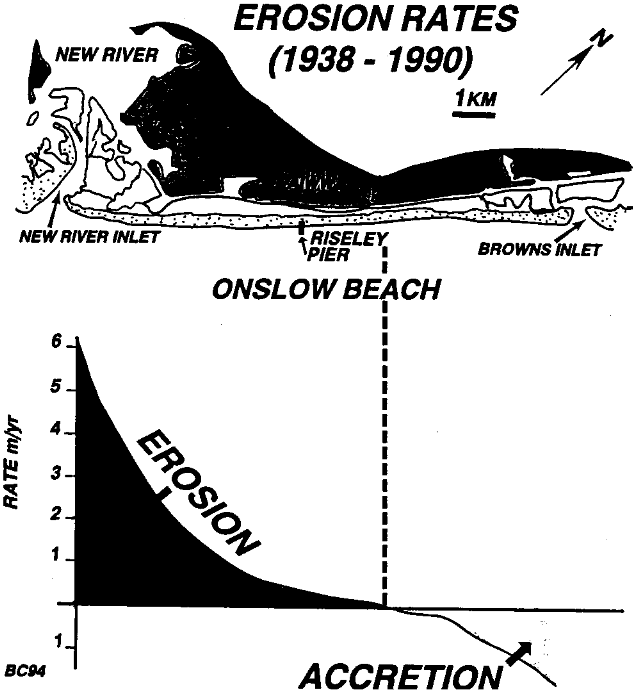


Figure 11. Map depicting the erosion rates along Onslow Beach (after Benton et al. 1993). Short term rates are much higher along the southern segment. Modification of New River Inlet plays a key role in the erosion updrift on Onslow Beach.

accerting slowly along a one and a half kilometer segment downdrift of the inlet (Cleary 1994)

Topsail Island

Topsail Island is the second longest barrier island within the Onslow Bay section of North Carolina. The island is bordered by the New River Inlet to the North and New Topsaillnl,et to the south (Fig. 1). The island is approximately 40 km long and averages approximately 280 m in width. The northeast- southwest barrier orientation exposes the island to frequent winter storms.

Studies by the US Army Corps of Engineers have shown that, between 1856 and 1933, the northern half of the island was eroding at an average rate of 0.40 m/yr while the southern portion had alternating sections of accretion and erosion. Data from the period 1933 to 1980 indicate a slight increase in the erosion rate (0.70 m/yr) for the northern half, while the southern segment was characterized by sections of both accretion and erosion.

Topsail Island is situated in a severe or chronic overwash zone (Fig. 12 A-E). Storms during the period 1944 to 1962 and in the late 1980's were particularly devastating to the island. Hurricane Hazel (1954) and the Ash Wednesday storm (1962) caused significant damage. Hurricane Hazel destroyed 210 out of 230 buildings and generated a 2.9 m above MSL flood level on an island whose average elevation

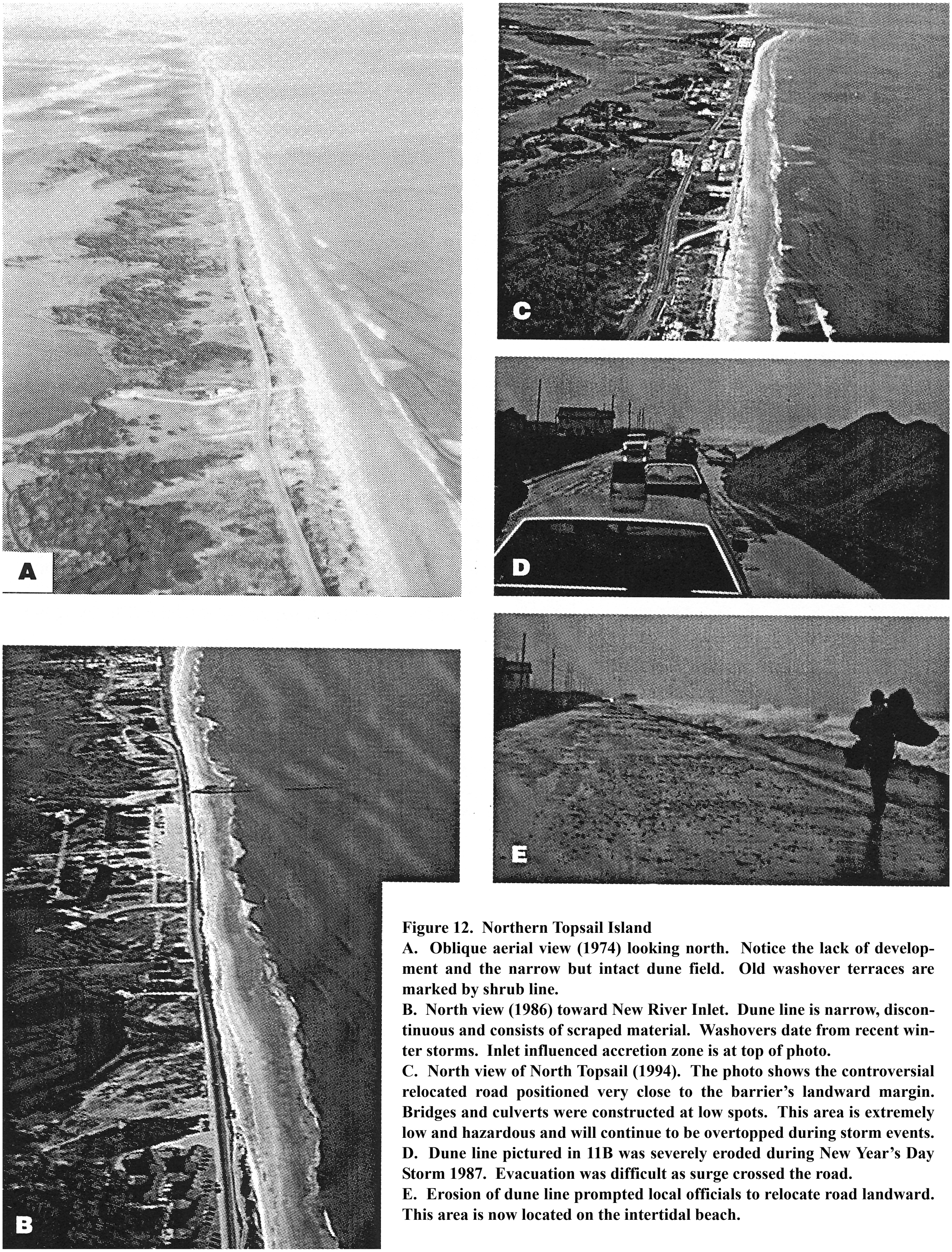


Figure 12. Northern Topsail Island

A. Oblique aerial view (1974) looking north. Notice the lack of development and the narrow but intact dune field. Old washover terraces are marked by shrub line.

B. North view (1986) toward New River Inlet. Dune line is narrow, discontinuous and consists of scraped material. Washovers date from recent winter storms. Inlet influenced accretion zone is at top of photo.

C. North view of North Topsail (1994). The photo shows the controversial relocated road positioned very close to the barrier's landward margin. Bridges and culverts were constructed at low spots. This area is extremely low and hazardous and will continue to be overtopped during storm events.

D. Dune line pictured in 11B was severely eroded during New Year's Day Storm 1987. Evacuation was difficult as surge crossed the road.

E. Erosion of dune line prompted local officials to relocate road landward. This area is now located on the intertidal beach.

Figure 13. Surf City. Surf City is located along the south central portion of Topsail Island. The town is sited within a former inlet zone (Stumpy Inlet, 18&19th c.). Finger canals dredged in the 1960's are sited on the former flood delta. The entire area is low and fronted by a relatively narrow dune field. The area is prone to overtopping.

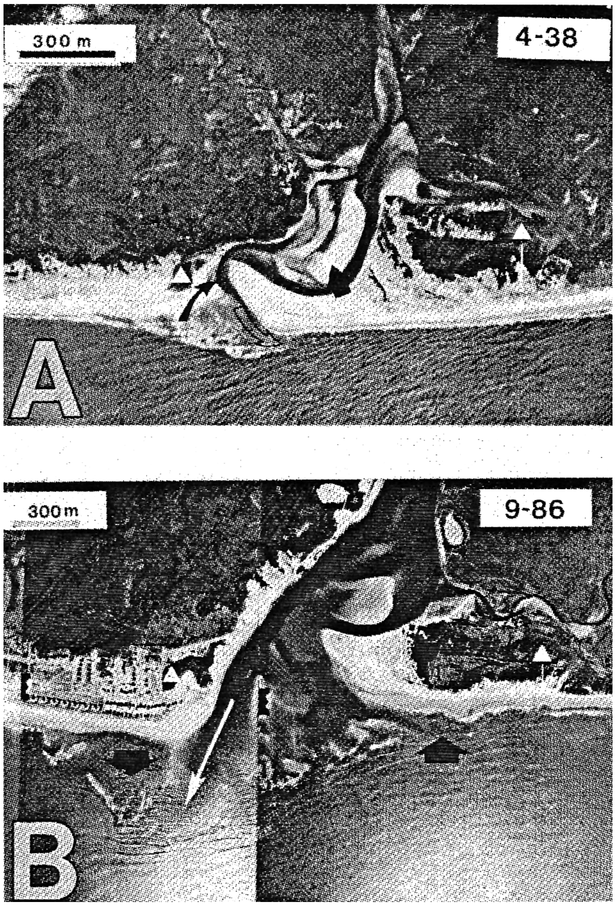


Figure 14. Aerial Photographs of New River.
A. 1938 the inlet was narrow and choked with sediment. The retention capacity of the ebb delta was limited due to the small tidal prism.
B. 1986 photograph illustrates the enlarged throat and ebb delta. Since maintenance dredging began in the early 1960's, erosion has accelerated on Onslow Beach while accretion has occurred along a 1.5 km stretch of Topsail Island. Note offset, compared to "A".

is 2.7 m MSL. Hazel also removed 650,000 m3 of sand from the beaches at Topsail Beach and Surf City. Some of this sand was transported across the island toward the sound and marsh in the form of washover fans. The grasslands and dune fields rest upon washover fan and terrace sediments. The crenulate border of the shrubs marks the landward edge of the overwash fans/ terraces (Fig. 12A) .

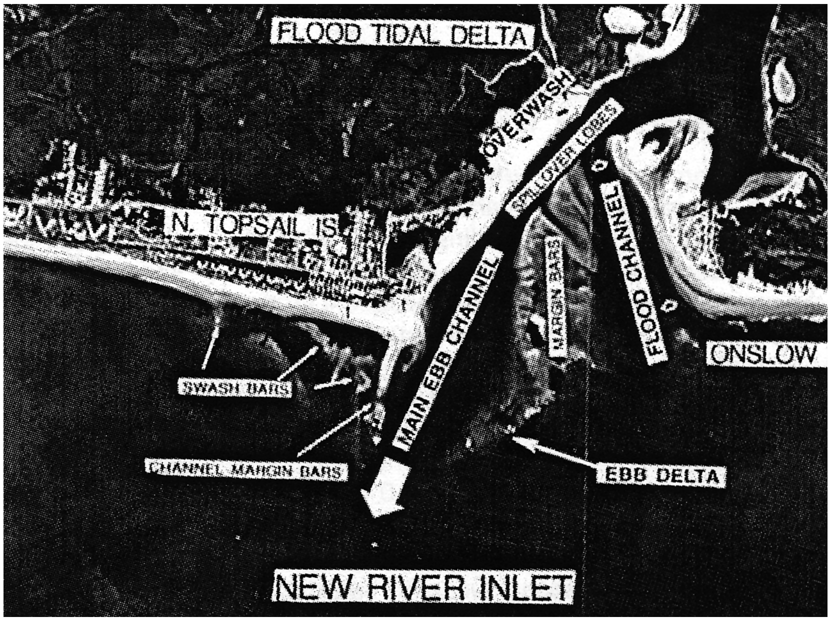
The dune system along most of the island is generally a single foredune often scarped and in some places discontinuous (Fig. 12A&B). Some areas do have massive or multiple dunes, such as the small one kilometer segment downdrift of New River Inlet area and portions of areas in the southern section (NC State Route 210 to Paradise Pier).

Three inlets have affected the morphology and sedimentation along Topsail Island since 1800. These are New River, Stump and New Topsail Inlets. Stump Inlet opened and closed in the mid-1800's. The extensive vegetated flood tidal delta of this inlet is now the site of Surf City. This area is low and prone to overtopping (Fig. 13).

New River Inlet which forms the northern boundary of Topsail Island fronts the largest coastal plain estuary in the Onslow Bay compartment (Fig. 1). The position)f the inlet is controlled by the location of the ancestral channel of the river system. Cores, seismic data and 'he distribution of outcrops on the innershelf indicate the paleochannel is incised into the Silverdale Formation. As a result of this incision, the shallow inlet las migrated within a 3.0 km zone along Onslow 3each and Topsail Island.

The hydrodynamics of this inlet were changed :considerably by the dredging of Atlantic Intracoastal Waterway (AIWW) and the channels connecting the 3stuary with the open ocean. The earliest photographs [1938) and charts indicate the inlet and the main channels were clogged due to

Figure 15. Aerial photograph (1986) of New River area. The dune ridge complex on Topsail Island began to develop in the early 1960's. The road landward of the multi-unit structures represents the 1960 shoreline. Accretion is related to the welding of swash bars and impoundment within the natural fillet on the downdrift side of the inlet. Ebb surge is likely to breach the Onslow Beach shoulder prompting a change in the erosion pattern.



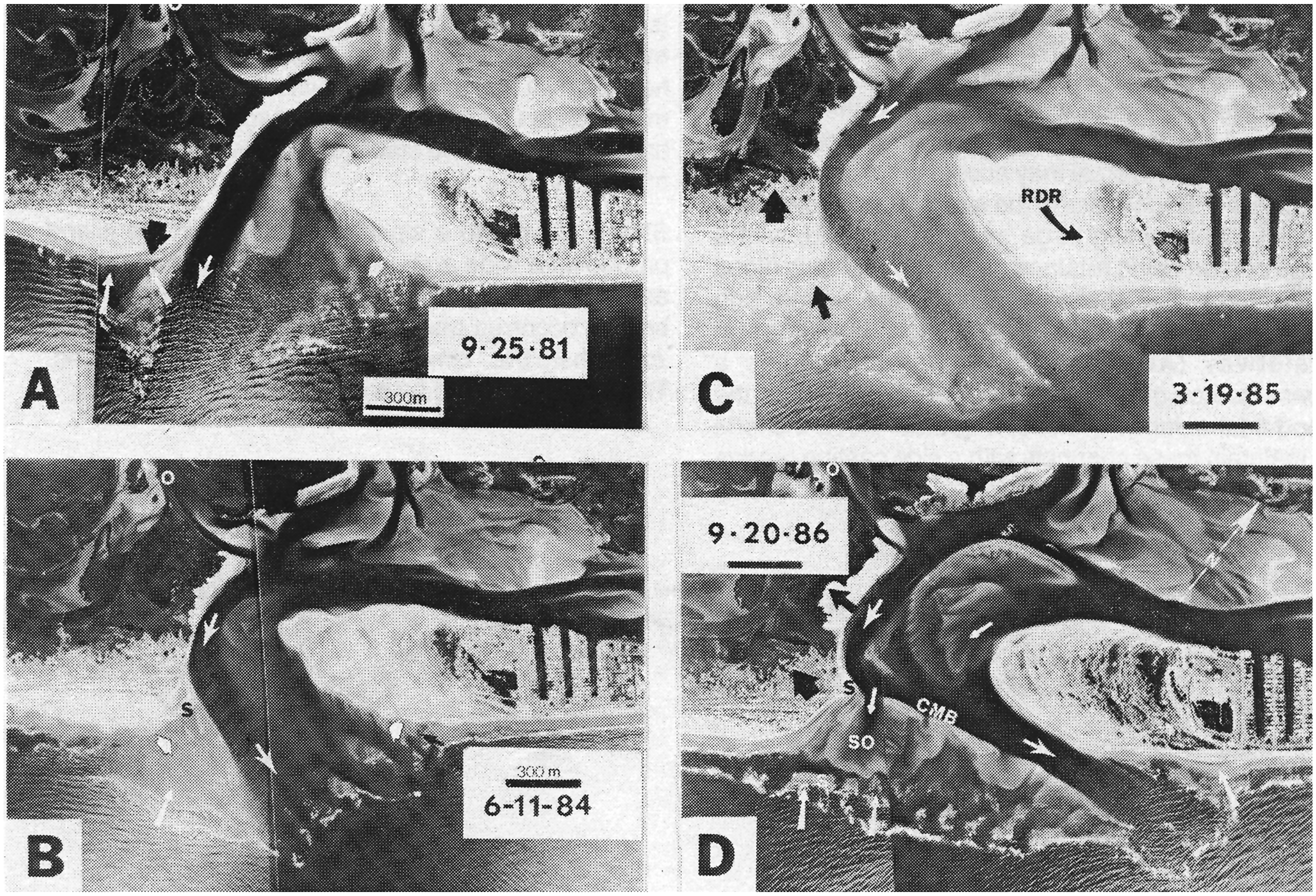


Figure 16. Aerial photographs depicting morphological changes in the ebb delta and a portion of an ebb delta breaching cycle. Symmetry changes are determined by channel orientation and position (A-D). Erosion or accretion commences as breakwater effect of ebb delta is altered. Breaching of the ebb delta bypasses large quantities of sand to Topsail Island. The stage is set for such an event in "D".

reduced tidal flow. In 1940 a 3.7 km long navigation channel was dredged connecting the Waterway with the inlet. The early 1960's marked the advent of sidecast dredging of the throat and outer bar channel for navigation purposes. Following dredging operations, the once small ebb tidal delta increased in areal extent from approximately 140,000 m^2 to 700,000 m^2. Due to the increased tidal prism, the volume of sand retained in the ebb delta increased by almost 50 percent (Fig 14 A&B).

Continuous southerly migration coupled with the dredging of the throat and outer bar channel has produced an ebb delta that is highly skewed toward Topsail Beach. In response, the Topsail Island shoulder has prograded 40 m since 1959. Accretion associated with the inlet extends along a 1.5 km zone and represents the only segment along the northern end of the barrier experiencing progradation (Fig. 15). Due to the repositioning of the ebb and flood channels across the asymmetric ebb delta, there has been significant changes in the seaward offset pattern of Topsail Island. All of the multi-unit dwellings along the northern end of the island are sited seaward of the 1960 shoreline. A breach of updrift Onslow Beach across the narrow spit will result in repositioning of the ebb delta and a concommitant recession of the former accretion zone (Cleary and Hosier 1987; Cleary 1994; Cleary 1996).

The large semi-circular pond on the northern end of the island marks the former location of the southern shoulder of the inlet in the early 1900's. The inlet is likely to re-occupy this location if the present trend continues.

New Topsail Inlet (Fig. 1) separates Topsail Island to the northeast and Lea Island to the southwest. Historic coastal. charts and maps indicate this inlet existed as early as 1738. Since 1738, New Topsail Inlet has steadily migrated to the southwest, a distance of approximately 10.0 km. During the period 1856-1963 the inlet migrated 1830 m to the southwest at an average rate of 19.2 m/yr. Migration rates of 35 m/yr have characterized the inlet over the last few years (1963-1994).

Inspections of controlled aerial photographs from 1938-90 suggest the inlet cross-section has been asymmetrical, with the gorge positioned close to the Lea Island shoulder during the majority of the period. As is commonly the case with inlets in this region, the orientation of the main ebb channel across the ebb tidal delta platforn changes on a cyclical basis, dictating the patterns of erosion/accretion on the adjacent shoreline (Fig. 16 A-D).

Extensive beach front development on the southern end of Topsail Island began in the early 1950's. The cottages and motels which date from this period were constructed on the primary dune which paralleled the recurved portion of the southwesterly extending spit. Between 1950 and 1975, Topsail Island's southern most 1500 m assumed a pronounced bulbous shape. This shape historically has been a by-product of: 1) the reorientation of the ebb channel across the ebb tidal platform which afforded protection to the adjacent shoreline, and 2) the location of swash bars welding onto the Topsail Island spit (Cleary 1994). As New Topsail Inlet migrated, the bulbous portion also reformed to the southwest in accordance with the position of the inlet. This resulted in a realignment of the trailing shoreline {Fig. 17).

The chronic erosion which currently characterizes this area {Fig. 18), stems predominantly from the recession of the primary recurved dune line as the inlet has migrated. Also, reorientation of the main ebb channel to the east-northeast has caused subsequent erosion of a portion of the updrift shoreline. Erosion of oceanfront lots associated with New Topsail Inlet migration and spit elongation has been accelerated by the occurrence of nor'easters and hurricanes. Figure 19 depicts the changes which took place in response to these processes over a 10 year period. Shoreline recession in this region amounted to over 110 m during the 10 year period {1972-1982). The erosion rates have decreased during the past decade.

A recent study by the US Army Corps of Engineers shows the predominant direction of sand transport is to the north; between 55 and 60% of the total drift moving in a northeasterly direction. These data are in contrast to findings of earlier studies. Also, it is difficult to resolve these data

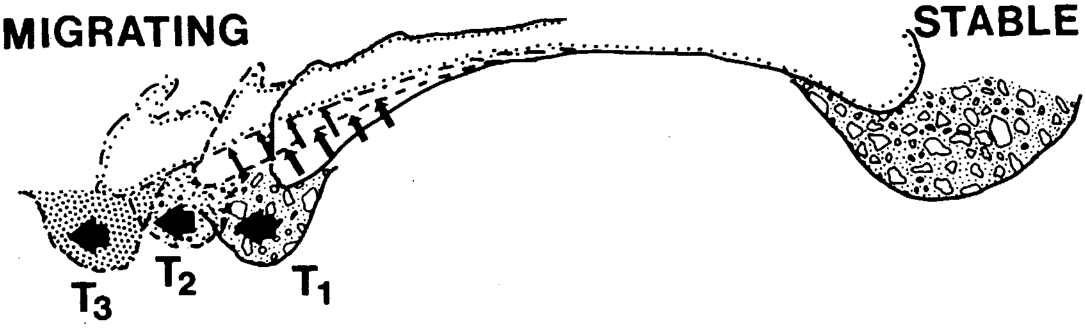


Figure 17. Trailing barrier realignment. Cartoon illustrates erosion of the updrift barrier shoreline is a consequence of inlet migration and associated planform changes.

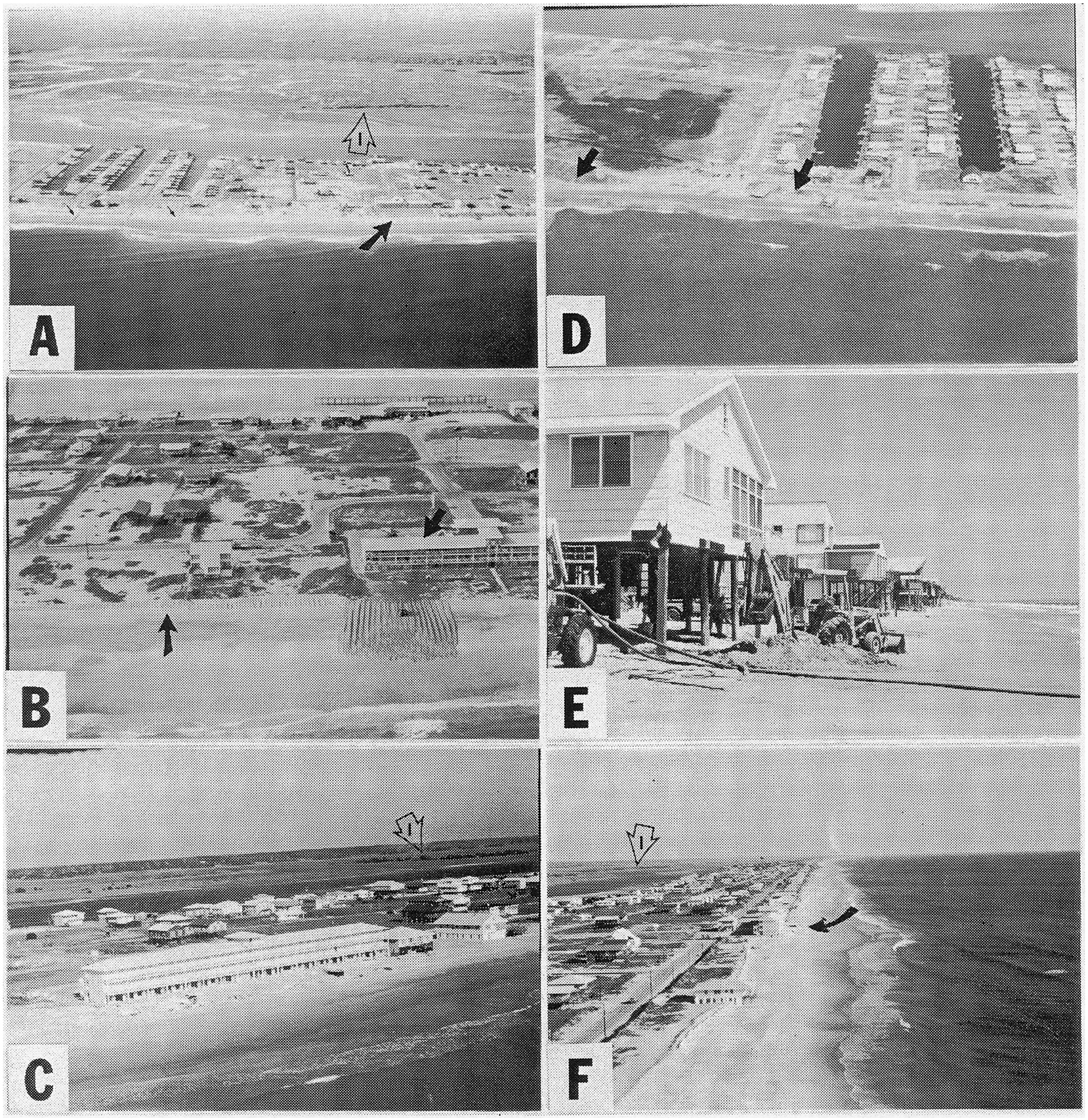


Figure 18. Erosion at Topsail Beach.
A. December 1974 photograph. Development began in the 1960's. Canals were dredges in 1969. Sea Vista Hotel (arrow) was completed in 1970 and was fronted by 130 m of uplands. Nylon bags were emplaced in 1972. Marsh islands (open arrow) representing former locations of the inlet are seen in the lagoon.
B. December 1978. The remaining single dune ridge was eroded by late 1978. Beach scarping followed.
C. December 1984. High water line has recessed over 130 m. Sand bags were emplaced to halt erosion of the hotel.
D. December 1984. Many of the homes located to the south of the Hotel were badly damaged due to erosion associated with shoreline realignment and storms. Shown are homes built along recurved dune ridges. Note truncations of ridges.
E. December 1984. Winter storms accelerated the erosion along much of south Topsail Island.
F. April 1986. North view of realigned shoreline with scarped grassland. No dune field exists. Sea Vista Hotel is marked by black arrow. A number of structures along this section were destroyed or relocated. The southern 5 km of the beach has been replenished several times with sand from the adjacent flood delta. Erosion and overtopping is likely to continue in this area.

with the fact that the inlet has migrated to the southwest over historical times. Localized drift reversal may account for the trends but it is unlikely. Regardless of the sand transport direction, the inlet is retaining large amounts of sand, with a large portion being retained on the inner shoals {flood tidal delta). The rapid shoaling in the sound side channels connecting the Atlantic Intracoastal Waterway {AIWW) and the open ocean is a consequence of the southwesterly movement of the flood tidal delta as the inlet migrates. Recent efforts to maintain these channels with a side casting dredge have met with little success.

Lea Island

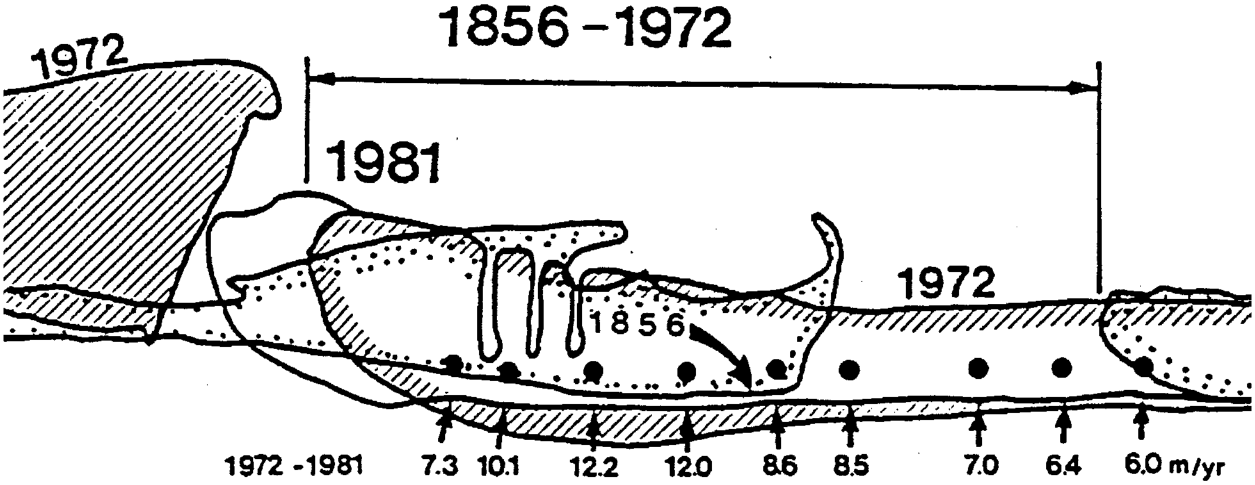
Lea Island is the shortest island in the chain between Cape Lookout and Cape Fear. It is approximately 2.5 km long and averages less than 200 m in width. Less than 8 % of the island has been in continuous existence for 50 years.

Old Topsail Inlet, the island's southern boundary is very shallow and is nearly closed. The lagoon, landward of this inlet, is choked with reworked sand shoals associated with the migration of the inlet. Data indicate that New Topsail Inlet is 'pirating' a portion of the tidal prism of Old Topsail Inlet. Much of Lea Island has been overtopped by major storms which have approached the area. As a result, overwash related physiography is dominant. The few large dunes which once existed were found on the north part of the island near New Topsail Inlet.

Coke Island

Coke Island, located immediately to the south of Lea Island, is an undeveloped 4.5 km long, 180 m wide, overwash-dominated barrier. Since 1938, the island has lost over 900 m of its shoreline due to the southerly migration of Old Topsail Inlet. The southern end of the barrier has remained stable due to the relative stability of Rich Inlet.

Storms have had a significant impact on the island producing a wide array of washover-related features and the opening of a short-lived inlet in 1959. This breach occurred about 2 km north of Rich Inlet in a zone where the 18th century Sidbury Inlet was located. This area is marked by a linear marsh island.



Dates	Amt.	Rate
1738 - 1986	9450 m	38 m/yr
1856 - 1963	2070 m	19 m/yr
1963 - 1981	680 m	34 m/yr

Figure 19. Shoreline erosion updrift of New Topsail Inlet. Cartoon depicts shoreline positions in 1972 and 1981, inlet positions in 1856 and migration rates. Maximum erosion rates were recorded at the 1972 position of the shoreline bulge, north of the finger canals. Erosion is a result of planform adjustment (modified in part after USACE 1990 and Cleary 1994).

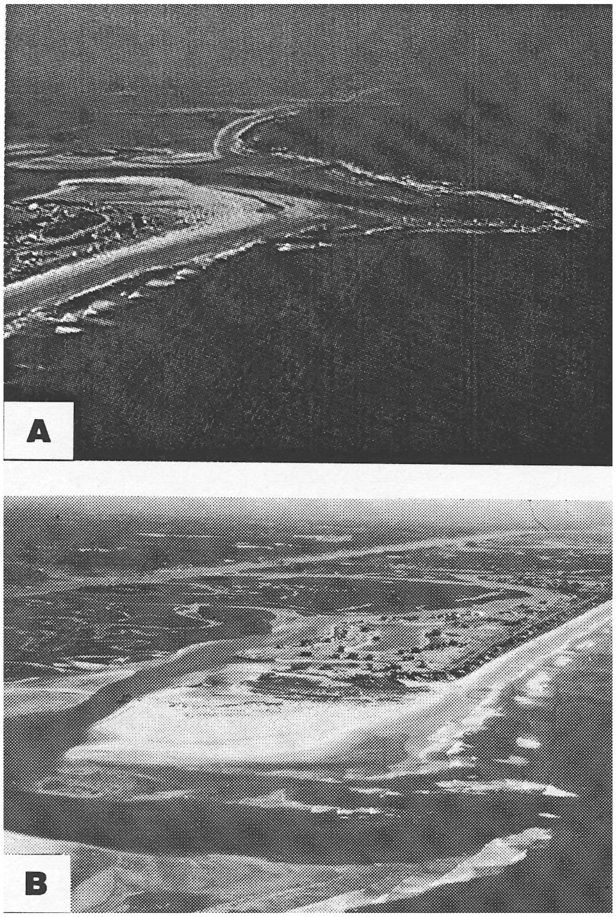


Figure 20. Figure Eight Island and adjacent inlets.
A. Rich Inlet, a stable inlet forms the northern border of Figure Eight Island.
B. Mason's Inlet a small migrating system borders Figure Eight Island to the south. Note the straightened shoreline updrift of the inlet.

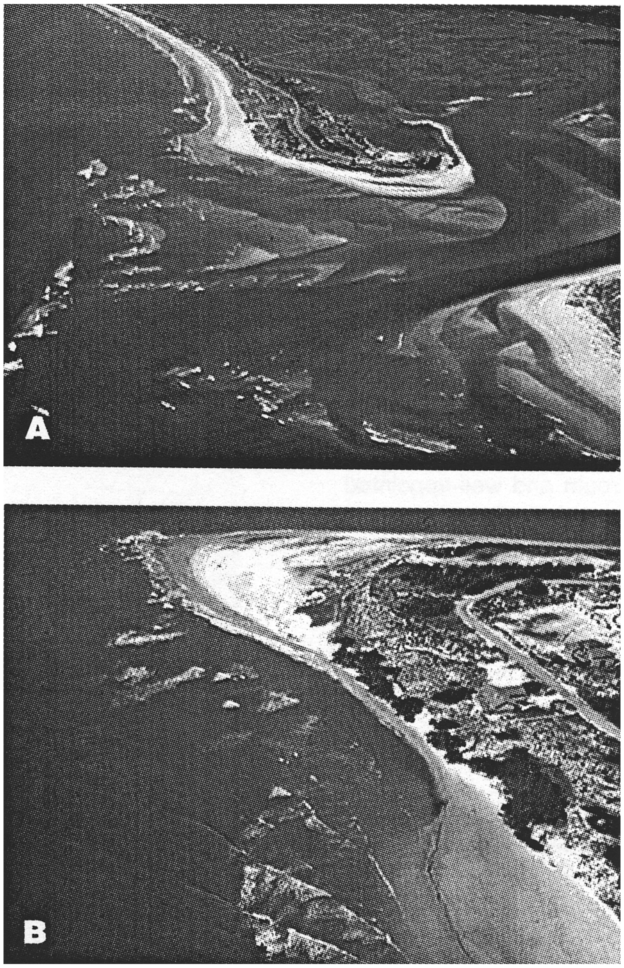


Figure 21. Rich Inlet Erosion.
A. Ebb channel is shore-normal and flanked by wide flood channel on Figure Eight shoulder. Encroachment of marginal flood channel onto south shoulder is prompted by deflection of ebb channel.
B. Welding and migration of attached bars produced temporary erosion in lee of sandbar. Sand packet eventually moves into estuary and accretion commences. Erosion rates were as high as 2 m/day for six weeks time period in mid 1984. Area is now fronted by a 200 m wide intertidal beach.

Figure Eight Island

Figure Eight Island is a narrow 6.5 km long island separated from Coke Island by Rich's Inlet and from Wrightsville Beach/Shell Island by Mason's Inlet (Fig. 20 A&B). The island exhibits two distinct physiographic sections. The northern half of the island is narrow, yet possesses a high, continuous, basically single, forested dune ridge. Toward Rich's Inlet, the island is offset seaward from Coke Island. The offset consists of a series of parallel dune ridges which undergo erosion or accretion as the ebb tidal shoals of Rich's Inlet change (Fig. 20 A). Rich's Inlet has shown little tendency to migrate, however, the cyclical re- orientation of the ebb channel can produce very rapid erosion on adjacent shorelines (Fig. 21).

Several 'marsh islands' are evident in the -lagoon behind Figure Eight Island (Fig. 20 B). These islands are characteristically narrow linear areas of higher elevation with the long axis of the island parallel.to the seaward barrier island. These islands form landward of an inlet where flood tidal delta sands overtop the marsh. The higher ground is occupied by less salt tolerant plant species, including various shrubs and trees. As an inlet migrates and/or closes, a chain of islands is preserved within the marsh. Thus, these islands can be used as indicators of the location of historic inlets in areas where lagoons are infilled with marsh. Several good examples of marsh islands are found in the lagoon behind Figure Eight Island.

The southern section of Figure Eight Island exhibits a generally low, washover, inlet-influenced shoreline (Fig.

20B). A large recurved foredune marks the historic northern limit of Mason's Inlet. Sequential aerial photographs show that the inlet has migrated more than 100 m since 1938. Bwfore construction of homes began along this section of the island in 1970, sand dredged from the sound side of the island was deposited on the berm. Erosion along the southern half of the island was inconsequential until Mason's Inlet re-initiated a rapid migration to the south. Similar to events at Topsail Island, migration of the ebb channel of Mason's Inlet removed protecting bars of the ebb delta and exposed the southernmost section of the island to erosion. Despite the positioning of large sandbags to form a protective seawall and subsequent nourishment of the intertidal beach, erosion continues to threaten homes. Since the island is privately owned, the landowners themselves, not the Federal Government, are responsible for re-nourishment. Several renourishment projects have attempted to mitigate the chronic erosion. An additional phase is planned for late 1996.

Wrightsville Beach and Shell Island

Wrightsville Beach is a 7.3 km long developed barrier island located east of Wilmington (Fig. 1). Because of its proximity to the city of Wilmington, it was one of the first barrier islands in North Carolina to be developed as a resort. Bath houses and summer cottages built in the 1860's were serviced by a trolley line that was completed in 1889 (Fig. 22 A-C). This trolley ran a distance of 11 km from Wilmington across the adjacent sound.

Along much of the length of the island, one can see examples of man's interference with natural shoreline processes. Compilation of data from aerial photographs, cores, and historical charts show that all of the island rests on inlet fill. Moore's Inlet, now closed (in the vicinity of the Holiday Inn), was the major inlet in the area during the past century (Fig. 23 A&B). As late as 1920, an inlet was located in the vicinity of Mercer's Pier. Today, much of the marsh north of the pier rests on tidal delta sands.

Masonboro Inlet (Fig. 1) to the south became a prominent inlet when Moore's Inlet began to close naturally in the late 1940'5. It too, has influenced lagoon sedimentation and has migrated over a distance of more than 2 km.

Early photographs (1915-1920) show that the northern portions of Wrightsville Beach had large elevated dunes and a wide island profile. To the south the island *Nas* very narrow and low. In order to create more 91evated land, Waynick Boulevard, the road parallel :0 Banks Channel, was built over tidal marsh in the 1930'5 (Fig. 24).

Erosion on Wrightsville Beach is not a new problem. From the earliest attempts at building along the oceanfront, erosion problems have existed (Fig. 25). For example, between 1923 and 1939, more than two dozen concrete and timber groins were emplaced along the shoreline in an attempt to halt erosion. The first attempt at replenishing the sand lost to erosion occurred in 1939, when 535,000 m3 of sand were pumped onto the beach (US Army Corps of Engineers, 1982).

Between 1944 and 1965, four major hurricanes (including Hurricane Hazel, 1954) and a number of winter nor'easters resulted in significant shorefront erosion. In 1965, the Wrightsville Beach Erosion Control and Hurricane Protection Project was constructed along 4515 m of ocean shoreline which extended north from the Masonboro Inlet jetty (Fig. 26 A&B) to the town's northern limit.

Additional sand was pumped onto the shore to close Moore's Inlet, located 450 m north of the town (Fig. 23 A&B). In all, a total of 2,280,000 m3 of sand was placed on Wrightsville Beach. Subsequently, the town annexed the 762 m section north of its original corporate limits which included Moore's Inlet.

Between 1938 and 1965, Moore's Inlet migrated along a 1.5 km section of Wrightsville Beach and adjacent Shell Island. Historic aerial photographs, maps, and charts show this inlet affected the shape of the adjacent barrier island beaches by producing a convex shoreline protuberance immediately adjacent to the inlet (Fig. 23 & 26 A&B). This bulge is common along inlet influenced shorelines where sand packets in the form of swash bars from the protective ebb tidal delta are welding onto adjacent beaches. The end result is a shoreline which curves seaward.

Following the artifical closure of Moore's Inlet (1965), the building line and roads along the new northern corporate limits were extended and basically paralleled the pre-closure curved shoreline. Much of the erosion along the restored northern part of Wrightsville Beach stems from the relict convex shape of the restored shoreline (Fig. 27).

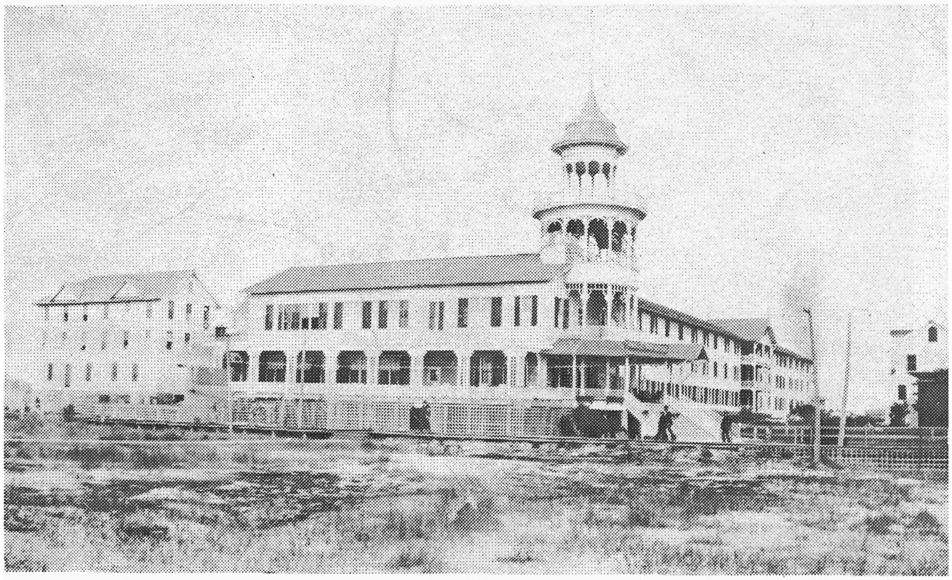
Evidence for rapid erosion along the newly annexed portion of Wrightsville Beach fronting Moore's Inlet was obvious by the late 1960's. This recession necessitated the placement of an additional 1 ,070,000 m3 of sand on the northern one-half of the beach. By the middle 1970's, homes and structures along the northern flanks of the bulge were fronted by bulkheads and walls of protective rip-rap (Fig. 28 A&B) .Additional restoration in 1980 and 1981 placed 1,380,000 m3 of fill along the northern 2450 m of the project, temporarily reversing the shoreline retreat.

In 1986, an additional 670,000 m3 Of sand was placed on the beach. US Army Corps of Engineers estimates that the convex shape of the shoreline accelerates the annual erosion (99,392 m3 of the fill by 31.5% (Jarrett, 1977; US Army Corps of Engineers, 1982). Figure 27 illustrates this erosion scenario at Wrightsville Beach where the continued restoration of the beach is aimed at protecting the structures along a seaward offset of the natural building line.

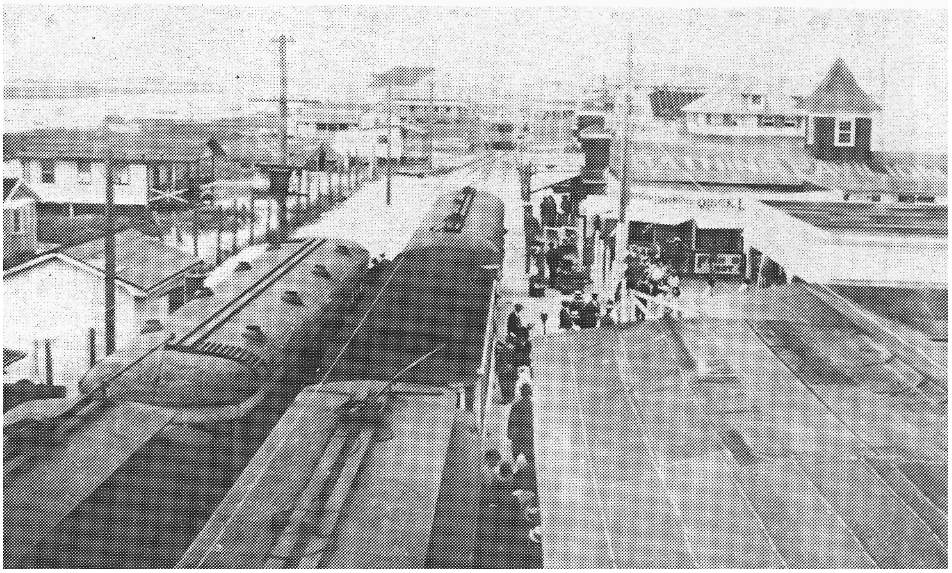
Wrightsville Beach is one of the most-replenished beaches *(i.e.* large. federally-funded replenishment projects) on the U.S. East Coast (Pilkey and Clayton, 1987; 1989), and has been funded under the widest variety of of federal autho-

Figure 22. Historic Photographs of Wrightsville Beach.

A. Early Banks Channel trestle. Trolley cars carried visitors to Wrightsville Beach (ca. 1920). The large hotel at the right is the Oceanic, a famous landmark in the early days of development of the beach. The original timbers of the trestle were driven in the 1899. The structure connected the Hammocks (Harbor Island) and Wrightsville Beach (D.H. Barnett collection).



B. Oceanic Hotel (ca. 1914). Near site of Wings (Newells) and Station #1. Originally constructed as the Hotel Trymore in 1905, the Oceanic offered its guests such amenities as a bowling alley, a spacious ballroom and well-appointed accommodations.



C. Station #7 (Lumina). North view (ca. 1925) along old electric trolley line. Note spacing of cottages, hotels and bath houses even at this early date. Waynick Blvd. is yet to be constructed. (D.H. Barnett collection).

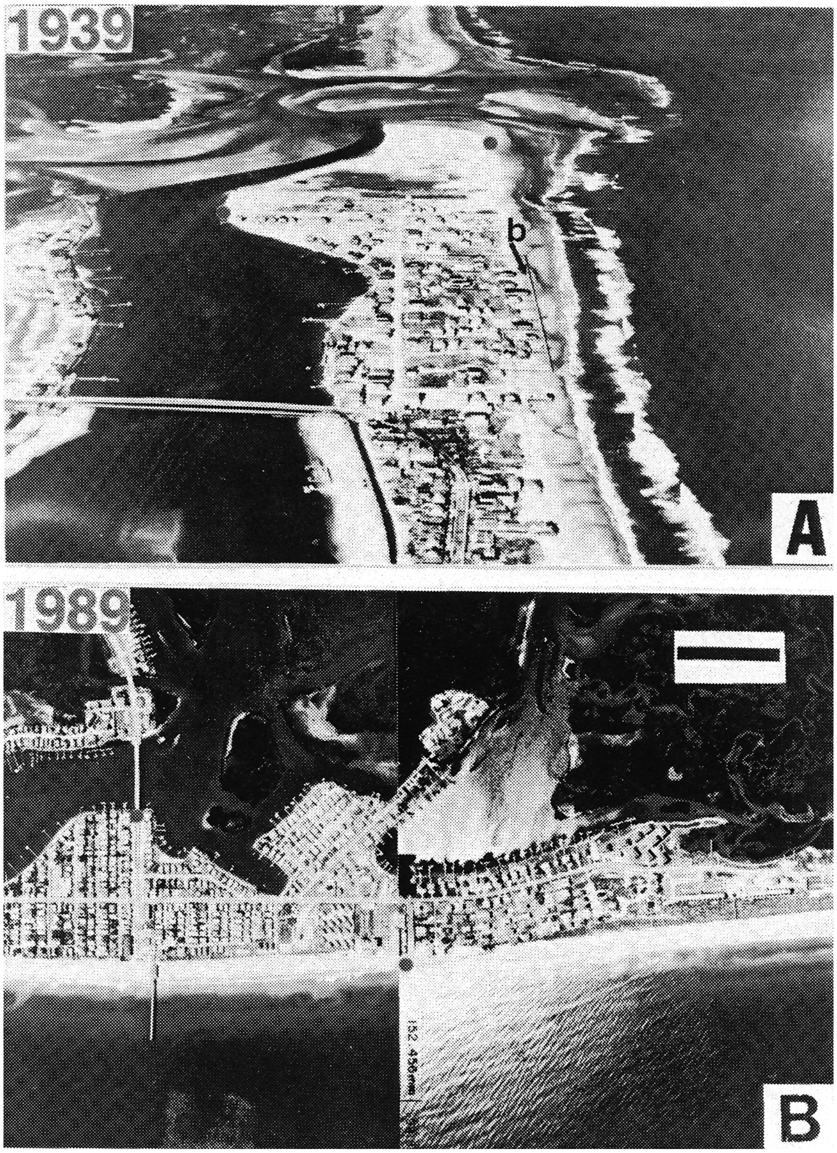


Figure 23. Aerial photographs of Moore's Inlet, scale bar = 1,667 ft. Dot represents the location of the Holiday Inn.
A. 1939. Photograph shows evidence of recent constriction of inlet. The main channel located on the Shell Island updrift shoulder is flanked by a wide shallow flood channel on the Wrightsville beach margin. Note curvature of dune lines on adjacent barriers.
B. 1989. Erosion along this section of the beach is attributed to the closure of the Moore's Inlet in 1965. Bulkheads, seawalls and revetments that fronted the homes in this area in the 1970's and 80's are now buried by the sand from the replenishment projects.

rizations of any beach in the U.S. (Pilkey and Clayton, 1987). These include 1) Flood Control; 2) Emergency; 3) Flood Control and Navigation; and 4) Mitigation of the Effects of that Navigation Project. Major replenishments have been carried out at approximately four-year intervals since 1965 (Table 1). each of which involved the placement of approximately 1 x1 06 m3 of material dredged from the backbarrier lagoon and portions of Masonboro Inlet (Fig. 29 A&B). Numerous engineering studies have investigated various aspects of the Wrightsville Beach nearshore system ant}7- ...ts predicted response to jetty construction and beach replenishment *(e.g.* Sager and Seabergh, 1977; Winton *et* a/., 1981; U.S. Army Corps ofEngineers, 1982). Over the past several years, we have collected extensive geologic and geophysical data off Wrightsville Beach. Nearly 300 km of 3.5 kHz subbottom profile and 100 kHz analog sidescan-sonar data have been obtained as part of previous projects funded by the NOAA National Undersea Research Program. The geophysical data were obtained in June 1992, and cover a broad area of the shoreface and inner continental shelf. A suite of over 100 short (-2 m) percussion cores, vibracores, surface sediment samples and diver observations was obtained between ,1991-1992. In March 1994, a fully georeferenced (:t 3m accuracy), high-resolution digital sidescan-

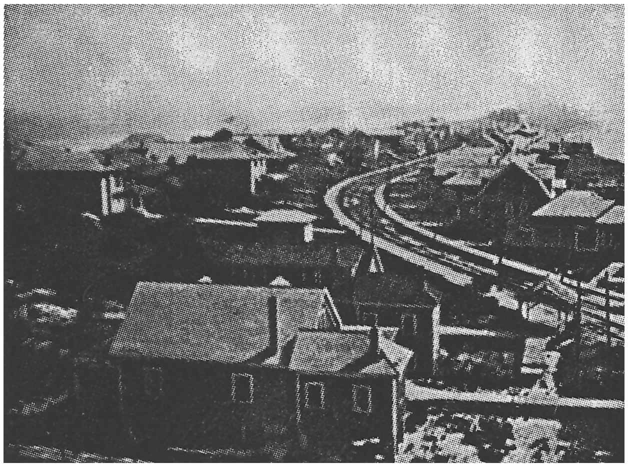


Figure 24. Southview of Wrightsville Beach (ca. 1920). Southview of Wrightsville Beach (ca. 1920) in vicinity of Station #1 (Wings). Note the narrowness of the southern portion of the barrier. Cottages and hotels line the island from ocean to soundside. The tracks for the early trolley were laid within the dune swales. The old road bed of the railroad underlies Lumina Ave. Banks Channel is seen on the right side of the photo. Dredge material from this channel provided fill for the construction of Waynick Blvd. and the initial USACE restoration of the beach in 1965. (D.H. Barnett collection).

Figure 25. Historic photograph of Wrightsville Beach (ca. 1930). Historic photograph illustrating location of groins and bulkhead along the area south of Moore's Inlet. Severe erosion is evident. Note bulkhead on soundside. Large Hotel is the Oceanic which burned in 1935.

sonar mosaic of the shoreface and inner shelf off Wrightsville Beach was produced as part of a joint cooperative research program with Duke University-U.S. Geological Survey. Another digital sidescan-sonar survey was conducted in early August1995, followed by the collection of additional vibracores and samples located on the basis of the two sidescan-sonar mosaics.

The morphology of the Wrightsville Beach shoreface is dominated by shore-normal rippled scour depressions (a genetic term used by Cacchione *et al.,* [1984] to describe similar features in other shelf environments). The depressions develop just outside the fair-weather surf zone at 3-4 m water depth, and extend to the base of the shoreface at about 1 Om depth. On the sidescan-sonar mosaic, the rippled scour depressions are defined by areas of high acoustic reflectivity. The depressions are floored with very coarse shell hash and quartz gravel, and on the upper shoreface are scoured up to 1 m below the surrounding areas of fine sand. Long, straight-crested, symmetric megaripples floor the depressions. The depressions terminate and the shore-normal morphologic fabric becomes shore-oblique at the base of the shoreface, due to a series of east- to northeast- trending relict ridges with 1-2 m of relief.

The more numerous rippled scour depressions along the southern part of the Wrightsville Beach shoreface may be the result of increased bedrock control, as evidenced by larger areas of rock outcrops on the shoreface and inner shelf. On the 1992 sidescan- sonar data, small areas (20-50 m2) of outcropping rock appear to be exposed above the fine sand between some of the depressions. Onshore water-well logs and ground-penetrating radar surveys on the island have also identified Tertiary limestone units in the near subsurface in the same area where rippled scour depressions are abundant offshore. In addition, the gross morphology of the shoreface and inner shelf did not change over a 21-month period between the 1992 and 1994 sidescan-sonar surveys.

The surficial sediment distribution in the 1994 and 1995 surveys is nearly identical to a sedimentary facies map presented by Thieler *et al.* (1995) based on analog sidescan-sonar and surface sample data collected in June 1992. These observations suggest that the locations of some rippled scour depressions on the shoreface may be controlled by bedrock topography; they may also be relatively permanent features.

The shoreface sediment cover off Wrightsville Beach is a patchy veneer blanketing low-relief, ancient units. The modern sediment, including the contribution from the nearby replenished beach, averages about 30 cm in thickness. The primary underlying units are a Plio- Pleistocene arenaceous limestone, unconsolidated Oligocene silt, and Quaternary fluvial channels. In addition to our geophysical data, Snyder *et al.* (1994) have also identified the seismic signature and distribution of these units across the southern Onslow Bay shelf .

Petrographic analysis of surface sediment samples on the shoreface and inner shelf indicate several distinct, local sediment source areas. The sources include the three ancient units, in addition to the modern beach. For example, there are a number of locations in the study area where limestone outcrops are present, some of which are productive hard-ground habitats. Bioerosion of the outcrops produces a residual sediment ranging in size from gravels to lime mud. This residual fraction is mixed with outcrop- associated, relatively

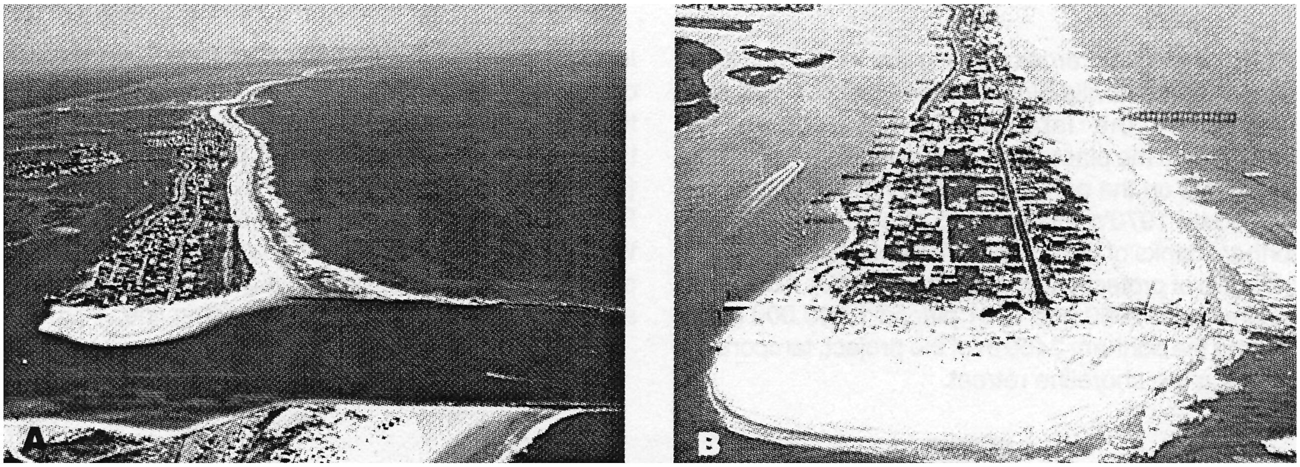


Figure 26. Wrightsville Beach Photographs.
A. North view of Wrightsville Beach and the bulge in the mid barrier shoreline. The north jetty was constructed in 1965 and the south rock jetty in 1981. Oceanic Pier is located north of the weir jetty. Much of Wrightsville Beach is fill material.
B. 1965 oblique aerial photograph showing construction of the weir jetty. The structure acted as terminal groin for the fill placed on the updrift beach. Oceanic pier (Crystal) is located in the foreground (USACE).

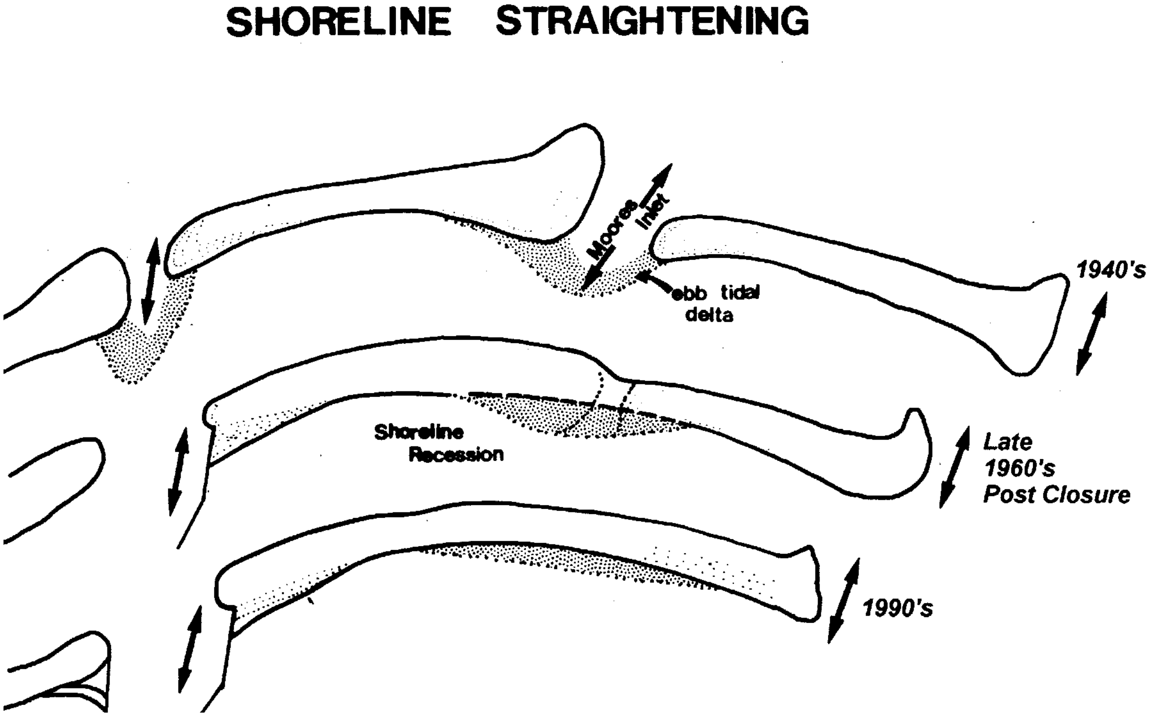


Figure 27. Shoreline changes associated with closure of Moore's Inlet in 1965. During the 1940's the inlet produced a curvature in the adjacent shorelines. Concurrent with closure, the building line was established that mimicked the curvature. Recession occurred as the offshore portion (ebb delta) of the bulge as well as the onshore region eroded. During the 1970's several houses required protection in the form of seawalls and bulkheads. Some structures were relocated. The hard structures can be observed after storms. During the 1980's and 1990's sand from replenishment projects have afforded some protection to this area.

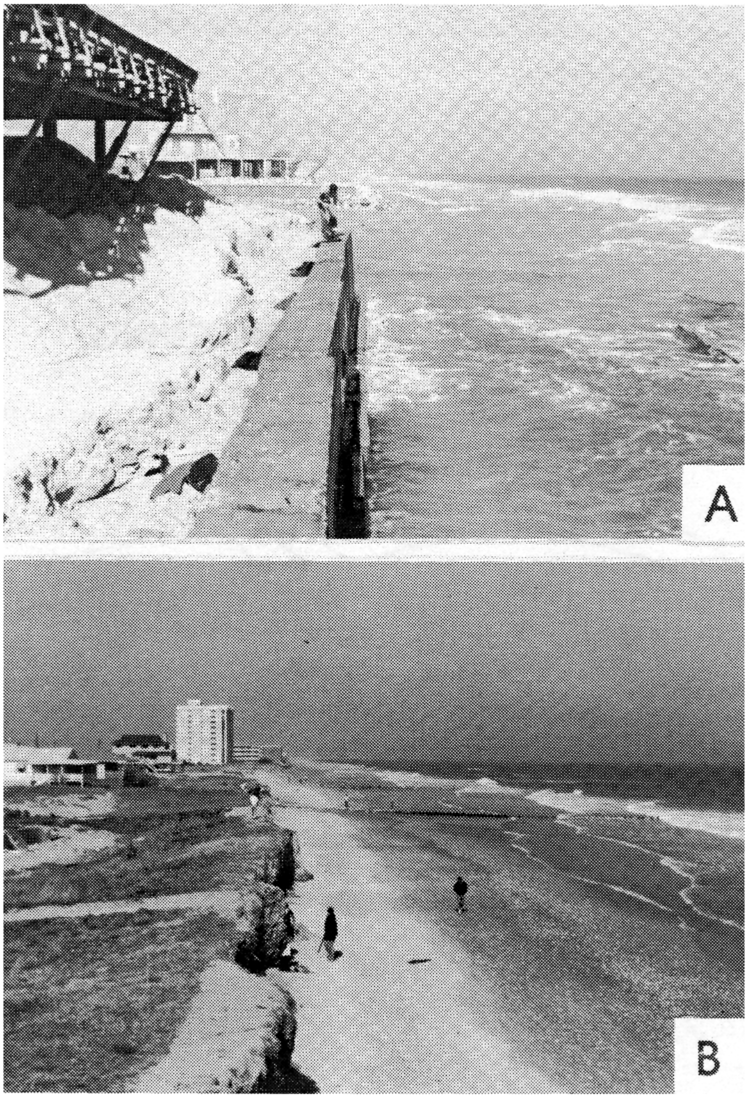


Figure 28. Erosion along the shoreline bulge.
A. Seawall shown was emplaced in late 1970's. Rip-rap fronts a bulkhead to the north. Area is located immediately north of Holiday Inn.
B. North view of Wrightsville Beach in 1980. Artificial dune is severely eroded. Old groins are exposed.

fresh invertebrate fragments, including small corals and shell material.

Most of the vibracores exhibit a sharp, erosional contact (the Holocene ravinement surface) between the active sediment cover and an underlying Oligocene silt unit, indicating periodic erosion and bypassing of material onto the shoreface. The similar mineralogy of the ancient unit and immediately adjacent modern sediments indicates the Oligocene unit is contributing glauconite-rich silt and very fine sand to the inner shelf. Backbarrier sequences deposited during the Holocene have infilled relict inlet and tidal creek channels incised into the Pleistocene and Tertiary units. Three radiocarbon dates for *in situ* oysters from these channels provide an age assignment of 8-10 ky, with age increasing with depth and distance offshore. These deposits, some of which are visible on the sidescan-sonar mosaics, are eroded and reworked on the mid- to lower shoreface during storm events, providing a minor source of material for the overlying shoreface sediment cover.

Sediment for beach replenishment projects was dredged from the backbarrier lagoon and portions of Masonboro Inlet. Of the total 7. 7x1 06 m3 of sediment emplaced, at least 60 percent (4.4x106 m3) is composed of a macroscopically identifiable, gray quartz sand with abundant, gray-black-stained recent oyster shells (*Crassostrea virginiGa)* (volume and source area data from U.S. Army Corps *of* Engineers, 1982). The replenishment sediment is nearly identical to the native beach and shelf material in terms of its

Table 1. Replenishment history of Wrightsville Beach.

Year	*Volume (m^3)*	*Cum. Vol. (m^3)*	*Cost*
1939†	700,000	700,000	$98,000
1955*	**38,000**	738,000	not available
1956*	**35,000**	773,000	not available
1957*	**304,000**	1,077,000	not available
1959*	**100,000**	1,177,000	not available
1965*	**2,993,100**	4,170,100	$739,339
1966*	**362,108**	4,532,208	$255,941
1970*	**1,436,533**	5,968,741	$578,545
1980*	**540,715**	6,509,456	$1,030,736
1980	36,108	6,545,564	not available
1981	1,249,699	7,795,263	$4,427,792
1982	124,533	7,919,796	not available
1983	93,755	8,013,551	not available
1985	19,399	8,032,950	not available
1986	898,593	8,931,543	$1,331,715
1987	76,556	9,008,099	not available
1989	96,771	9,104,870	not available
1991	1,016,684	10,121,554	$2,682,412
1994	619,031	10,740,585	$1,973,591
Total backbarrier	**5,809,456** m^3		

Notes: *backbarrier source; †source unknown (likely backbarrier). Pre-1986 data from Pilkey and Clayton (1989); post-1986 data from U.S. Army Corps of Engineers, Wilmington District (pers. comm.). Cost for 1994 based on USCOE estimate.

grain size distribution, carbonate content, and physical attributes *of* the carbonate fraction (shell abundance, particle sizes, *etG.)* (U.S. Army Corps *of* Engineers, 1982; confirmed by our unpublished data). The major difference between the beachfill and the native sediment is that the faunal component of the beachfill material is characterized by black- and gray-stained oysters, while the native beach and shelf sediment contains oxidized, brown- and orange-stained shells of marine genera *(e.g., Anadara, Donax).*

Some of the sediment from the early beach replenishment projects can be found on the shoreface and inner shelf. Pearson and Riggs (1981) first noted the occurrence of this replenishment sand, which is identifiable on the basis of its gray color, black-stained shell material, and high oyster shell content. The replenishment sediment is visibly distinct from the "ancient" oyster-bearing sediments described above. Specifically, the physical condition of the oyster shells in the two suites is quite different. The ancient oysters are typically a bleached, whitish color, and are fairly fragile. When exhumed by shoreface erosion, the shells quickly break up, and are oxidized to a light, brown-orange. This contrasts sharply with the well- blackened, durable, modern specimens from the replenishment projects. We are presently using this unique sediment tracer to identify decadal-scale sediment dispersal patterns on this shoreface.

Masonboro Island

Masonboro Island extends along 13 km of the shoreline between Wrightsville Beach and Carolina Beach Extension. Masonboro Inlet separates the island from Wrightsville Beach; Carolina Beach Inlet separates it from Carolina Beach to the south (Fig. 30 A&B). Masonboro Island was continuous with Carolina Beach until 1952 when Carolina Beach Inlet was opened.

Masonboro Island is typical of the low islands forming the eastern limb of the Cape Fear Foreland. This is the only open ocean barrier island in North Carolina that is currently in a state of migration. Characteristically, the island possesses low relief and borders a narrow (ca. 2 km) partially marsh-infilled lagoon. The subaerial portion of the island varies from 50 to 600 m in width; most of the island averages 175 m. Since the island is situated along the major storm tracks, it receives significant impacts from hurricanes and nor'easters, and is frequently overtopped.

The morphologic character of the barrier has changed dramatically over the past 20 years. Photographs from 1938 show that vegetated dunes formed a continous dune line

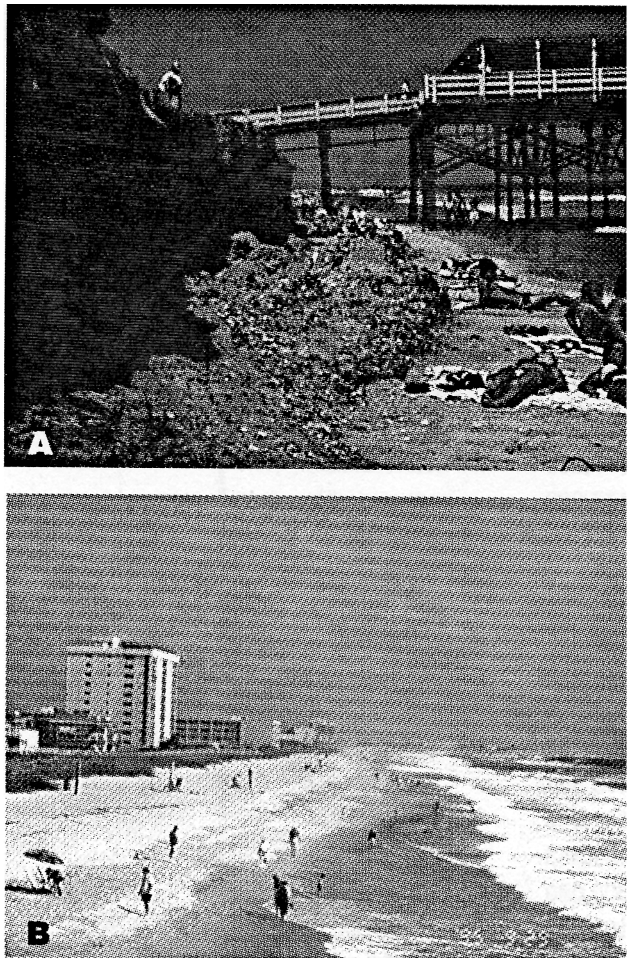


Figure 29. Wrightsville Beach.
Eroded "dune". The 1975 photograph shows the nature of the original USACE fill which consisted of poorly sorted oyster shells, shell gravels, fine sand and mud. The material was derived from Banks Channel.
North view of Hurricane Protection Project (1995). The project extended along approximately three miles of the southern portion of the beach.

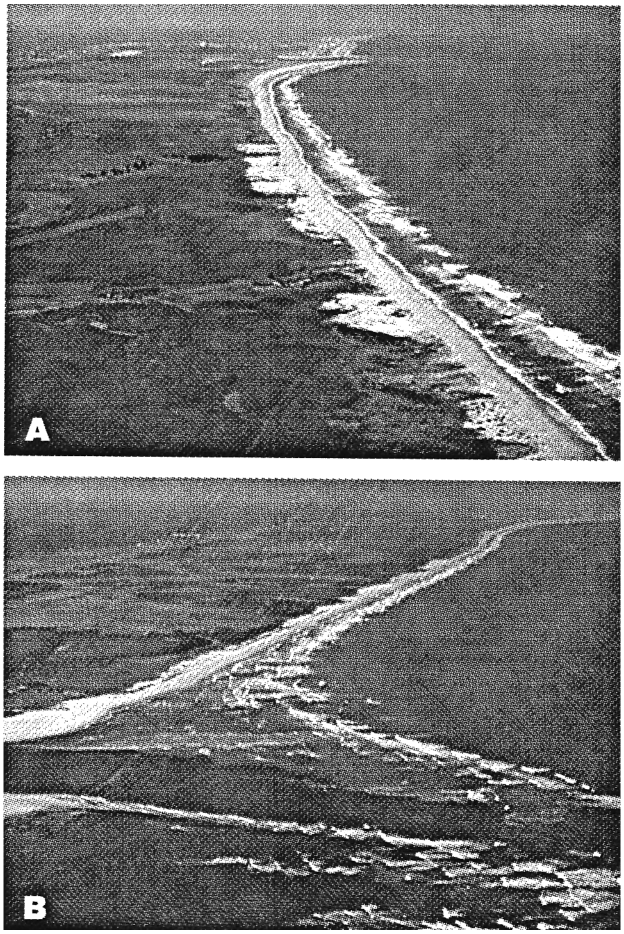


Figure 30. Masonboro Island aerial photographs.
North view of Masonboro Island (1981). Storm deposits characterize the barrier. Since the 1980's the island has receded rapidly. The 1996 shoreline is located within the maritime forest in the center of the photo.
North view (1994) of Masonboro Island from Carolina Beach Inlet. The southern segment of the barrier is low and eroding rapidly due to the opening of Carolina Beach Inlet in 1952. Overwash during storms is the driving variable that is most important in island migration. Currently the area shown is a single continuous washover terrace.

along the island length except near Masonboro Inlet. The storm period between 1954 and 1962 produced extensive overwash fans and terraces. Following the 1962 "Ash Wednesday" extra-tropical storm, nearly 70 % of the island exhibited washover topography.

The dune system that had been obliterated during the 1960's began to recover and by 1980, 80% of the barrier shoreline was characterized by scattered redeveloping dunes. A series of storms in the mid 1980's coupled with the modification of Masonboro Inlet has dramatically altered the character of the island. During -the 1987 New Year's Day storm, 80% of the barrier was overtopped forming extensive fans that extended into the adjacent estuary. Currently, about 18% of the shoreline exhibits a dune line.

Downdrift of Masonboro Inlet, dune progradation is evident, the first since 1945. The progradation followed the construction of the south jetty in 1981. Except for this small shoreline segment the remainder of the barrier is rolling-over on itself fairly rapidly. Short term erosion rates are 4-5 m/yr. The increased washover suseptibility and high erosion rates are attributable to the maintenance of Carolina Beach Inlet and the dual jetties at Masonboro Inlet. The reduced by-passing at the island's southern end and the nearly complete retention of sediment at the northern boundary has drastically reduced the sediment supply. The combined effect of these two sediment sinks has produced a defecit of approximately 250,000 m/y.

If present trends continue, it is highly likely that the

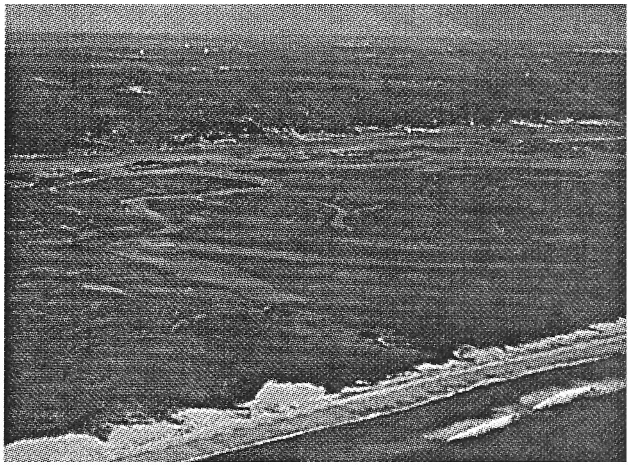


Figure 31. Cabbage Inlet. 1994 aerial photograph. Cabbage Inlet opened in 1761 during the most intense storm to make landfall in the area. Closure occurred in 1780. The extensive tidal marsh behind the island represents the vegetated former floor tidal delta. Note the forested hammocks which represent the shoulders of the former inlet. Currently washovers extend beyond the forest.

southern two-thirds of the island will resemble Assateague Island, Maryland in the next several decades. The high erosion rate, lack of dunes, and chronic overwash will lead to rapid translation of the barrier toward the mainland. It is likely the island will migrate the equivalent of several island widths by the year 2025 and have a markedly different shape.

An extensive area of marsh exists in the lagoon approximately in the center of the island. This marsh marks the position of Cabbage Inlet, a major inlet which was open during the 1700's (Fig. 31). Inlets have not been long lived along the island, probably due to the small tidal prism associated with the narrow lagoon. Vibracores recovered from the lagoon indicates the thickness of the Holocene fill ranges from 3 m on the interfluves to more than 10 m in the deeper parts of the backfilled incised valleys. Sands or muddy sands dominate the sequences refelecting the influence of ephemeral inlets and oceanic overwash. Core data suggest that inter-tidal environments have characterized the lagoon since the initial flooding began 5,000 years ago.

Carolina Beach, Carolina Beach Extension and Kure Beach

The barrier island chain of the Cape Lookout to Cape Fear section of the North Carolina Coast Is interrupted at Carolina Beach. The marsh-filled estuary found north, and again south, of Carolina Beach does not exist behind the Carolina-Kure Beach section of the shore (Fig. 32 A). This portion of the coast is characterized by a perched mainland beach. Elevations directly landward of the beach are 6 to 10 m. Pleistocene-aged, erosion-resistant subsoils extend onto the beach at several locations. This shoreline has had a colorful history of shoreline stabilization attempts similar to those undertaken at Wrightsville Beach. Various generations of groins, beach berm construction and beach nourishment are evident along the shoreline. The projects undertaken since development began (early 1900's) have proved to be short-term; the erosion of the mainland beach has persisted. Erosion rates of up to 1 m/yr have been measured.

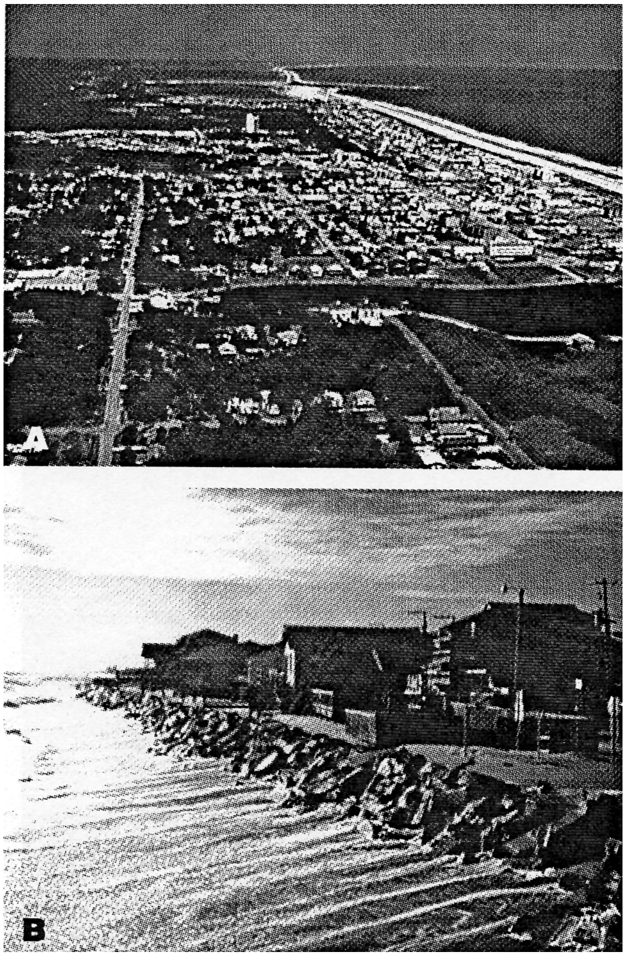


Figure 32. Carolina Beach/Kure Beach aerial photographs.
A. North view of Carolina Beach and southern terminus of the lagoon. Carolina Beach Inlet is seen in foreground. Masonboro Island and Carolina Beach were contiguous until 1952 when the inlet was opened. Erosion rates increased markedly for several years following the breach. The lake in the lower right portion represents a former estuary that was connected to the ocean at the turn of the century. The connection was infilled creating a hazardous situation during times of heavy rainfall or overtopping. Flooding is typical and roads are impassable.
B. Rip-rap along Carolina Beach Extension. The rock rubble was emplaced in 1970-73 in an attempt to prevent further erosion downdrift of Carolina Beach Inlet. The 2000 ft long structure fronts a re-entrant in the shoreline.

A major beach fill borrow site has been targeted on the

Figure 33. Fort Fisher aerial photograph. North view (1987). The beach along the Fort Fisher/Kure Beach section is perched atop Pleistocene units comprised of two lithologies: Coquina and a friable humate rich sandstone. Coquina crops out on the beach front of the townhouses in center of photo. The underlying geology plays a critical role in the local erosion.

hardbottom dominated shoreface off Carolina Beach. The site represents an anastomosed channel complex of the ancestral Cape Fear River. The Pleistocene channels are estimated to contain in excess of 15 million cubic meters of sand, a sufficient volume to satisfy the local needs for the next decade.

Carolina Beach Extension marks the northern end of the barrier island physiography. This section of the shoreline is sediment starved. Carolina Beach Inlet intercepts considerable quantities of sand moved alongshore by the longshore current. As a result, a re-entrant has formed south of the inlet (Fig. 32 B). Overwash is the dominant process along this section of beach. Dunes have little time to recover before washover events erode their edges. Despite a severe shoaling problem, proposals to close Carolina Beach Inlet have not been favored because recreational and fishing boats anchored at Carolina Beach would be required to enter and exit the ocean at Masonboro Inlet, 13 km distant from Carolina Beach Inlet.

Fort Fisher Beach and East Beach

In this area, an extensive eroding subaerial headland intersects the coastal zone without a barrier island- estuarine system (Fig.1 & 33). The shoreline segment consists of a wave-cut platform incised into Oligocene through Pleistocene units (Fig. 34 A&B) of the mainland peninsula, with a thin beach perched on top of the irregular geometry of the Pleistocene units (DuBar et al., 1974; Moorefield, 1978; Meisburger, 1979; Cleary and Hoiser, 1979; Snyder et al., 1994, Riggs et al., 1995; Cleary et al., 1996).

Erosion resistant, lithified and crossbedded coquina sandstone forms a headland in the shoreline north of Fort Fisher (Fig. 34 A). Friable humate and iron- cemented Pleistocene sandstone forms a 2 m high wave-cut cliff and terrace that fronts the shoreline immediately south of the headland and seaward of the Civil War Fort Fisher. South of Fort Fisher is a nonheadland segment characterized by a channel-dominated, valley-fill shoreface underlain by 10 m of muddy estuarine sediments (Swain and Cleary, 1992) . The shape and evolution of the three different coastal compartments around Fort Fisher is clearly related to the presence and lithology of the outcropping and underlying Pleistocene geologic framework.

Moorefield (1978) mapped beach outcrops of Pleistocene coquina north of Fort Fisher and their seaward extensions on the inner shelf. Our ongoing studies clearly show that coquina and its associated lithologies form a series of widespread, irregular bathymetrically high hardbottom features with > 3 m of relief. This karstic mosaic includes one extensive hardbottom area known as Sheephead Rock that lies in 9 m of water with pedestal-like hardbottom features rising to within 2.5 m of the ocean surface (Fig. 35 A&B). Diver observations and cores suggest that the sediment cover is both patchy and very thin across much of this region and in many areas is totally lacking. The extensive series of coquina outcrops on the inner shelf act as barriers that could significantly affect the refraction of wave energy, as well as the movement of sand across this shoreface. Sand from both the rapidly eroding beach at Fort Fisher and littoral drift, is transported seaward of the outcrops during storms and prevented from returning to the beach during subsequent low energy periods. The result of this process is a net sediment deficiency in which the rapidly retreating bluff shoreline is consuming the historic fort.

Although the coast from Kure Beach to Fort Fisher is technically part of the mainland, the location of Cape Fear River on the back side of the area effectively creates a landform similar to that of a barrier island. Most of the development here is more than 7 m above mean sea-level, on stable, vegetated areas and can be considered safe. This safety is indicated by the hurricane record for Kure Beach as compared to that of other beach resorts in the area. Hurricane Hazel, for example, severely damaged or destroyed hundreds

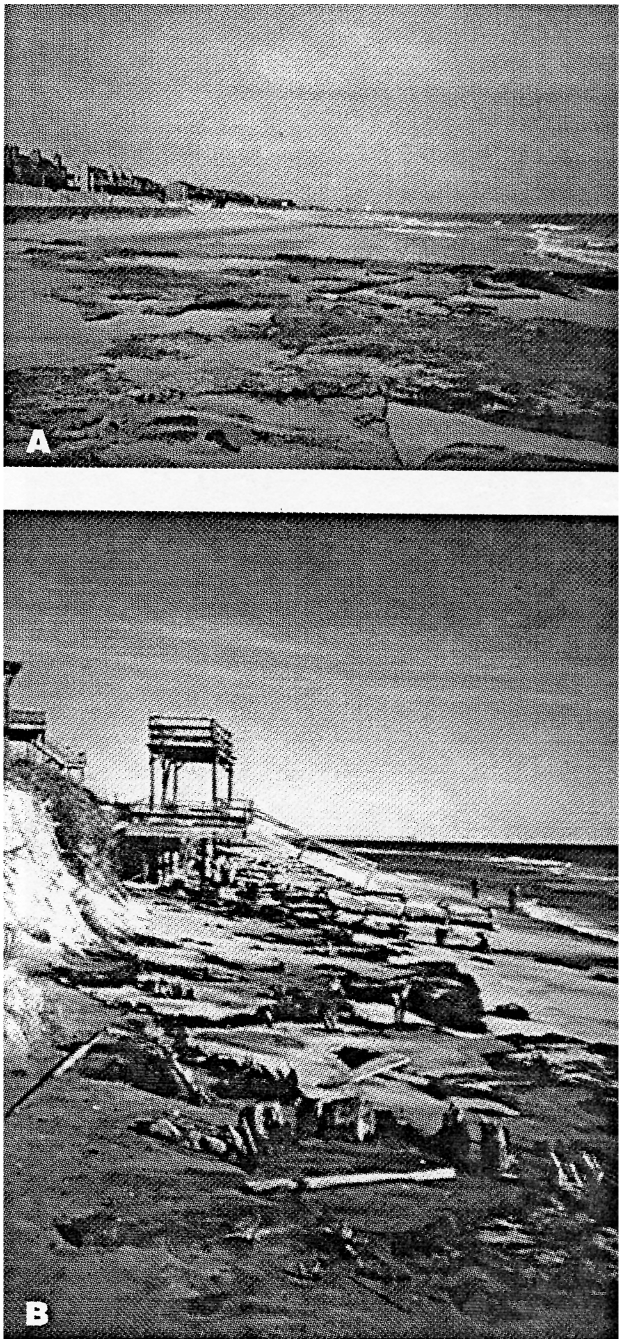


Figure 34. Coquina, sandstone outcrops and perched beach.
A. Coquina units crop out on the beach and underlie much of the headland beaches. The unit extends onto the shoreface and plays a crucial role in cross-shore transport during storms.
B. Organic rich sandstone. Dark brown humic stained sandstones overlie the coquina units. The sandstones and the paleo pine forest stumps are frequently exposed after storms.

of buildings at Carolina and Wrightsville Beaches, but only 80 buildings at Kure Beach. In most of the other 1950's storms, Kure Beach survived with minor damages, and Hurricane Diane (1955) is said to have helped build up the dune line. Even if an area is considered safe, shoreline development is still at risk. It is not uncommon for sand to be washed into the streets of the first block facing the beach. Some structures, such as piers, must be placed on the beach. Owners should plan for damage and replacement. (Kure Beach fishing pier has been destroyed eleven times.)

The beach south of Fort Fisher to the Brunswick County line resumes the barrier island chain. The East Beach complex (Fig. 36 A&B) extending south from Fort Fisher is a 9 km complex spit which connects the Holocene sediments of the Cape Fear Foreland and the older Pleistocene headland section (Carolina- Kure-Fort Fisher).

Use of off-road vehicles on the beach south of Fort Fisher has caused changes in the physiography and vegetation. Vehicle use is somewhat restricted; vegetation removal has opened sands on the subaerial portion of the spit to remobilization. As a result, the dune system covers a larger portion of the spit when, compared to East Beach further south. The overall vegetation cover has been decreased by vehicles. The potential for erosive, ocean-to-sound washovers is more likely on the beach where vehicle use is uncontrolled (Hosier and Eaton, 1980).

The East Beach section of the shoreline has thinned to the point where the subaerial portion of the island ranges in width from 40 to 300 m and inlet breaches and washovers are common (Cleary and Hosier, 1979). The foredunes are weakly developed and form a discontinuous ridge. Shoreline recession has been calculated to occur at a maximum rate of approximately 5 m/yr immediately south of Fort Fisher.

Migratory inlets have been a common feature of East Beach during the last 150 years. Extensive areas of marsh built upon flood tidal deltas fill the lagoon behind East Beach. Currently New Inlet occurs in this section (Figs. 36 B&37). Historical records and charts show the original New Inlet opened in 1761 during a severe hurricane. The breach occurred in a low and narrow region known as the 'haulover'. It is very likely that one or more historic inlets preceded New Inlet.

The inlet channel which formed in 1761 deepened and remained essentially stable until 1839 when it began to shoal and migrate in a southerly direction. In 1854, attempts were made to close the breach which led to an accumulation of sediments in the Cape Fear River Channel to the west. In 1881, a dam {'The Rocks') was completed which effectively cut off tidal exchange between the Cape Fear River and the estuary riverward {landward) of East Beach {Fig. 37). Between 1895 and 1960, a cycle of inlet opening, migration and closure was repeated three times along a 2 km section of beach. Recurved spit features and a network of tidal creeks in the lagoon landward of East Beach indicate the historic

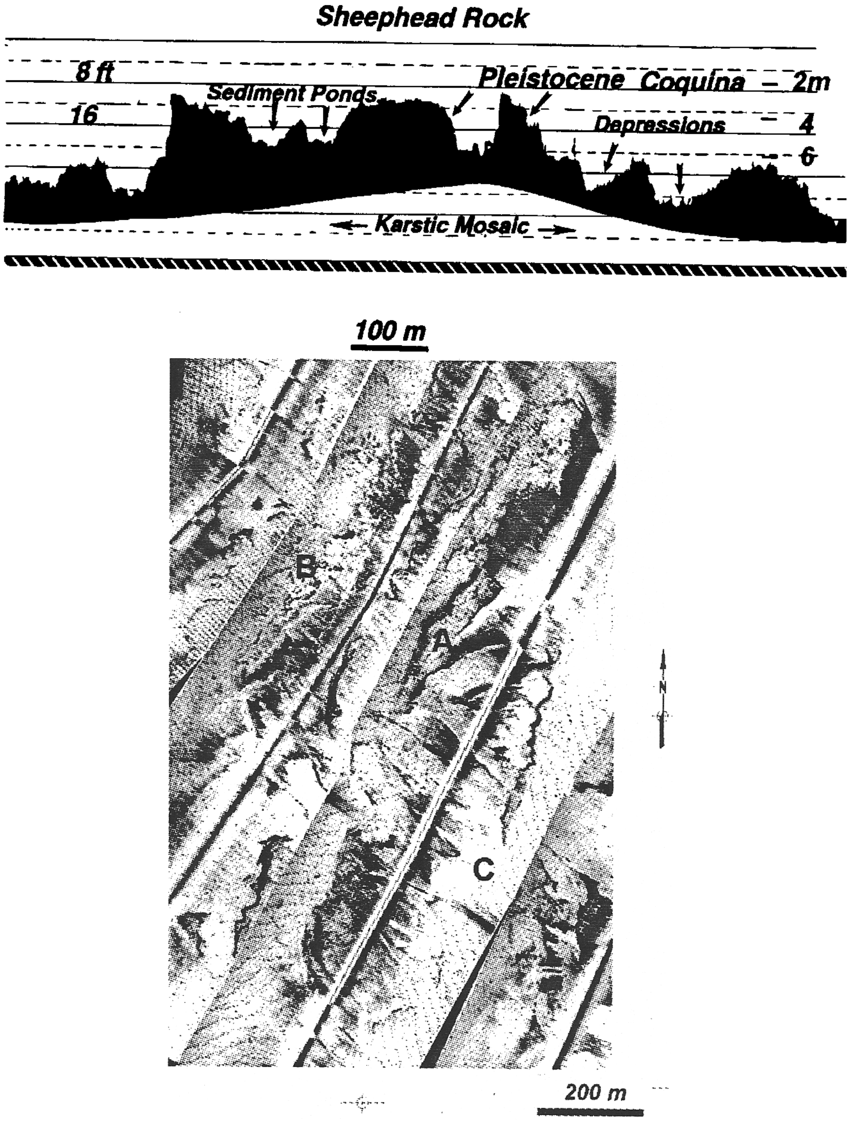


Figure 35.
A. Sheephead Rock Fathometer Traces (Coquina Outcrops). Representative bathymetric profile across a large high relief outcrop of Pleistocene age coquina, located offshore 3.7 km due south of Fort Fisher. Coquina is composed of coarse shell-hash and 10 cm pelecypod valves. Well indurated Pliocene barnacle rich hardbottom surfaces underlie this calcarenite sequence. Depressions at various depths are partially sediment filled.
B. Sidescan-Sonar Mosaic of Coquina Outcrops (Sheephead Rock). Sonograph shows area of high relief (>4 m) coquina (calcarenite) outcrops that rise to within 2m of the sea surface. (A) A series of ridges delineate well indurated gravel-rich coquina units, indicated by high backscatter (dark areas). (B) "Fishscale patterns" denote Patchy sands and gravels covering rocky outcrops. (C) Areas of fine sand are indicated by low backscatter (white areas).

location of these former inlets.

Construction of the dam not only produced a unique type of estuarine system, it also set the stage for subsequent erosion events along the updrift shoreline segment at Fort Fisher. Prior to inlet closure in 1881 , a large asymmetric ebb shoal containing a minumum of 30 million m3 fronted the Fort Fisher shoreline. The highly skewed ebb delta acted as a natural breakwater and protected the updrift shoreline segment against direct wave attack. Closure of the inlet prompted the collapse of the shoal as the tidal prism of the inlet was drastically reduced. The remobilized sediment infilled the former throat section and fed the newly developed spit (Fig. 37).

In the early part of this century, major sections of the coquina that crops out on the beach along the Fort Fisher area were removed for road building and construction materials. Closure of New Inlet and the removal of the coquina ultimately led to a shoreline recession exceeding 17 m/yr

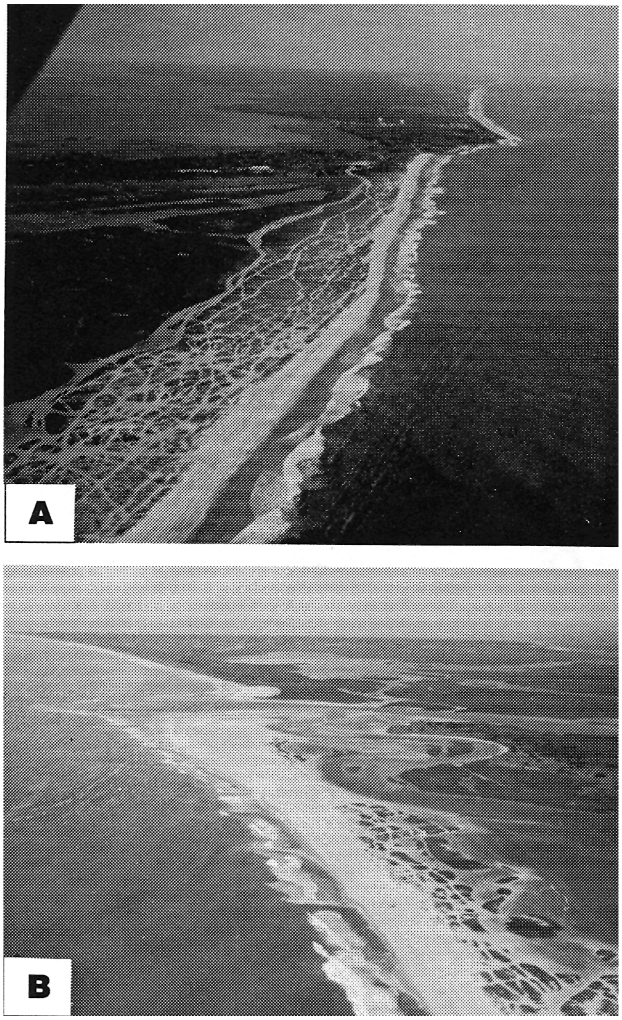


Figure 36. East Beach aerial photographs.
A. North view of spit attached to Fort Fisher headland. Off road vehicle traffic has impacted much of the dune field.
B. South view of East Beach toward New Inlet. The inlet's migration rate is a function of its position within various compartments of the Zeke's Island estuary. The Cape Fear River is in the upper right portion of the photo.

between 1926 and 1931 (Beach Erosion Board, 1931). Following the hurricanes of 1954 and 1955, several small groins and rubble from storm related destruction were placed in the embayment immediately south of the coquina outcrops. In 1970 a rock revetment consisting of limestone from Castle Hayne was emplaced. Since the mid 1970's a variety of construction rubble has been added to the site. Erosion rates of approximately 3 m/y were recorded in the 1980's along the shoreline segment fronting the fort (USACE 1993).

In order to mitigate the rapid erosion, a Beach Erosion Control Project was authorized in 1976 to protect the Civil War earthen mound fortifications. The historic fort was reduced to approximately 50 % of its original extent at the time of the authorization. After obtaining a variance from the state, the project was initiated in 1995. Plans called for a 3,050 ft. rock revetment with a crestal elevations of 10-16.5 ft., a base width of 70 ft. and an armored toe consisting of 5 ton interlocking STA-POD units (USACE 1993). The project was completed in the spring of 1996 at a cost of approximately $4 million (Fig. 39).

The debate over the Fort Fisher seawall was an important one, made more difficult by the fact that there is no room for compromise on the shoreline armoring issue. The variance granted to construct this wall was the first one given out on non federal land. It has already been cited by homeowners anxious for shoreline armoring as reason for another variance. A number of other historic sites on barrier islands have fallen victim to the sea including Fort Wagner (the location of the events in the movie Glory) on Morris Island near Charleston. If we are to prohibit shoreline armoring for the goal of preserving beaches for future generations, can exceptions be made?

The state of North Carolina will be monitoring the impact of the seawall on the adjacent beaches. There is concern that the structure will enhance the headland effect of the coquina outcrops and accelerate the erosion of the downdrift beaches and possibly the updrift segment as well. Many other environmental concerns have been raised and are beyond the scope of this brief discussion of the site.

Bald Head Island

Bald Head Island is an exclusive developed barrier island located at the mouth of the Cape Fear River Estuary. Bald Head Island is a 9 km long, forested, beach-ridge barrier. Bald Head, and 3 smaller islands separated from it by tidal marsh, are part of once more extensive Holocene regressive sequence that has since been drowned by rising sea-Ievel. Collectively, the sequence is part of the offshore shoals that extend onto the continental shelf from Cape Fear.

The origin of the Cape Fear Foreland as well as the other two Capes in North Carolina (Capes Hatteras and Lookout) have been related to ocean current eddies (Dolan and Ferm, 1968) and erosional remnants of Pleistocene deltas (Hoyt and Henry, 1971). Data from the shelf shoals suggest the Capes 1lay be quite old and related to subtle structural leatures (Blackwelder, *et al,* 1982).

Regardless of their antiquity or origin, the present day morphology of the three islands that form the foreland complex date from approximately 4,500 years B.P. when sea-Ievel rise is thought to have decelerated. At this time shoreline progradation commenced. The progradational phase may have lasted 2500 years or longer, the exact length is speculative for it is difficult to determine without detailed stratigraphy and radiocarbon dates on the age of the beach ridges. Since the last progradational episode, rising sea level has drowned the low swale areas, all of which are now infilled with tidal marsh and crossed by large tidal creeks.

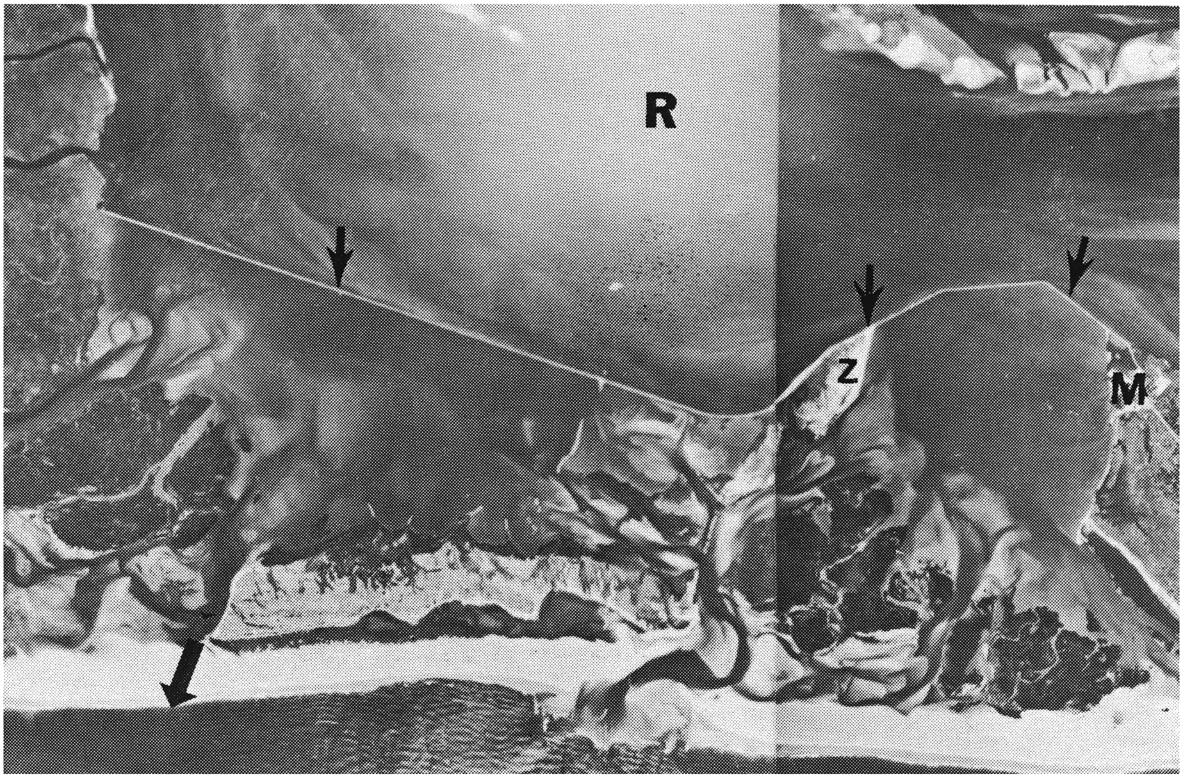


Figure 37. Aerial photograph of the Zeke's Island Estuary and the "Rocks". The dam (Rocks) was a major engineering feat of the nineteenth century. Upon completion in 1881, it stretched for one mile between the headland and Zeke's Island. The southern section was completed in the subsequent five years. The former New Inlet which opened in 1761 was a major inlet and was used by the Blockade Runners during the Civil War and was one of the main reasons for the construction of the Fort. Rapid infilling of the newly formed estuary occurred as the offshore shoals collapsed and the shoreline adjusted. Closure ultimately played a major role in the erosion of the shoreline fronting Fort Fisher. Currently (1996) the inlet is located at the southern end of the estuary (arrow).

The geometric arrangements of the historic multiple dune sets reflect the change in the pattern of the shoals immediately offshore both at the eastern and western ends of the island. The eastern end is characterized by truncated forested beach ridges with sets of smaller multiple dunes oriented perpendicular to the ridge complex. During major storms the majority Df the eastern shoreline is overtopped resulting in the formation of large overwash terraces which extend into the marsh.

SUMMARY

The Onslow Bay section of the North Carolina coast Jetween Cape Lookout and Cape Fear possesses a lariety of barrier islands and a short section of 11ainland. Islands vary from more than 40 km to less han 3 km in length with island widths similarily lariable. In addition to the underlying geologic ramework, the processes of oceanic overwash; inlet ormation, migration, and closure and eolian transport ~Il affect these islands with differing patterns and ntensities. As a result, each island, like individual people, takes on a different 'personality' based on the relative influence of each of these processes. In a similar fashion, each of these islands are different with regard to the potential for development. Although ndividual homesites on any island can be relatively safe" or relatively dangerous, some valid island wide Jeneralizations can be made about developmerJt ;uitability. The low transgressive islands such as ropsaillsland are much less suitable for development han the sand rich regressive islands such as Bogue 3anks. The heavy forests of Bogue Bank provide ;ome high wind protection while treeless Carolina 3each provides none. By analyzing the existing norphology of the barrier islands, some of the history of an island can be inferred and a reliable prediction of future changes can be made.

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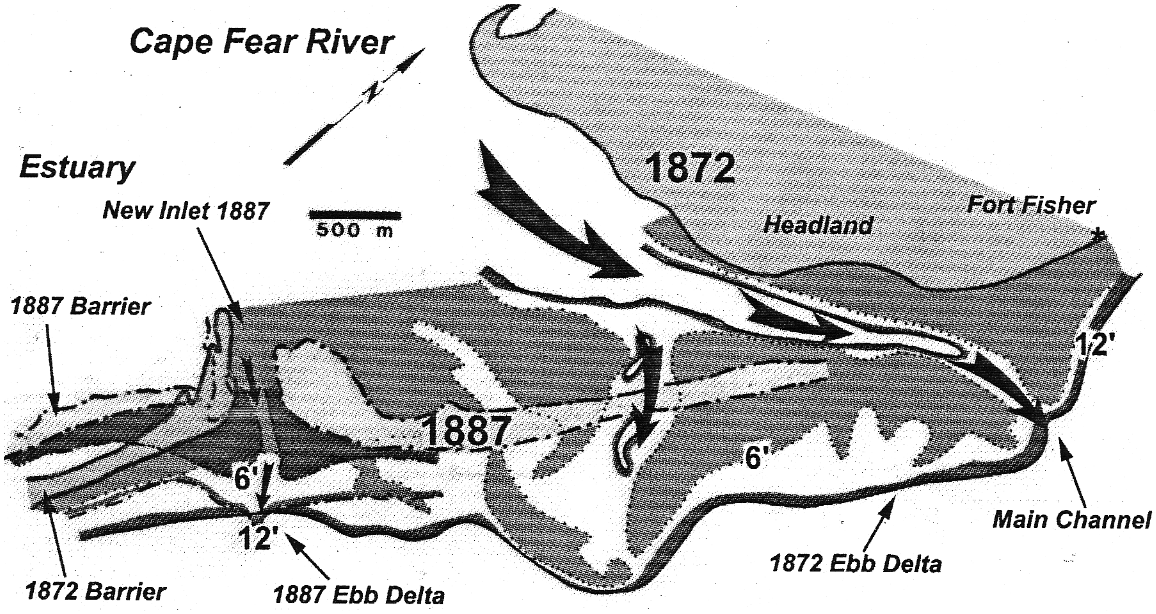

Figure 38. New Inlet closure. Cartoon illustrates changes in the shoreline and ebb delta due to inlet closure. The civil works project produced a unique type of estuary and led to the collapse of the large ebb delta (80% reduction) as the tidal prism was drastically reduced. The long term consequences led to erosion of the Fort Fisher shoreline as the ebb delta reorganized and its breakwater effect was eliminated.

Figure 39. Fort Fisher Seawall. Aerial Photograph (1996). The 3,050 ft long revetment completed in early 1996, was a controversial issue which required a variance and special permit. Crestal elevations range from 10 to 16.5 ft. The 70 foot wide base is fronted by huge 5 ton interlocking pods. The structure faired reasonably well during Hurricane Bertha and suffered minor damage during Hurricane Fran.

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APPENDICES

Appendix 1. North Topsail Island 1986-87

Appendix 2. Post Hurricane Bertha (7/18/96) Northern Topsail Island

Appendix 3. Post Hurricane Bertha (7/18/96) Northern Topsail Island

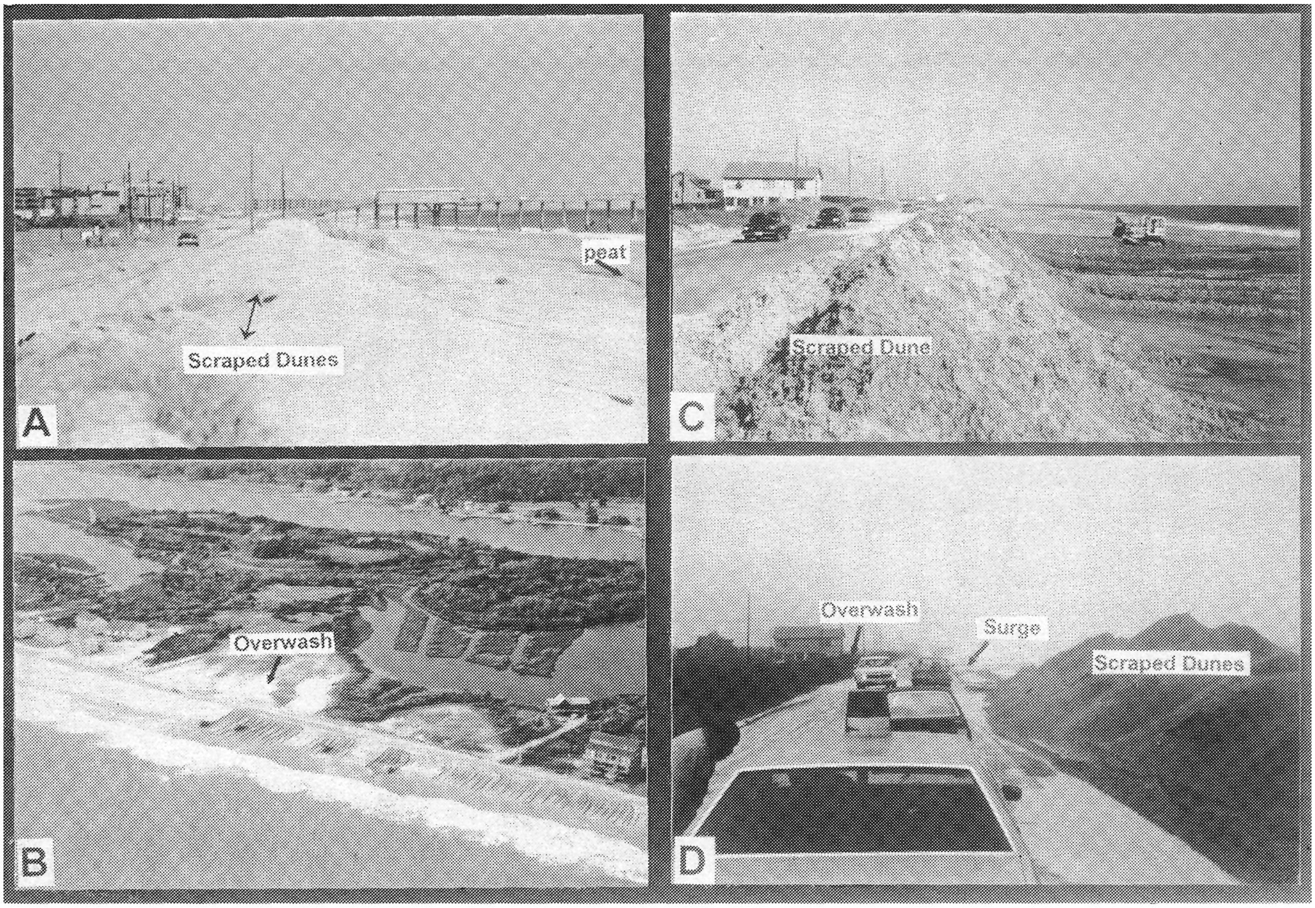
Appendix 4. Post Hurricane Bertha. Northern Topsail Island

Appendix 5. Post Hurricane Fran (9/15/96) Northern segments of Topsail Island

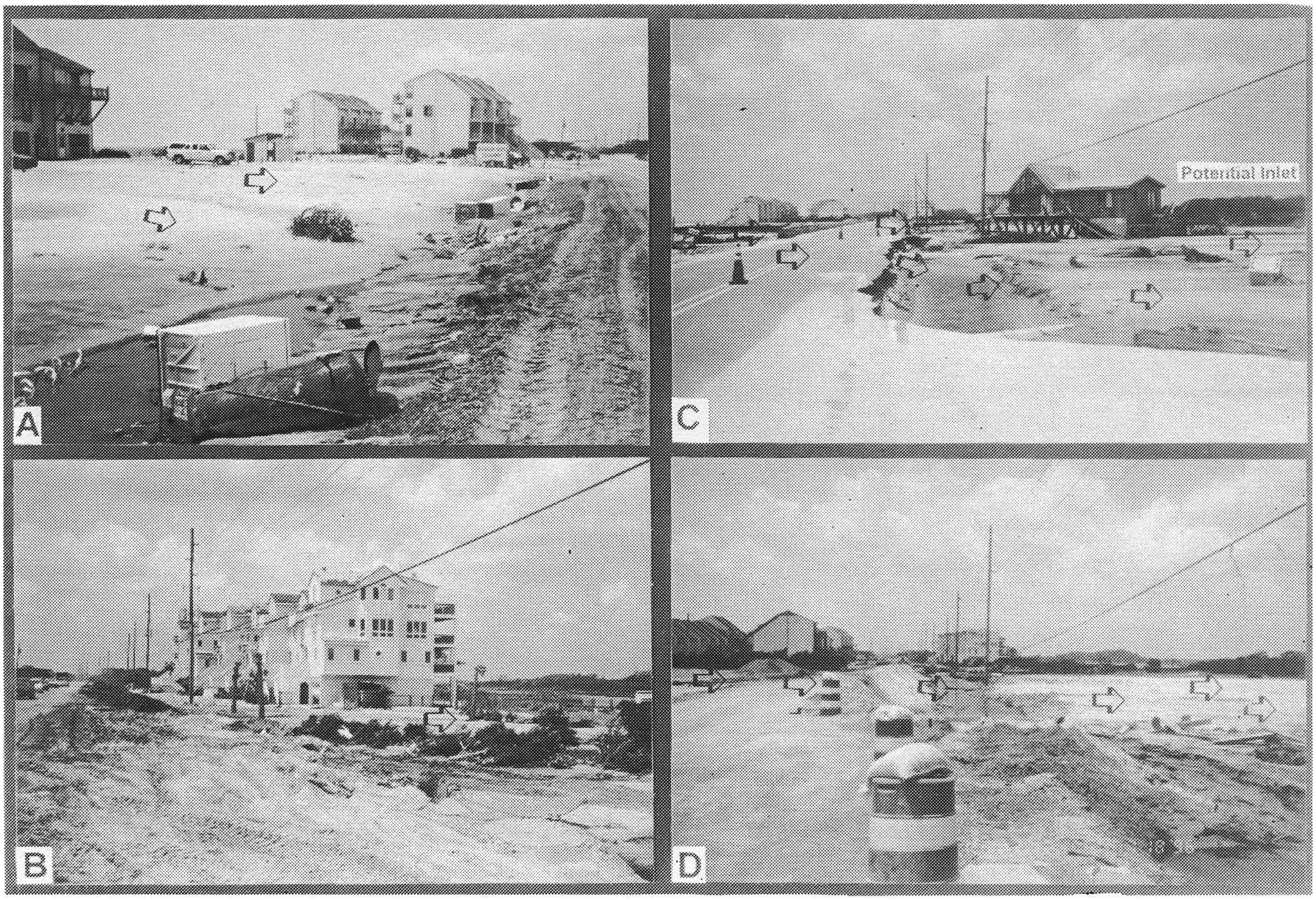
Appendix 6. Post Hurricane Fran (9/15/96) Surf City

Appendix 7. Post Hurricane Fran (9/16/96) Surf City

Appendix 8. Post Hurricane Fran (9/15/96) Masonboro Island



Appendix 1. North Topsail Island 1986-87
A. Bulldozed dunes were commonplace along the northern segment of the island. Note relative difference in elevation of berm and road. Peat is exposed near old pier.
B. Bulldozers were employed to scrape sand from the lower beachface after the numerous winter storms that impacted the area in the mid 1980's.
C. Bulldozers often exhumed peat and cedar stumps during excavations. Wave swash during high tide reached the base of the scraped dune line. Natural dunes did not rebuild.
D. The surge associated with the New Years Day Storm of 1987 eroded much of the bulldozed dune line.



Appendix 2. Post Hurricane Bertha (7/18/96) Northern Topsail Island
A. The 5-6 ft surge produced ocean to sound washovers. Lower floods and garages were most vulnerable.
B. Washover fans extended into sound along much of the northern section of the island. One meter thick deposits were common on the marshes and former grasslands.
C. The low spots traversed by the relocated road were particularly prone to overwash and scour during overtopping. These same locations were hard hit by Hurricane Fran.
D. The washover events associated with Hurricane Bertha in some instances penetrated the marshes almost to the edge of the ICWW.

Appendix 3. Post Hurricane Bertha (7/18/96) Northern Topsail Island

A. View looking north. Low lying developed areas near bridges and culverts were severely damaged. Guardrail was damaged by large concrete slab transported from beach 25 m seaward.

B. Sheets piles were emplaced along low areas crossed by the relocated road. Overwash sediments infilled the low regions and built fans that extended into the open water areas.

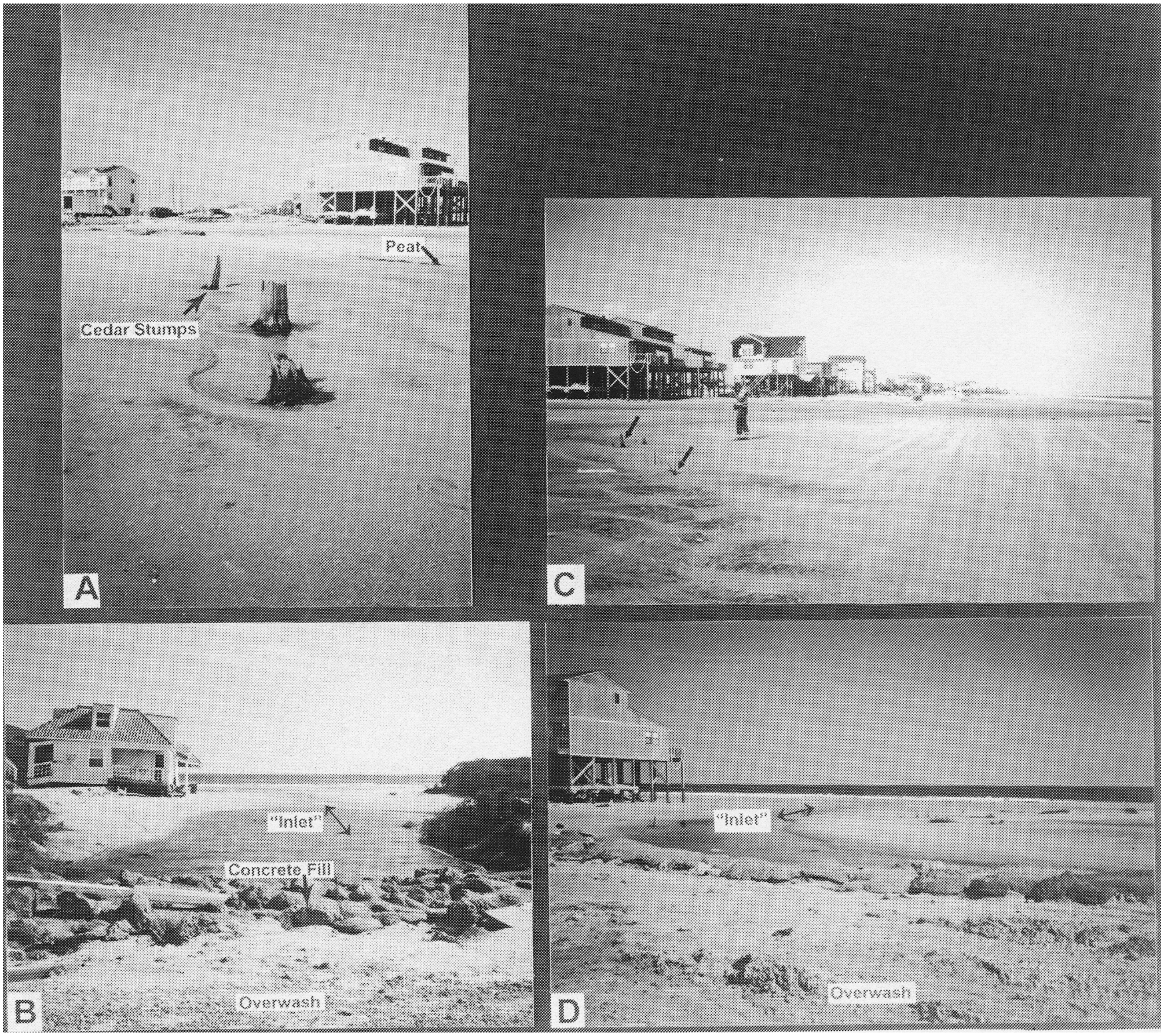
C. The narrow scarped dunes and portions of the grasslands along much of the northern segment of Topsail Island were eroded. The former road is exposed.

D. Fragments of the old road bed could be found on the relocated road after the storm. In some instances the old road rests atop peat and cedar stumps.The narrow scarped dunes and portions of the grasslands along much of the northern segment of Topsail Island were eroded. The former road is exposed.

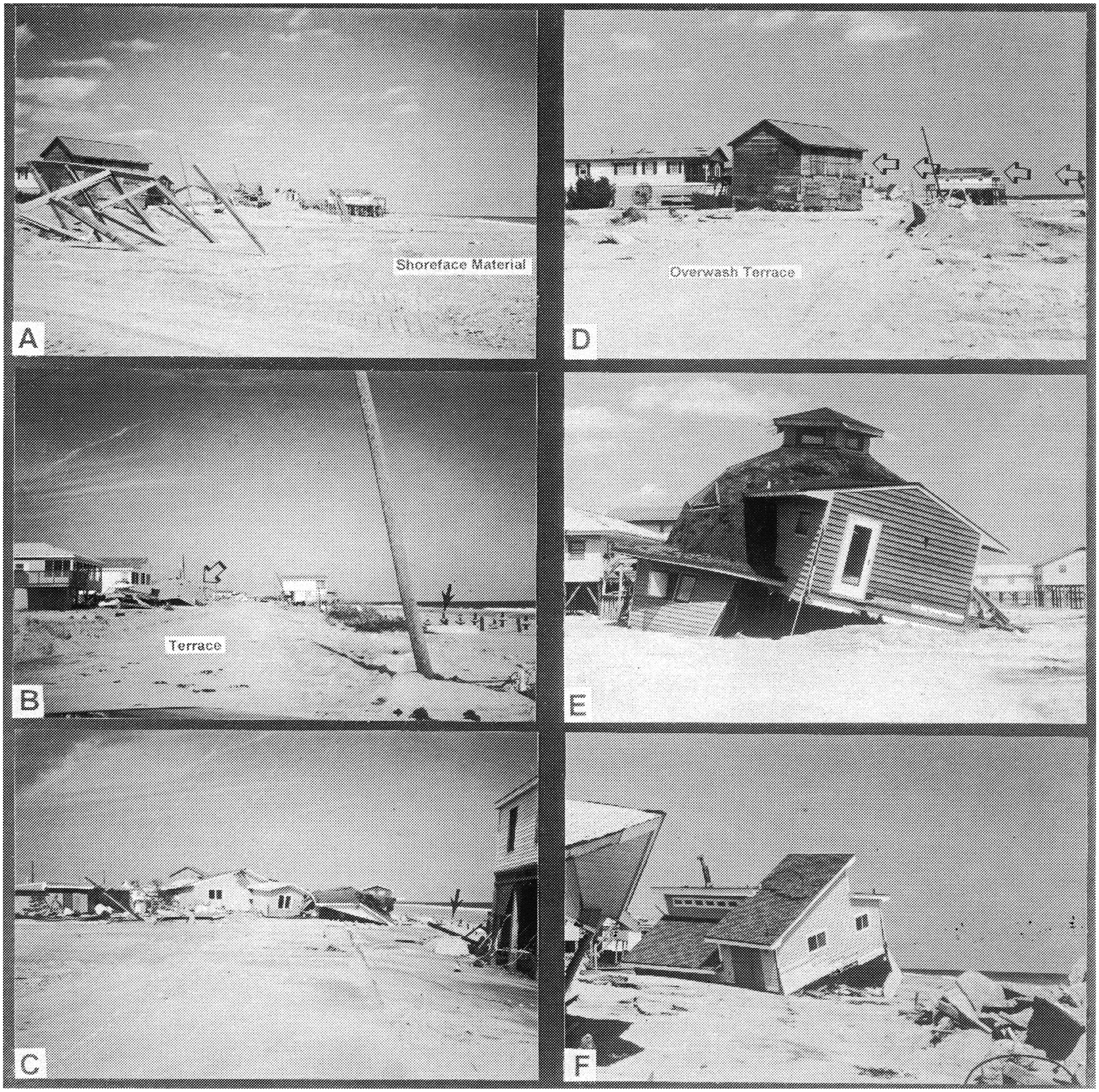
E. Erosion of the uplands along this section set the stage for the destruction wrought by Hurricane Fran.

F. All the fronting dunes have been eroded as well as the majority of the grassland. The lower floors of all the units in this photo were damaged. No storm protection was in place for the hurricane that was to follow.

Appendix 4. Post Hurricane Bertha. Northern Topsail Island
A. Low spots beneath bridges acted as washover passes or sluices. Overwash penetrated from ocean to sound. Dark areas on beach represents garnet rich heavy mineral lag deposits. Some peat is exposed.
B. Northern top of island. View to south from New River Inlet. The dune field downdrift of the inlet afforded protection for the multi-unit dwellings along the northern 1 km of the island.
C. Several of the seaward dune ridges of the accretion complex were eroded during the storm. Overwash deposited material in the intervening swales as breaches in the dune ridge were opened.
D. Oblique view south. See caption for "A".
E. Aerial view to south. Overwash is located in and around the Villa Capriani. Note the position of the old road and the relocated highway. Dune line is basically non-existent. The bridge to the mainland is located near the designation for the Pleistocene barrier.

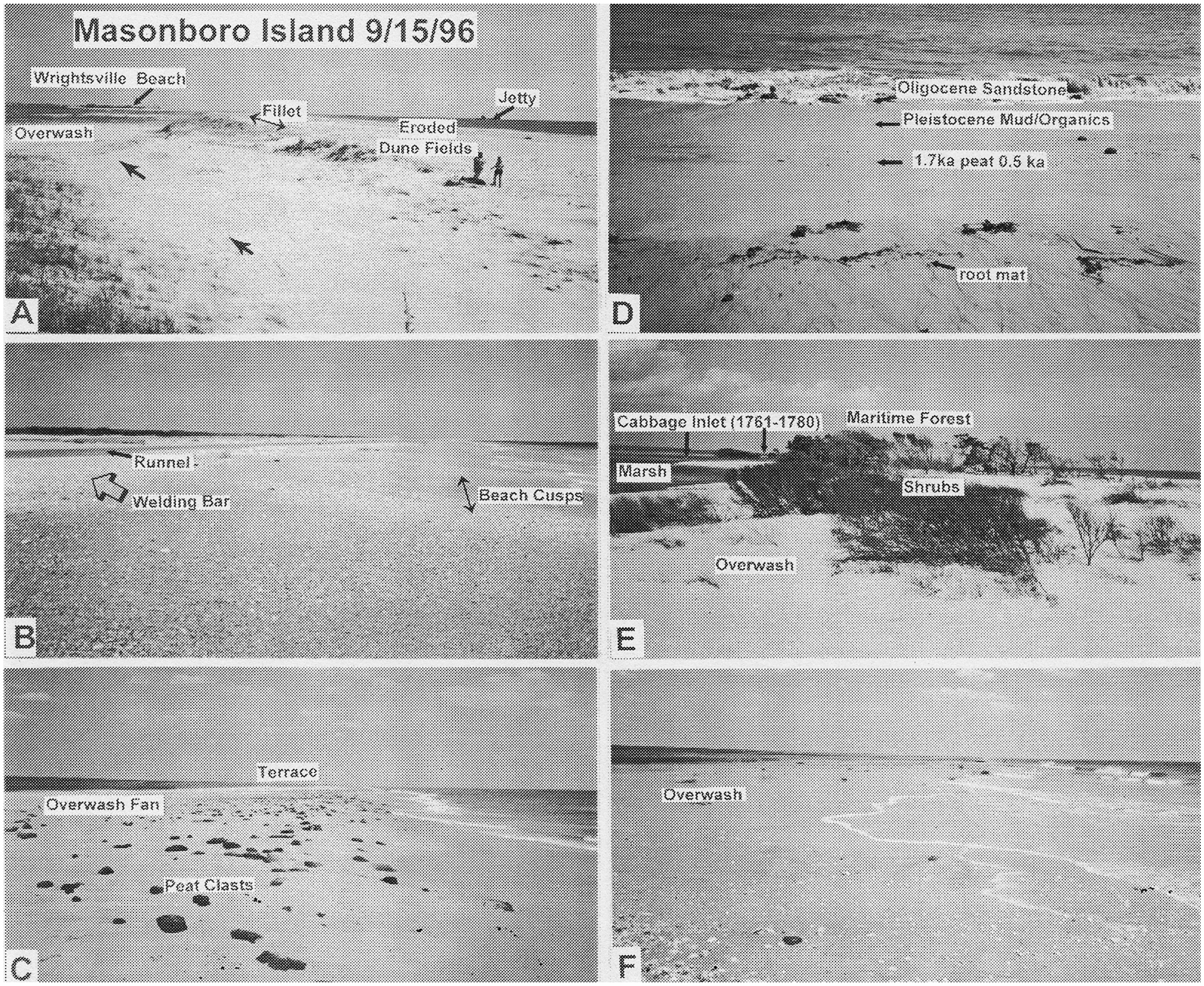


Appendix 5. Post Hurricane Fran (9/15/96) Northern segments of Topsail Island
A. Peat and relict cedar stump forests outcropped along much of the beach. The old road was built atop the peat and forest soil.
B. Most of the "inlets" were low spots of former wetlands. Peat was found in most cases on the seaward side of the beach. Concrete was poured along the road bed to prevent future breaching and failure.
C. Beach looking north. Recovery of the beach was not evident along this portion of the island. Arrows mark the locations of cedar stumps. Rock and large fragments of fossil oysters litter the upper beach.
D. Stump filed in the right portion of photo is the same field pictured in "C". Erosion during Fran removed all remaining dunes and buried or eroded grasslands in the region. Lava-like concrete is in place to protect road and hasten "closure".



Appendix 6. Post Hurricane Fran (9/15/96) Surf City
A. North view. Front row of homes were destroyed along a portion of Surf City. Poor construction provided the tools and projectiles for the surge to further damage the landward row of homes. Notice orientation of pilings. Beach consists of a variety of gravels and boulders derived from the shoreface. Ridge and runnel systems were evident along this sector of Surf City.
B. Homes once located on the seaward row were rafted off their pilings (arrow). Most if left intact, came to rest against the landward row of homes, resulting in major damage. Note the complete lack of a dune field.
C. Multiple surge pulses associated with the storm produced a stacking of poorly constructed homes as they piled one against another.
D. Some of the rafted homes remain remarkably intact. Some rested upon thick overwash deposits.
E. & F. Establishing the setback line along much of Surf City will be the subject of much debate. The natural dunes are unlikely to redevelop to their former extent. Scraped dunes offer little protection and provide a false sense of security. Much of this area is a natural hazard zone and once was the site of Stump(y) Inlet. It is likely to be impacted by every major storm event.

Appendix 7. Post Hurricane Fran (9/16/96) Surf City
A. Site is south of new high rise bridge. All of the lower floors and garages in this development were damaged by overwash. Wash-over fans and terraces extend along the entire area into the marsh.
B. Locations where mobile homes were sited did not fare well due to the 10-12 ft surge. A meter of more of sediment was deposited in this area. Many of the trailer clusters were located in the lowest and most vulnerable spots.
C. Seaward view. Debris is from destroyed oceanfront homes. Much of the region fronting the mobile homes had a poorly developed dune.
D. Overwash terrace. Many cars and other groundfloor items were "washed out" by the pulses of surge.
E. A trailer jam on the seaward side of the road in Surf City. This site was a portion of an extensive overwash terrace.
F. Debris consisting of pilings and concrete footings and framing caused considerable damage.



Appendix 8. Post Hurricane Fran (9/15/96) Masonboro Island
A. View looking toward Wrightsville Beach and the Masonboro Jetty. The dune field developed in the fillet were destroyed for the most part. The remaining dune ridge was breached in several places. At these sites washover fans extended into the marsh.
B. View to north, approximately 2.5 miles south of the jetty. A steep beach was characterized by a large ridge and deep runnel system. Along this section washover terraces extended well into the tidal marsh. No dunes remain and most grasslands are eroded as well.
C. View to north approximately two miles north of Carolina Beach Inlet. Terrace is extremely flat and overtopped by waves at high tide. Boulder size peat clasts are derived from the surf zone. Peat ages are less than 1.5 ka.
D. Seaward view immediately south of Cabbage Inlet. Oligocene sandstones and Pleistocene mud along with organic rich units of varying age crop out on the steep beach. The sandstone forms a bulge in the Masonboro Island shoreline.
E. The forested and shrub thickets that developed on the shoulders of the old inlet are now covered by extensive washover deposits. Recession of as much as several hundreds of feet has occurred in this area in the last several years.
F. View north. Site is located approximately one mile south of "E" at Old Cabbage Inlet. Inlets which were reported to have opened in this area were low, broad and extremely flat terraces. Photography was taken at high tide. Elevations in this area should increase with time as a berm rebuilds. It is highly unlikely that dunes will redevelop. The entire southern 9 km of the barrier is being translated landward via overwash.

Post Hurricane Fran
Aerial Views
Onslow Bay
Barrier Islands